Reusable Deck Support Frame for Float-Over Installations

Feasibility Study and Conceptual Design

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by

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PREFACE

This thesis is the concluding work in order to obtain my Master of Science degree in Offshore- and Dredging Engineering at the TU Delft. In the past two years, I learned a lot about the Offshore industry. I was favoured to perform my graduation thesis simultaneously at two of the leading companies in the industry: Boskalis and Mammoet. This really unique internship gave me the opportunity to learn from many experts, where I could just walk by for any discussion. The visits to the Bokalift, the Asian Hercules III, and the PTC-200 were some of the highlights during my stay. I have really enjoyed my time at both Boskalis and Mammoet and I hope to see everyone again in the future.

Although the subject was sometimes challenging and the desired direction was contradictory at times, I am happy with the result and I hope my work will kick-start a change in the future of float-over installations. I could not come to this result without the help and support of several people. I would like to use this moment to thank them for their contributions.

First of all, I would like to thank the graduation committee members, for their guidance during my master thesis. Frank Sliggers for the extensive knowledge about the subject. Jeroen Hoving for all the feedback and for providing clarity in my technical writing. I also want to thank Huub Kroezen, Bart Horsten and Robert Jan van Zijl for the supervision and the critical looks on my ideas during the graduation project.

I would like to thank all my colleagues of the solutions and innovation department of Mammoet, for having interesting and helpful discussions and of course for the Friday lunches in Schiedam.

Furthermore, I would like to thank the fellow graduate students from Boskalis for the many lunches, drinks, and all the laughs. And last but not least, I would like to give special thanks to my siblings and parents, who supported me unconditionally during my study.

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ABSTRACT

The float-over installation method is a cost-effective method for offshore platform integration. The topsides is transported in one piece to the offshore location with a heavy transport vessel or barge, there it is positioned on top of the substructure by ballasting. One of the most prominent cost assets of the installation method is the deck support frame (DSF) which supports the topsides during all phases of the float-over operation. A DSF is designed and fabricated specifically for one individual project and can cost tens of millions of dollars. After installation of the topsides, the DSF is scrapped. Due to the increasing competition, there is a need for cost-reductive innovation among installation contractors. This could be achieved by reusing the deck support frame. The purpose of this thesis is to investigate the feasibility of a reusable deck support frame (RDSF) for float-over installations.

A feasibility study is conducted in which a conceptual design of a reusable deck support frame is developed. To ensure a targeted and cost-effective design, data of past float-over installations is collected and analysed. Implementation of the RDSF must be a betterment to the float-over concept. Therefore, to effectively integrate this support frame in the already existing method, the float-over operation is optimized, followed by the development of the reusable deck support frame itself. The operational, technical and economic feasibility of the resulting design is checked on four topsides float-over projects that together form a good representation of the past.

Market analysis shows that the float-over concept is a popular method for installing fully integrated topsides. Over 95 platforms have been installed in this manner. In addition it shows the topsides between 5,000 and 20,000 tonnes with DSF heights between 5 and 15 meters are most common. Reusing the deck support frame could benefit the installation of this category as these topsides are expected to remain important in the future.

The conceptual design of the RDSF system is composed of either four, six or eight RDSF units that support one single topsides node. These individual modules make the system independently movable in the horizontal plane. Each unit consists of a set of key reusable components: one topsides interface block and four skid shoes. The components are connected by interchangeable legs which enable the system to adjust for differences in the layout of topsides. The individual RDSF units together form the RDSF system that is fully applicable on a wide range of topsides with heights up to 25 meters above deck and weights up to 25,000 tonnes. Additionally, the RDSF system offers the possibility to integrate an existing jacking system so that one onshore operation can be eliminated. This results in a faster and more cost-effective installation.

The RDSF system is found technically feasible for the most critical design loads that occur during the voyage. It is perceived that the capacity of the system is mainly limited by the load introduction capacity and stability of the heavy transport vessel. A configuration tool is developed to assess the global strength, geometry and estimated weight of the different RDSF configurations. This tool helps designers with configuring the system during preliminary design of future float-overs. The cost analysis has shown that the system's break-even point is reached after two projects with four topsides nodes and after four projects with eight topsides nodes on average, considering a steel fabrication price which is 33% higher than for a single-use DSF.

It can be concluded that the designed RDSF system is feasible and an attractive cost-saving asset, particularly for topsides with four support nodes. It is recommended to perform a detailed structural analysis of the grillage and RDSF system before commencing fabrication of the system. In addition, the market conditions must be validated as the design is targeted based on historic data which may not apply to future projects.

ABBREVIATIONS

Important abbreviations in this thesis:

DSF	Deck Support Frame. This is the current solution to support topsides during float-over installations. A single-use deck support frame is dedicated to only one topsides float-over installation. The current DSF is used as a threshold throughout this report.
LSF	Load-out Support Frame. Similar to the DSF.
RDSF	Reusable Deck Support Frame. The 'RDSF system' is the name of the conceptual design of the reusable deck support frame, the main subject of this report.
H_{ad}	Transportation height above deck. The distance between the deck of the vessel and the bottom of the topsides. This distance is equal to height of the DSF and grillage together.
HTV	Heavy transport vessel.
GBS	Gravity based structure.
TLP	Tension leg platform.
SPMT	Self propelled modular transporter.
T&I	Transport and Installation.
EPIC	Engineering, Procurement, Installation and Commissioning.
HHI	Hyundai Heavy Industries.
SHI	Samsung Heavy Industry.
DP	Dynamic positioning.
MCA	Multi-criteria analysis.
GM	Upright stability arm.
CoG	Centre of gravity
VCG	Vertical centre of gravity.
LCG	Longitudinal centre of gravity.
TCG	Transverse centre of gravity.
USD	United States Dollars

CONTENTS

1

INTRODUCTION AND PROBLEM STATEMENT

Petrochemical offshore platforms are designed for the exploration, production, storage and processing of oil and natural gas in offshore oil fields. From a structural perspective, an offshore platform consists of two sections. The upper section, called the topsides, consisting of all the facilities such as drilling, production, and/or accommodation units and the lower section, called the substructure which supports the topsides at a certain 'safe' height above sea level.

Generally, the topsides and substructure are designed and fabricated separately [1]. The complex topsides fabrication often takes place in Asia, whereas the substructure fabrication is spread more globally. After the fabrication of both sections, the topsides and substructure are transported to the installation site in order to complete the offshore platform and become fully operational. The substructure is positioned and secured in the seabed. Thereafter, the topsides is installed on top of the substructure at a safe distance above sea level.

The offshore installation of the topsides on top of the substructure can be executed in several ways. The following two are the most common methods [2]:

- Lift installation,
- Float-over installation.

The lift installation is the most common method for installing topsides offshore. The method makes use of a heavy (semi-submersible) crane lift vessel to lift the topsides onto the substructure. However, the lift installation method is limited by the capacity of the crane vessel. Only a limited number of heavy lift crane vessels is able to install the topsides heavier than 5,000 tonnes [3]. This group of vessels comes with high day rates and mobilization costs. Modularizing the heavier topsides and installing them with the aid of multiple lifts avoids this problem, however, extensive offshore hook-up and commissioning work is involved.

The float-over method is an effective installation method for installing topsides and it has been considered to constitute normal practice since the eighties [4]. The float-over installation method makes use of a vessel or barge which first transports the topsides to the installation location and then mates the topsides onto the substructure by ballasting. The float-over installation procedure is described in chapter 2. The method becomes cost-effective for the heavy topsides that exceed the capacity of locally available heavy lift crane vessels, where the weight of the topsides exceeds approximately 5,000 tons.

Figure 1.1: Arkatun Dagi topsides including DSF structure

The float-over installation can achieve significant savings both in time and costs for the offshore hook-up and commissioning which takes place onshore rather than offshore. In recent years, the float-over installation method has evolved to a fast and safe method for installing topsides. It has proven to be a competitive solution in areas where semi-submersible crane vessels are a rare commodity. For topsides installations exceeding the largest available lift capacity of about 10,000 tons, the float-over installation is actually the only feasible platform integration option.

New offshore oil and gas platform installations are initiated by field operators. Some experts expect that offshore oil will be important until at least the year 2050. Offshore oil production, however, is expected to constitute half of today's production rate [5]. It is also expected that from 2020 onwards offshore gas production will start to decline, due to the decrease in the price of unconventional onshore gas such as shale. However, others say that in the longer term, the shale production is expected to plateau, leaving offshore oil and gas well placed to meet the subsequent demand growth [6]. Despite all these different expectations, the oil price level of the recent years have resulted in only a few offshore platform investments. The small selection of new platform installations leads to the more competitive float-over installation market currently being observed by installation contractors. Cost reduction for the entire installation operation needs to take place for the method if it is to remain competitive.

The three most prominent cost assets of a float-over operation are the deck support frame (DSF), the ballast tanks and the mooring system. The DSF is used to support the topsides during all phases of the float-over operation. The DSFs are designed and fabricated specifically for each individual project and can cost up to tens of million of Dollars. After topsides installation, this DSF is broken down into small pieces of steel and recycled for new purposes. The heaviest topsides Arkatun Dagi on top of the DSF are shown in Figure 1.1.

Steel is the most recycled material in the world and it is, in essence, a 100% circular product [7]. However, re-purposing steel by melting requires vast amounts of additional energy. When intensifying the use phase of the DSF by reusing (and or re-manufacturing) it for multiple installation projects, the service life of DSFs can be extended. The extension of the service life reduces the additional required energy for the entire steel cycle. Next to these environmental benefits a substantial economic advantages can be achieved by reusing the DSF. The single investment for engineering and manufacturing the reusable DSF can be depreciated over multiple projects, where it currently is depreciated only over one single project.

1.1. RELEVANCE OF THE STUDY

Due to increasing competition, there is a need for cost-reductive innovation among installation contractors. This could be achieved by reusing the deck support frame. Installation contractor offer the service to transport and install (T&I) topsides at offshore locations.
This report is realized for Boskalis N.V. and Mammoet B.V.. Both Boskalis and Mammoet are topsides installation contractors that make use of the float-over installation method in their businesses. They have their own disciplines within the float-over installation process as described in chapter 2. Due to the competitive market Boskalis and Mammoet are facing difficulties in acquiring new topsides installation projects. They are therefore looking for cost reduction solutions to offer more cost efficient tenders. Boskalis and Mammoet support this research by offering knowledge and making their extensive data accessible. The aim of this study is to increase their market share, therefore the strategic decisions made in this study tend to be aligned within their capabilities.

The collaboration between Mammoet and Boskalis is expected to lead to a more efficient float-over process thereby reducing the cost of the whole process. Currently Mammoet's procedure does not include any float-over installations, so the collaboration provides a change to expand their market.

Next to the benefits for the installation contractors, the realization of the RDSF is expected to also have a significant influence on other main stakeholders, including the field operator (like Shell, BP, or Total) and the topsides fabrication yard (like Samsung or Hyundai). Their interest does not necessarily lie in cost reduction but rather in increasing safety and workability.

1.2. STUDY OBJECTIVES

At first sight, the RDSF is expected to lead to a cost reduction for the float-over installation operation, by replacing the design and manufacturing of dedicated single-use support frames. In this study the intended feasibility of the RDSF is further investigated. The main research question of this study is as follows:

Is it feasible to perform float-over installations with a reusable deck support frame?

Here the word 'feasible', captures the operational, technical and economic feasibility of an RDSF. This research question has led to the main objective:

Design a reusable deck support frame in order to optimize the float-over installation method and reduce the costs of the entire operation.

This objective is achieved by answering the following specific sub objectives:

- *To acquire an overview of all the topsides installations by the float-over installation method.*
  Equipment dedicated for reuse has to comply with future topsides specifications. However, determining the future specifications of the topsides is an impossible task. Therefore, design decisions will be made based on the collection of past float-over installation projects.
- *To identify the most interesting range of topsides for repetitive installation with a reusable deck support frame.*
  The defining parameters of the collection of float-over installations will be investigated from the point of view of trends. The 'special' float-over installations will be discarded from the main study as they are not o interest to repetitive design.
- *To assess all the stakeholders interests and translate them into a set of requirements and preferences.*
  The establishment of clear requirements for the design ensures a measurable solution for the problem. In order to set up the requirements, a clear perception of the problem is needed. Therefore, the requirements and preferences of all stakeholders need to be balanced.
- *To generate various concepts of the reusable deck support frame which improve the float-over installation operation.*
  To demonstrate the technical feasibility of a reusable deck support frame, multiple preliminary concept designs will be developed. The current process surrounding topsides installation will be examined to see where improvements can be made in conjunction with the reusable deck support frame.

- *To evaluate the technical feasibility of the reusable deck support frame concept design.*
  The technical feasibility of this reusable deck support frame concept design will be validated for both its working principles and its structural integrity.
- *To study the economic feasibility of the reusable deck support frame.*
  Technical innovations only succeed when they are economically feasible. In order to study such economic feasibility, a preliminary business case will be set up.
- *To evaluate the applicability of the reusable deck support frame design on different topsides and vessels.*
  To conclude, the overall feasibility the reusable deck support frame concept will be evaluated.

1.3. APPROACH TO THE STUDY

This study sets out to answer the research question and to achieve all the stated research objectives. The phases of the "Methodological design approach" are used to determine the most suitable concept [8].

1. Exploration
   The aim of the exploration phase is to define the problem. The problem statement is developed by conducting multiple in-house interviews. The outcomes are processed with the 5W2H method to acquire an accurate problem statement, as can be seen in section E.1. All the data on float-over installations that was gathered during the exploration phase, was mainly obtained through an in-house study conducted at Boskalis and Mammoet. All the data on competitor projects was mostly obtained through journals, newspapers, databases or specific professional websites.
2. Analysis
   The existing float-over method and the corresponding single-use DSF was analysed using the collected data. The entire topsides installation process was examined using the function analysis method to see where improvements could be achieved using the RDSF. To ensure that the innovation fitted the demand, a stakeholder analysis was performed which led to a program of requirements [8].
3. Development
   Multiple concepts of the RDSF were developed in this phase. This development was split up into two parts:
   (a) The first part of the concept development focused exclusively on the operations of the float-over method. This concept development develops the most efficient operational sequence with the use of an RDSF. During this analysis the reusable deck frame concept is seen as a 'black box'. The result of this chapter is an operational sequence of all the steps of the float-over installation with the use of a RDSF.
   (b) The second part of the concept development focuses on the development of the RDSF (the former 'black box') itself.

   Both parts follow the same steps but both at a different level of detail. Solutions are found for the sub-functions by means of different techniques, like brain-storming sessions. These solutions were collected by using a morphological overview [8]. After that a number of unique concepts were created by a combination of the previously mentioned solutions. The unique concepts are evaluated with regard to the functional requirements and the preferences set up in the exploration phase. With help of a multi-criteria analysis the preferred concept can be chosen [9].
4. Detailing
   The preferred design is developed to form a more detailed design. The preferred design is elaborated in some detail and evaluated with regard to the feasibility described by Easterbrook [10] involving operational, technical and economic feasibility. The fourth type of feasibility, schedule feasibility, is related to the time when a new system is introduced. This is not taken into account in this study, as it is not expected to become a problem.
5. Realisation
   The realisation phase embraces the goal of entering the market with the innovation. This part of the methodological design approach was not performed during this study.

1.4. STRUCTURE OF THE REPORT

The purpose of this report is to provide a concise package of information illustrating the design and feasibility study pertaining to the reusable deck support frame for float-over installations. The main body of the report is divided into four sections containing one or multiple chapters corresponding to the various phases of the "methodological design approach" which are: Exploration, Developing, Design and Conclusions. The report is supported by the appendices but can also be read individually. The outline of this study is illustrated in Figure 1.2.

The report starts by introducing the problem and providing the justification for this study in Chapter 1. Chapter 2 describes the state-of-the-art of topsides installations regarding the float-over method. In Chapter 3 the market analysis is presented which is used to develop the program of requirements for the design that is given in Chapter 4. The development of the RDSF is given in Chapter 5 and 6. In Chapter 7 the preferred design is elaborated in some detail. The economic feasibility results in a preliminary business case which is described in Chapter 8. The conclusions and recommendations for implementation of the design are given in Chapter 9.

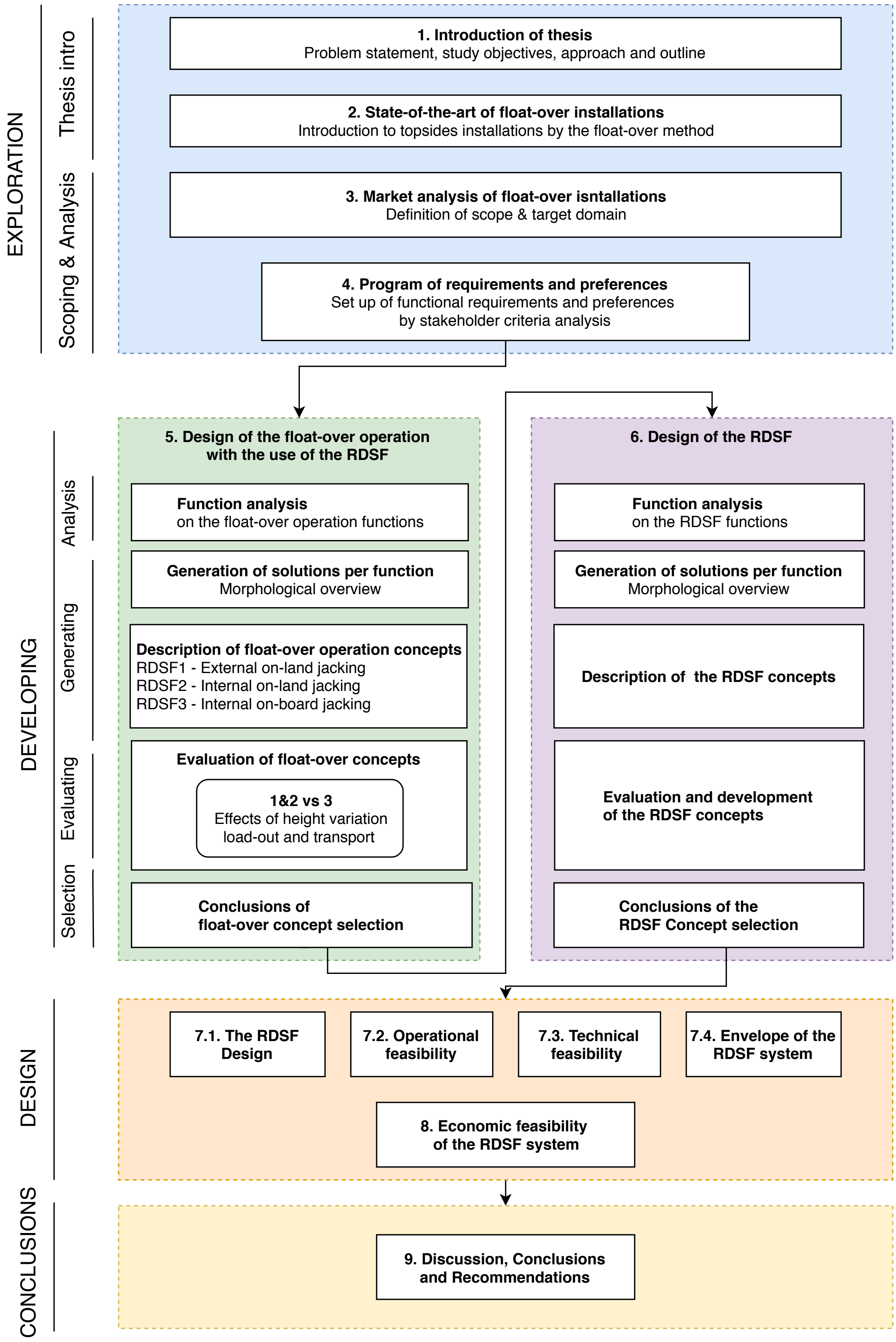
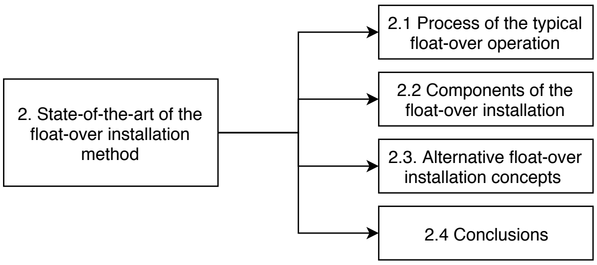


Figure 1.2: Study Outline

2

STATE-OF-THE-ART OF THE FLOAT-OVER INSTALLATION METHOD

The topsides float-over installation method is used to integrate topsides safely at an offshore location in order to complete the platform since 1970 [1]. Since the introduction, the float-over technology has matured over the years to a cost-efficient installation method. In this chapter, the state-of-the-art of offshore topsides installations by the float-over method is described. A brief introduction of the float-over installation concept is given and the role of Boskalis and Mammoet within a float-over project is described in this chapter. For a more elaborate description on topsides installation by the float-over method see Liu [1].



2.1. PROCESS OF THE TYPICAL LOAD-OUT AND FLOAT-OVER OPERATION

The typical single vessel/barge is the most common float-over method, whereof an overview is shown in Figure 2.1. The numbers 1 to 4 indicate the main components of the method. The topsides (1) is transported on top of a (semi-submersible) heavy transport vessel (HTV) or barge (4). The topsides is supported by the deck support frame (DSF) (3) which spreads the loads to the deck and enables installations at heights. The topsides protrudes on both sides of the HTV to enable set-down of the topsides on top of the substructure (2). The typical float-over operation requires a substructure with slot in order to set-down the topsides.

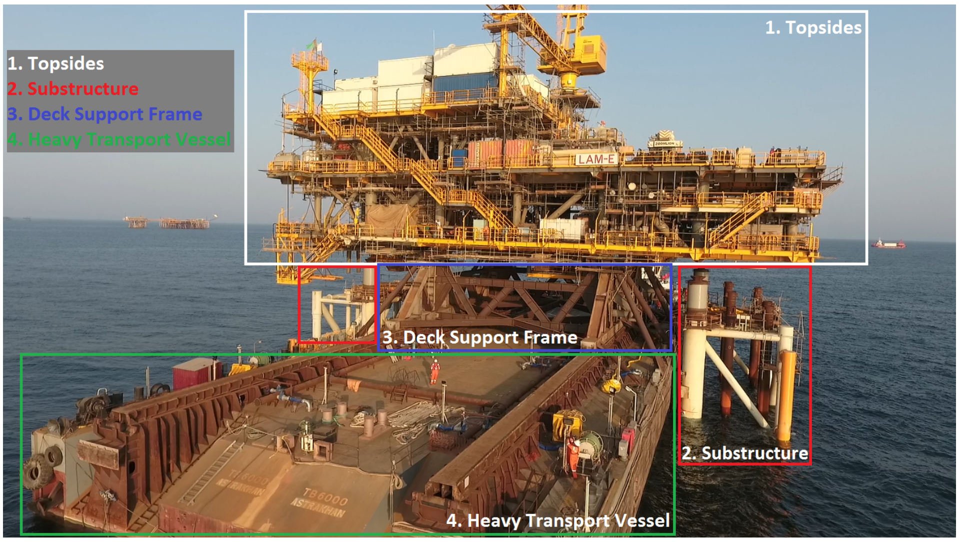


Figure 2.1: Main components of a typical float-over installation (Orca Offshore)

The installation of a topsides by the float-over method has five main operations from start to finish: the fabrication phase, the jacking phase, the load-out phase, the transportation phase and the float-over phase. The operations are illustrated in Figure 2.2 and elaborated individually below. The numbers in this figure, correspond to the phases of the installation process.

Boskalis' scope within a float-over project includes all operations at sea: the load-out operation (including ballasting), the voyage and the float-over operation at the site. Mammoet scope includes all on-land activities: the jacking and the load-out operation. The red line in Figure 2.2 illustrates Mammoet's current business and the blue line Boskalis' current business. The DSF is the blue object in the figure and is the main subject of this thesis.

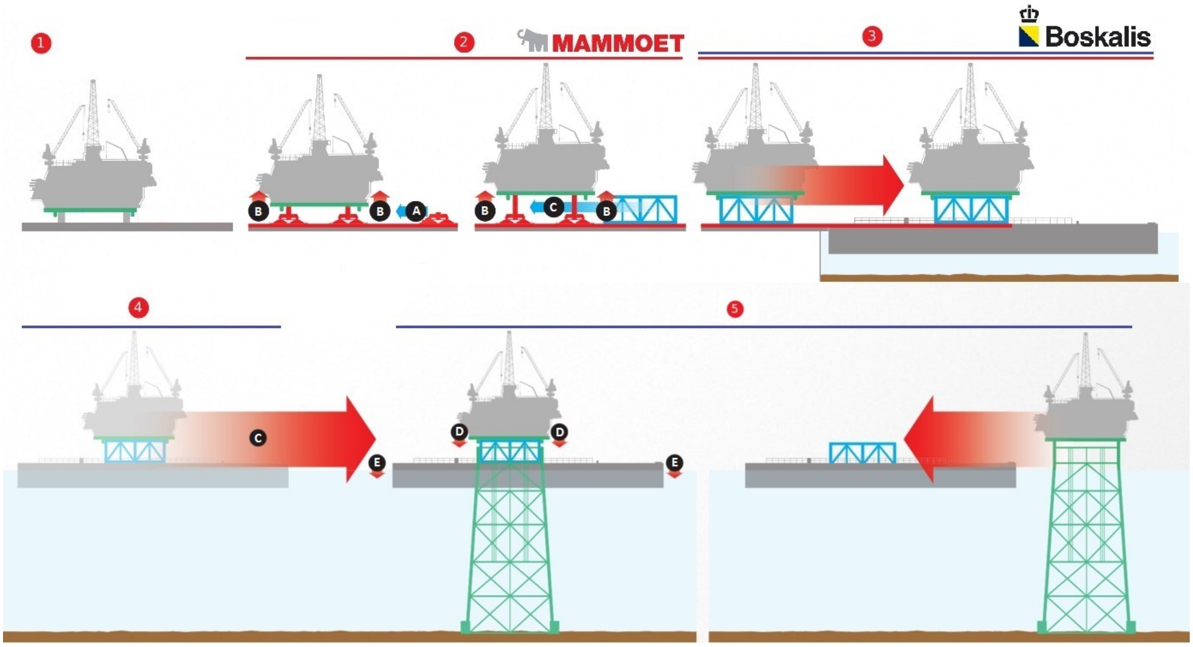


Figure 2.2: Load-out and float-over process *(Mammoet World, 2014)*

1. Fabrication phase

The fabrication of the topsides is done by specialized yards all over the world. In general, topsides are fabricated as low to the ground as possible due to the economic and operational benefits.

2. Jacking phase
For installation at the offshore site a certain vertical air gap is required. This air gap is obtained by pushing-up the topsides at the yard with a jacking system. This jacking phase includes three sub phases corresponding to the letter (A, B, C) in Figure 2.2; the installation of the jacking equipment (A), the actual jacking of the topsides (B) and the installation of the DSF underneath the topsides (C). The jacking system consists of hydraulic jacks and modular stacking pieces which are stacked on top of each other. Each cycle the hydraulic jack pushes the topsides up, a new modular stacking piece is inserted, and the cycle is repeated until the required elevation is obtained. After the completion of the jack-up, the DSF is installed underneath to perform the load-out. Jack-ups are currently only performed in quasi-static environments at solid grounds. The Mammoet JS2400 is one of the heaviest jacking system with a capacity of 2400tons per tower.

3. Load-Out phase
During the load-out phase, the topsides is moved onto a heavy transport vessel (HTV) or barge. This load-out can be done by skidding, where the topsides slides over low friction panels by puling or pushing with hydraulic cylinders. The load-out can also be executed by Self Propelled Modular Transporters (SPMT). Dominating requirements for the load-out stage are governed by the topsides weight, the tidal range, and the quayside dimensions. During the load-out, the weight of the topsides is gradually transferred from the quay to the HTV.

4. Voyage phase
After completion of the load-out, the topsides is sea-fastened for voyage to the installation site. Environmental conditions are most severe during transportation and therefore the DSF loads are based on these conditions. However, the intensity of the environmental conditions do really depend on the distance and route of transport. The voyage operation is a weather unrestricted operation. This in contrast to the float-over operation which is weather restricted. For weather unrestricted operation apply stricter regulations than for weather unrestricted operations [11].

5. Float-over phase
After transportation of the topsides to the installation site, the topsides arrives at stand-off location where preparations for the float-over start. Float-over preparations contain removing the sea fastening, start-up mooring or dynamic positioning (DP), and monitoring the incoming weather. When a large enough allowable weather window is expected, the float-over operation can be performed. These operations are indicated with a letter in step 5 of Figure 2.2. The float-over operation starts by moving the vessel into the substructure slot (C) to the point where the topsides nodes are vertically aligned with the substructure legs. Once the go-decision has taken place, the mating of the topsides starts by ballasting the HTV to lower the topsides (D). Once the topsides contacts the substructure, the load is gradually transferred onto the substructure. When the topsides loads are fully transferred to the substructure and the topsides comes loose from the vessel (E), the HTV is retracted and the installation is completed.
The float-over operation is governed by relative movement and impact loads between substructure and vessel. The long waves of swell sensitive areas do have a significant influence on the vertical motion of the vessel and complicates the mating operation. For these areas, it is common to use an additional fast mating system by retracting hydraulic cylinders.

2.2. COMPONENTS OF THE FLOAT-OVER INSTALLATION

In this section, the main components of the most common typical single vessel float-over installation are described. Understanding of the float-over installation method and its components is required to apply innovation on the process.

THE TOPSIDES

The topsides is the main subject of the float-over installation. Topsides installed by a float-over installations are fully integrated with minimal commissioning time after installation. For the heavy topsides, fully integrated topsides installation is more attractive than modularizing it in order to perform crane lift installations.

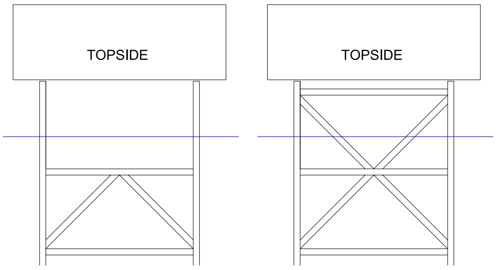
SUBSTRUCTURES

There are two types of substructures which differ in the method of obtaining vertical support forces. The first type,the floating substructure, obtains the vertical support of a buoyant force caused by the submerged volume. The second type, the fixed substructure, is supported by the sea floor. Amongst the floating substructures are tension leg platform (TLP), semi-submersibles and SPARs. Fixed structures can be categorized into jacket structures and gravity based structures (GBS). The float-over installation method is applicable for topsides integration on both floating and fixed structures. However, the location of topsides integration for floating structures (and sometimes GBS structures) can be chosen, because floating platforms are still transportable after topsides installation. Desired environmental conditions for topsides installation can be found in an inshore sheltered area. Making the float-over operation for floating structures less complex. The floating platforms can be tugged away from a calm environment to the final installation location after the float-over installation.

Different float-over concepts can be applied for each substructure, which are described in section 2.3. Ideally, during the platform's feasibility study, the float-over method is decided before the commencement of the substructure design. From this point on, the selected concept should not be changed during the project execution. Changing the selected installation method affects the substructure selection and design.

There are two types of substructure designs for both floating as fixed structures. Examples of both types are shown in Figure 2.3.

1. **Substructures with a slot (Figure 2.3a).**
   A substructure with a slot is specifically designed for float-over installations. A slot is an opening in the substructure where the HTV can sail through in order to position the topsides exactly on top of the substructure. For floating structures, this slot is between the floating columns and for fixed structures, this is a protruding frame above the waterline.
2. **Standard substructures *without a slot* (Figure 2.3b)**.
   Standard substructures, like normal jackets, mono-piles and SPAR's do not have an opening (slot) for an installation vessel. The standard substructures without a slot, are build more efficient and require therefore less steel. Standard substructures are therefore more cost-efficient. This in contrast to the float-over operations on standard substructures, which are more difficult to perform and therefore more expensive.



(a) Substructure with slot (b) Standard substructure

Figure 2.3: Substructure types

HEAVY TRANSPORT VESSEL

A (semi-submersible) heavy transport vessel (HTV) is used to transport the topsides from the yard to the installation site. Once arrived at the installation site, the HTV lowers the topsides onto the substructure by ballasting the vessel. In appendix F, a list of HTVs of Boskalis and competitors is given that have performed float-over installations in the past. The following criteria are set for HTVs to perform a float-over installation [11]:

1. **Deck capacity must not to be sufficient to support topsides.** The deck stresses must not exceed vessel strength capacity. Every HTV has a limited deck capacity depending on the local strength parts,

including stiffeners, frames, bulkheads and girders. This limited capacity can be increased by using grillage structure and a DSF for load spreading.

2. **Ballast capacity must be sufficient to ensure vertical clearance during mating phase**.
   The ballast system of the HTV must have sufficient capacity to ensure clearance after mating the topsides with the substructure.

3. **HTV must have an open aft**.
   The HTV must have an open aft deck or removable caissons to be able to sail away from the jacket the after installation of the topsides. This does not apply for alternative float-over methods on standard (non-slotted) jackets, where the vessel can sail sideways to ensure clearance from the substructure.

4. **Width of vessel has to comply with substructure slot width.**
   The HTV breadth has to match the the substructure slot width in order to perform the mating operation.

5. **System (HTV and cargo) has to comply with stability criteria.**
   Stability criteria are set up to by classification society / warranty surveyor to ensure for safe operations. The following stability criteria are: the IMO A167 & IMO A749, these are approved by warranty surveyors including DNV-GL. The stability criteria are subdivided into intact stability criteria and wind stability criteria:

   Intact stability criteria: IMO A749 CH.33536 Intact criterion:

   (a) The initial metacentric height, GM, is not be less than 1.0 meters.
   (b) The angle from 0 deg to RAzero is not be less than 35 degrees.

   Wind stability criteria:

   (c) The angle from 0 deg to wind-RAzero is not be less than 10 degrees.
   (d) The intact stability ratio is not be less than 1.4 times the absolute wind area ratio.

   Criteria b, c and d are based on extreme environmental conditions which can occur during transport and do not apply for weather restricted operations.

DECK SUPPORT FRAME

The deck support frame (DSF), or load-out support frame (LSF), is one of the cost dominating assets of a float-over operation. The DSF has two main functions. First, to make installation at a certain air gap possible. And second, to spread and introduce the heavy loads into the HTV deck during all phases of the installation. The air gap value depends on the local environmental conditions at the platform's site and is therefore varying widely among all installed topsides. The DSF weighs about 10-15% of the topsides depending on parameters such as installation height.

It is exceptional to reuse the DSFs in for multiple float-over installations. EPIC contractor McDermott, however, did make use of a reusable DSF for its yard in Indonesia. The McDermott Load-Out Beams illustrated in Figure 2.4 consist of two very stiff beams in longitudinal direction, where each beam is supported by two skid tracks. Adjustments in transverse direction are possible by varying the distance between the skid tracks. The distance between support points over the length and height of the beams is fixed in this design. The applicability of the McDermott Load-Out Beams on different sized topsides is therefore minimal.

Figure 2.4: McDermott Load-Out Beams (McDermott)

Jacking system

The jacking system pushes heavy loads, the topsides in this case, upwards to gain elevation. The jacking system allows the topsides manufacturer (or yard) to build the topsides at ground level and subsequently raise it to the desired level to install the DSF.
Jacking is performed by a hydraulic cylinder system, that lifts the topsides step-by-step while inserting new stacking modules below the structure. The modular nature and cumulative lifting capacity allow the system to lift any load to a variable height. The jacking system is limited to an high amount of side loads. Therefore, the jacking operation is only done in a static environment.

Figure 2.5: North Rankin B Topsides with DSF and Mammoet Jacking System JS2400 (courtesy Mammoet

Skid system or SPMT's

The load-out operation is commonly performed by either a skidding system or SPMT's. Both options to horizontally move extremely heavy topsides. The skid system includes a reinforced skid track where blocks with very limited friction are placed in. Inside this track, on top of these blocks, a skid-shoe or skid-beam is placed which is able to slide along the track. A horizontal force obtained by cylinders pushes or pulls the topsides along the track. The skid track can only be fitted in a straight line which limits sideways manoeuvrability. The self-propelled modular transporters (SPMT). These trailers are highly manoeuvrable but have a limited load capacity. SPMTs are mostly used for transports of the less heavy topsides modules.

2.3. ALTERNATIVE FLOAT-OVER INSTALLATION CONCEPTS

The following alternative float-over concepts are used to install topsides. These concepts slightly differ from the typical method described in 2.1.

2.3.1. SELF-INSTALLING PLATFORMS

The topsides and substructure of self-installing platforms are already combined before stationing at the destination. An example of a self-installing platform is Shell's Malampaya phase 3, where the platform is positioned by tugboats and elevated by lowering its legs using a jacking system [12].

2.3.2. SMARTLEG INSTALLATION METHOD

A Smartleg installation method (Figure 2.6a) is a relative new float-over concept and uses the same techniques as the typical single vessel concept. The main difference with a typical float-over is that the elevation of the Smartleg structure is obtained by jacking the topsides at the substructure *after* the float-over installation. With this method, the topsides can be transported low on deck and therefore only a small DSF is required. There are three different Smartleg installation methods that can be considered. They differ on the jacking method at the substructure. The different Smartleg structures are described below.

1. **Jacking with extendible legs through topsides**.
   This concept makes use of legs penetrating through the topsides. The topsides is elevated by pulling the topsides through the legs upwards. This installation method is already been performed by Mammoet using a strand jacks system for the transformer station Sylwin Alpha of operator Tennet, see (Mammoet - Sylwin Alpha case) and Figure 2.6a.
2. **Jacking with extendible legs through substructure**.
   For this method, the extendible legs are pre-installed into the jacket substructure. The topsides is lifted by lifting these legs using a stand-jack system. This method has never been used before. Intensive modifications to the jacket required to install the extendible legs.
3. **Jacking in-between substructure and topsides**.
   This method makes use of step-by-step jacking of the topsides between the substructure and the topsides. For this method minor adjustments to the topsides and structure are required. An example of jacking in between topsides and substructure is Ekofisk 1987 and Indonesia 2013 [13].

Recently in the North Sea, a couple of Smartleg topsides are installed. However, the Smartleg installation method is shown to be unreliable. For example, for the Yme Mopustor platform where after just 1 year of production cracks were found in the grouting connection of the legs [14]. This resulted in consequently removal of the platform in 2016 by Allseas [15].

Many Smartleg platforms are subjected to structural issues caused by the loose connections between substructure and topsides. Cracks can propagate in this connection and cause structural faults to the platform due to the repetitive character of external (sea) loads. Also operational challenges play a significant role by the Smartleg method. For example, the jacking operation is performed in the splash zone (which is the impact zone of waves), where any delays in the during the operation could lead to serious damage to the topsides.

2.3.3. MULTI-VESSEL CATAMARAN FLOAT-OVER

Multi-vessel catamaran float-overs are mainly performed on standard substructures. A catamaran is formed by two (or more) float-over vessels/barges and the topsides. The opening between the vessels is large enough to envelop the substructure for the mating operation. The most challenging part is the mating operation where the motion of multiple bodies needs to be controlled in a synchronized way. Therefore, multi-vessel catamaran float-overs are only executed in sheltered conditions like Norwegian fjords. The workability of the installation operation decreases drastically when subjected to harsher conditions. The catamaran is formed near the installation site. A third vessel is required for the transport of the topsides from the yard to the installation location. A beautiful example of a catamaran float-over is the recent Aasta Hansteen float-over by Boskalis in 2017, see Figure 2.6b (Aasta Hansteen).

2.3.4. SINGLE VESSEL CATAMARAN FLOAT-OVER

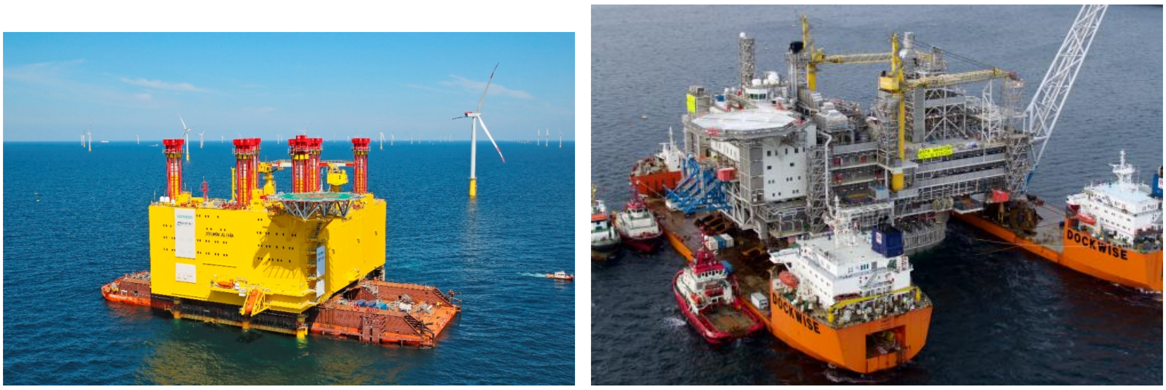
A single vessel catamaran float-over envelops the substructure to install the topsides. The method combines the advantages of the cost- and steel-efficient substructure design and single body motions. The Allseas Pioneering Spirit is a vessel which uses this installation method, see Figure 2.6c. The method is however restricted to the slot dimensions of the vessel. In the case of the Pioneering Spirit: a 122 meter long and 59 meter wide slot (Allseas Pioneering Spirit). Since the depth of this vessel reaches 30 meter, a second barge is required to perform the load-out of the topsides at shallow ports. Another topsides transfer is required from this second barge to the Pioneering Spirit.

2.3.5. FORKLIFT METHOD

With the forklift float-over method, the topsides is skid out over the stern or side of the vessel over two parallel cantilever beams. The dimensions of the beams are chosen so that the substructure fits in between the cantilever beams. The forklift concept is used for standard substructures as shown in Figure 2.6d. During the transport, the topsides is located at centre of vessel in order to have minimal vessel stresses during transport. This means that the topsides needs to be skid outboard in order to perform the mating operation. During the mating operations, roll motions can cause large relative motions at the topsides, making the workability for the mating operation limited resulting to apply on low sea states only. The outboard centre of gravity also causes reduction of stability and therefore requires large vessels with sufficient ballast capacity. The outboard weight of the topsides needs to be spread into the vessel and therefore a certain height for the forklift construction is required. This minimum topsides height limits the number of topsides which can be installed using the forklift method.

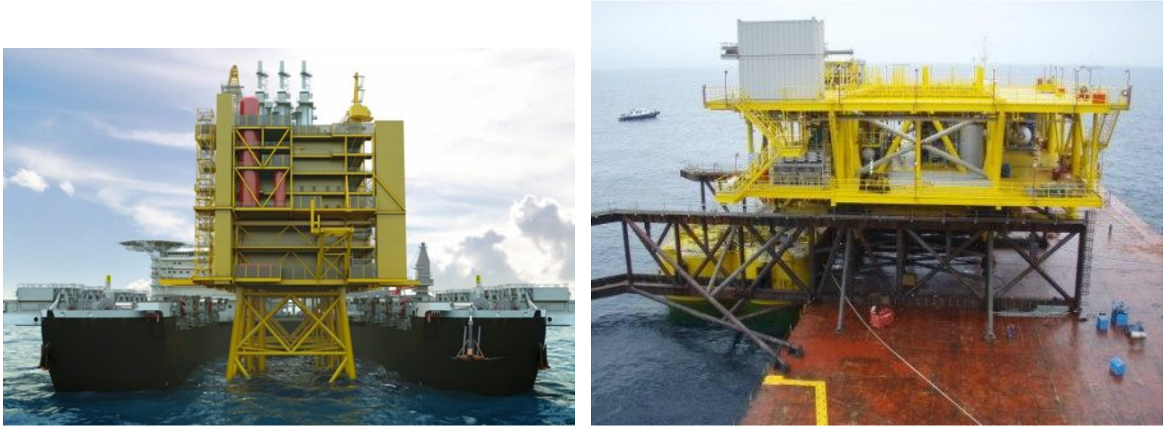
2.3.6. SKID-OUT INSTALLATION

The jack-up and skid-out concept of Global Maritime (GM-J350M) has never been used before. This jack-up and skid-out installation method can be compared to a reverse load-out operation, with the substructure as the solid base and the vessel as moving object. However, (skidded) load-out operations are only performed in port conditions. A load-out operation requires tight tolerances on relative motions. Limits the workability enormously which makes this solution not interesting for repetitive float-over installations. A solution to prevent the high relative motions is found by using a jack-up vessel which is fixed onto the ground next to the substructure. The jack-up ensures a stable platform where minimal relative movement occurs between the jack-up and substructure.



(a) Smartleg Platform (Sylwin Alpha by Siemens)

(b) [Multi-vessel catamaran (Boskalis)



(c) Single vessel catamaran (Allseas)

(d) Forklift (ICON Engineering)

Figure 2.6: Alternative float-over concepts

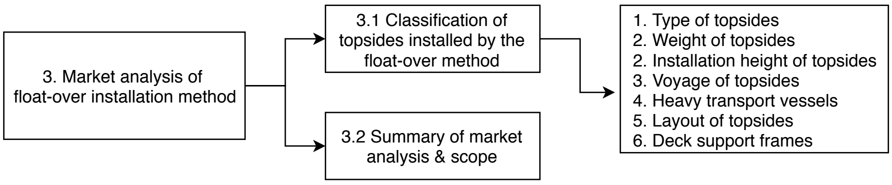
2.4. CONCLUSIONS OF STATE-OF-THE-ART OF FLOAT-OVER INSTALLATIONS

The float-over installations method is a competitive solution for installing topsides without the use of a crane vessel. Several float-over concepts are used up to now. The most used method is the typical float-over method. This method uses a heavy transport vessel to sail through the substructure in order or mate the topsides on the substructure by ballasting. This method requires an irregular substructure with a slot, which is more costly than a steel-efficient substructure without slot. Generally, topsides require a high air gap position above the sea level. To install the topsides at this higher level, the topsides are placed on the deck support frame (DSF) during voyage. Every topsides has an entirely different geometry and weight. Until now, the DSFs are designed and fabricated specifically for a single topsides installation project. In this report, the idea of reusing the DSF is studied. In the next chapter, the most interesting topsides category for repetitive installation are selected.

3

MARKET ANALYSIS OF THE FLOAT-OVER INSTALLATION METHOD

The goal of this market analysis is to find a range of topsides which are technically and economically appealing for repetitive installation. This is done by analysing data of historic float-over installations. The market analysis results in a set of limitation to the scope. The scope assures an cost-effective and targeted design of the reusable deck support frame. The scope of work will be rewritten into requirements and preferences which are described in chapter 4.



3.1. CLASSIFICATION OF TOPSIDES INSTALLED BY THE FLOAT-OVER METHOD

Data of several float-over installation projects from Mammoet, Boskalis, the Wood Mackenzie Infield database [16] and others is collected and presented in Appendix A. This dataset is analysed to get a thorough understanding of what has happened in the past. All float-over projects under 5,000 tonnes are not considered in this data analysis. These topsides are not interesting for installation by the float-over method. The competition with heavy crane vessels causes installation with the float-over method to be unprofitable [2].

The characteristics of a reusable deck support frame are dependent on what the future brings. The trends in the past are analysed to make an estimation of the future of float-over installations. The past float-over installations are categorized based on the parameters that determine the way each project is addressed. These parameters are listed below. In this chapter, the most interesting scope for these items is given.

The main topsides' parameters for float-over installations are:

1. Type of topsides
2. Weight of topsides
3. Installation height of topsides
4. Voyage of topsides
5. Heavy transport vessels
6. Layout of topsides
7. Deck support frames

3.1.1. TYPE OF TOPSIDES

The topsides types are introduced in chapter 2. The float-over installations above 5,000 tonnes are divided into three categories: fixed jacket structures, floating structures, and smartleg structures. In table 3.1 and figure 3.1, the collection of installed topsides for the different substructures by the float-over method are shown.

Table 3.1: Float-over installation per category

Topsides substructure	Fixed	Floating	Smartleg
Typical single vessel	58	6	2
Catamaran	6	4	0
Self installing	0	0	3

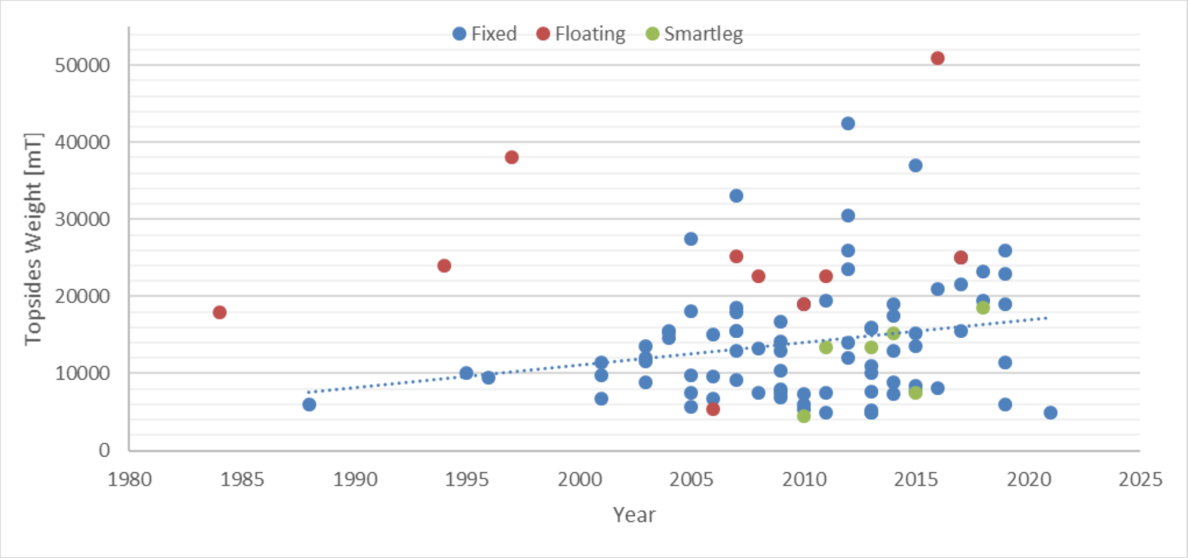


Figure 3.1: Topsides float-over installations for fixed, floating and smartleg structures.

- It can be seen, that the vast majority of float-over installations are installed using a single vessel/barge on a fixed slotted jacket on offshore locations. Expected is that typical single vessel float-overs on fixed slotted jackets will be still the major part of float-over installation and is therefore the interesting for the design of the RDSF.

- Float-over installations on floating structures have a small part in the total number of installations. Floating substructures are lowered to minimize the air gap for installation. This is often performed in sheltered waters, where an ideal installation situation is created. This makes float-overs on floating structures relatively easy. It is expected that the RDSF for offshore float-over installations can also handle the easier inshore and low air gap conditions for floating structures. This statement is however invalid for the special SPAR installations, where multiple vessels (catamaran) are required which makes the installation more complex.
  Because of the low amount of past installations and the relatively easy operations, the floating structures are therefore an uninteresting input for the RDSF design.

- The Smartleg installation method is an undesirable method for topsides installation. Since the structural and operational issues presented in chapter 2.3 appear. It is expected that Smartleg structures are not being build in the future.

The float-over installations on floating and Smartleg structures are disregarded in further study. The structural issues of Smartleg structures and the relative ideal conditions of floating substructures make them uninteresting for the scope. The focus of this study is only on topsides for fixed substructures. And consequently, on the corresponding single vessel's, since the vast part of fixed topsides is installed according to this method. This makes the single vessel float-over on fixed slotted substructures the most appealing method for a reusable design.

3.1.2. WEIGHT OF TOPSIDES

The weight of the topsides directly influences the weight of the RDSF system and thus the costs. In order to keep the costs of the RDSF system in control the selection of a certain weight range is applied. The list in Table 3.2 shows the amount of topsides installations per number weight range.

Table 3.2: The amount of past and tender projects classified on weights

Weight class from	 to	Past topsides #	Boskalis tenders #
5,000	10,000	31	5
10,000	15,000	16	13
15,000	20,000	18	1
20,000	25,000	4	1
25,000	30,000	2	1
30,000	35,000	2	0
35,000	40,000	1	0
40,000	45,000	1	0
5,000	45,000	78	21

The topsides installations projects are divided into three categories based on their weights. These weight categories are developed with experts within Boskalis.

1. Simple & Light *Topsides weight < 5,000mT*
   The lightest topsides are not considered in this analysis as earlier mentioned. The competition with crane vessels make the float-over installation economic infeasible for most projects.

2. Moderate Complex *25,000mT > Topsides weight > 5,000mT*
   In the Moderate Complex weight range, there are about four topsides installations each year. Only the largest crane vessels can compete with the float-over method in this range. These (semi-submersible) crane vessels have extremely high mobilization costs. The float-over installation method is therefore competitive for areas where these crane vessels are limitedly available. This category is interesting for a RDSF because of the repetitive character, the moderate level of complexity, the competition with costly large crane vessels and the large transport distances.

3. Extreme Heavy Specials *Topsides weight > 25,000mT*
   In this range, less than one topsides is installed each year. The topsides fabrication locations are mostly inter-regional wherefore early commitment to/from the installation contractor is required. The float-over method is the only feasible installation method because its exceeds the capacity of all available cranes. These projects tend to go to the boundaries of the possibilities. The chance of a reoccurring projects with similar parameters is minimal. Therefore, this category is not interesting for a reusable DSF.

It is concluded that the most interesting weight range is the 'Moderate Complex' topsides weight range. Together with the amount of past installations, it is chosen that the design of the RDSF must handle topsides from 5,000 – 20,000 tonnes. Consequence of this selection is that the RDSF system covers 90% of all Boskalis' tender projects and 83% of all past topsides float-over installations. It is preferred to enlarge this scope to 25,000 tonnes, increasing the coverage to 95% of the tenders and to 88% of the past topsides.

3.1.3. INSTALLATION HEIGHT OF TOPSIDES

The installation height of the topsides is an important parameter as it determines the height of the (R)DSF. There are many ways to indicate the required air gap after installation, for example MSL/LAT to bottom of steel (B.O.S), or height of topsides above deck, or total jacking height. Inconsistency in these parameters between the different data-sets make these numbers hard to compare. The height of the reusable DSF including the GSB is exactly the Height Above Deck (H_{ad}) during installation. The parameter "H_{ad}" is used in further investigation as the standard parameter. Height Above Deck, "H_{ad}", indicates the distance between HTV deck and the bottom of the topsides, which is exactly the same height as the grillage and DSF together.

The height variation needs to be obtained by the jacking system during jacking phase. In figure 3.2 the large deviation of transportation height above deck (H_{ad}) can be seen. Important note to make is that this plot is based on limited available information, therefore the plot does not give the full image. There is no clear correlation between the Height Above Deck (H_{ad}) and the weight of the topsides (W). Therefore, a division in height capability for the RDSF cannot be made. Though, there is a clustering seen for the heights between 5 and 15 meters. This clustering is interesting for an RDSF system. A clustering in topsides parameters means only small adjustments to the reusable deck support frame. Therefore, the RDSF system is *required* to handle topsides with H_{ad} values of 5.0 meters to 15.0 meters.

However, it is not yet known what the influence of the large H_{ad} on the design of the reusable deck support frame is. Therefore, it is preferred to include the H_{ad} values until the highest observed 25.0 meters into account for the scope. These wide limits to the height capabilities of the RDSF system are to include as many topsides as possible. The requirements$^{(R)}$ and preferences$^{(P)}$ of both weight and H_{ad} are added into Figure 3.2. Consequence of the requirement is that the RDSF covers only 83% of the projects in the historic data. If the preference of $H_{ad} = 25.0m$ is met, a 100% coverage is obtained.

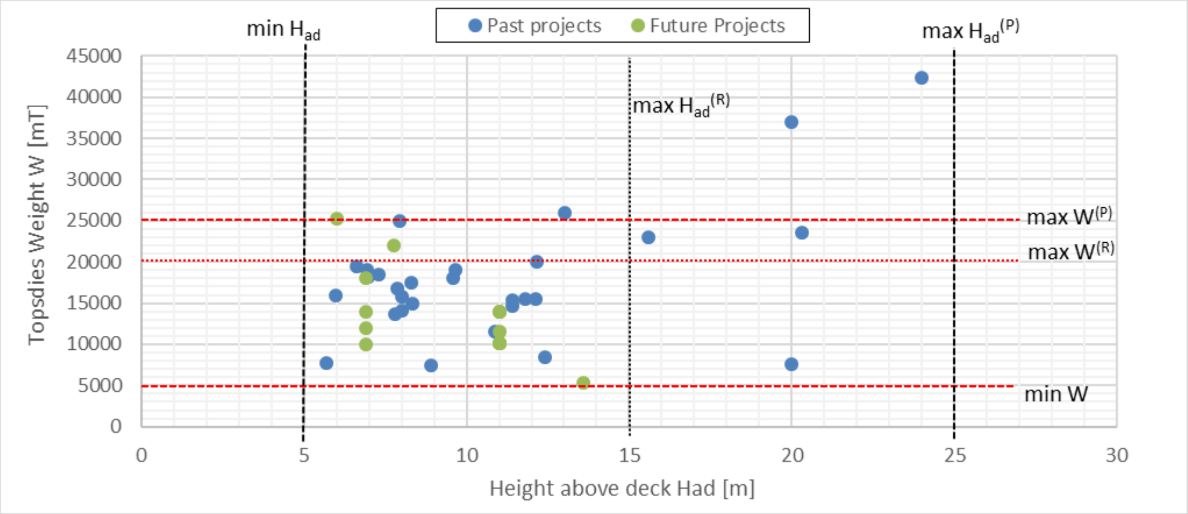


Figure 3.2: Variation of topsides heights above deck

3.1.4. VOYAGE OF TOPSIDES FROM FABRICATION TO INSTALLATION LOCATION

The topsides transportation or voyage can be depicted, when combining fabrication yards to the installation locations of the database in Appendix A. This is illustrated in figure 3.3.

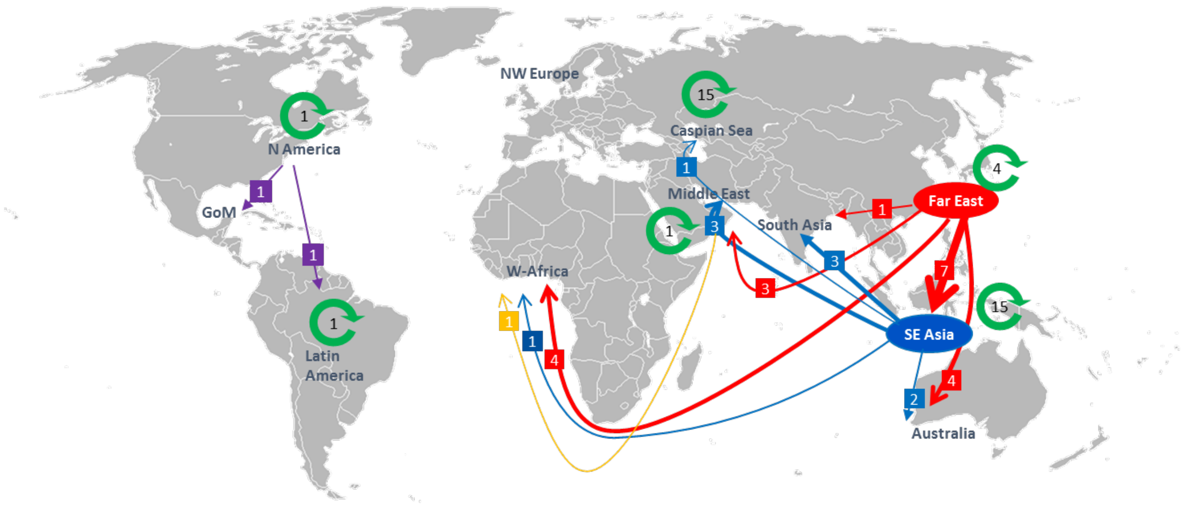


Figure 3.3: Voyage from fabrication to installation location

The following conclusions can be drawn from the analysis on the historic voyages.

- Most topsides are fabricated in Asia (South East Asia and Far East Asia). The heaviest and most complex topsides are fabricated in the Far East where the specialized construction yards SHI, HHI and DSME are located.
- Topsides installations with weights of 5,000 to 20,000 tonnes are seen for all locations. Installation locations in Australia and the Far East Asia are the outliers with weights of topsides to more than 40,000 tonnes. These most heavy topsides are all fabricated in the Far East.
- Short regional voyages are mostly performed with barges. The longer inter-regional transports are performed with HTVs. Logically, because the barges have a low workability in severe seas making these voyages infeasible.
- There are only six voyages around the Cape of Good Hope where most severe environmental conditions can be expected. These topsides were all destined for West-Africa, where swell conditions complicate the installation.
- It is seen that, the Caspian Sea is almost self sufficient. Lukoil and BP are dominating this market where installations of the topsides is being done with a specialized float-over barge of Lukoil, ‘the T-barge’. The Northern Caspian Sea is a subarctic area where cold winters appear, however, all installations takes place during the summer. Nevertheless cold temperatures could still occur and therefore the design should be applicable for temperatures from -20°C.

Main strength of Boskalis is to be competitive on long distance voyages with its HTVs, making it not appealing to only focus on several regions. Therefore, the scope of the RDSF system is not restricted to fabrication and installation locations. Consequently for this decision, the RDSF is expected to be over-dimensioned for the ‘mild’ voyages. Additional special mating systems for extreme swell conditions are taken into account as preference for the frame.

For all operations at sea, a design environment is established. The operational design environment is a set of maximum environmental conditions wherein this specific operation can be performed. For every operation (i.e. load-out, voyage, float-over installation, etc.) this design environment is different. The design environment is established by taking the the worst case conditions of the Boskalis reference float-over projects (which are Bongkot, Ofon, Heera, Aasta Hansteen, CKX and Shwe). This resulting design environment is shown in Table 4.2. It shows the most severe encountered accelerations.

3.1.5. HEAVY TRANSPORT VESSELS FOR FLOAT-OVER INSTALLATIONS

The heavy transport vessel (HTV) limits the applicability of topsides that can be installed by it geometry and capacity. The scope of the RDSF system is limited to the Boskalis vessels only, as the study is commissioned by them. Within the fleet of Boskalis, the Black Marlin is the vessel with the largest track record with 6 float-over installations. The track record of all the vessels of Boskalis and competitors can be found in appendix F. The Black Marlin is a type IIa vessel, which is a collective name for multiple vessels within the Boskalis fleet. Boskalis vessels within this type IIa class are Fjord, Forte, Black Marlin, Blue Marlin, HYSY 278, Transshelf and Mighty Servant 3. All vessels are capable of performing a float-over installation. Because they all have a high ballast capacity, a deck capacity around the 50,000 tonnes and a breadth of 36 to 42 meter.

To ensure a focused design in a restricted amount of time of this study, the scope of the RDSF system is limited to the Black Marlin only. The parameters of the Black Marlin will be used for further design of the RDSF and GSB. The feasibility of the RDSF is proved when it is applicable to one vessel. Although, it is preferred to have the RDSF applicable for more type IIa vessels. Consequences of this preference, is that the RDSF system should be applicable on vessels with a web frame spacing of not only 2500 mm but also 2400 mm.

3.1.6. LAYOUT OF TOPSIDES FOR FLOAT-OVER INSTALLATIONS

Generally, the topsides for a typical single vessel/barge float-over operations have a rectangular raster frame. The topsides extends outboard at each side of the vessel to enable the vertical alignment with the substructure. The layout of a topsides on top of a HTV is shown in Figure 3.4. The topsides structure consists of several set-down support nodes indicated with a (+) in the figure. The set-down nodes connect the topsides with the substructure after installation. The temporary DSF support nodes are indicated with a (x) in the figure. These nodes support the topsides during transport and are located at the centre of the topsides. The raster lines running in a longitudinal direction are indexed with a number (1,2,3,...) and in a transverse direction with a letter (A,B,C,...).

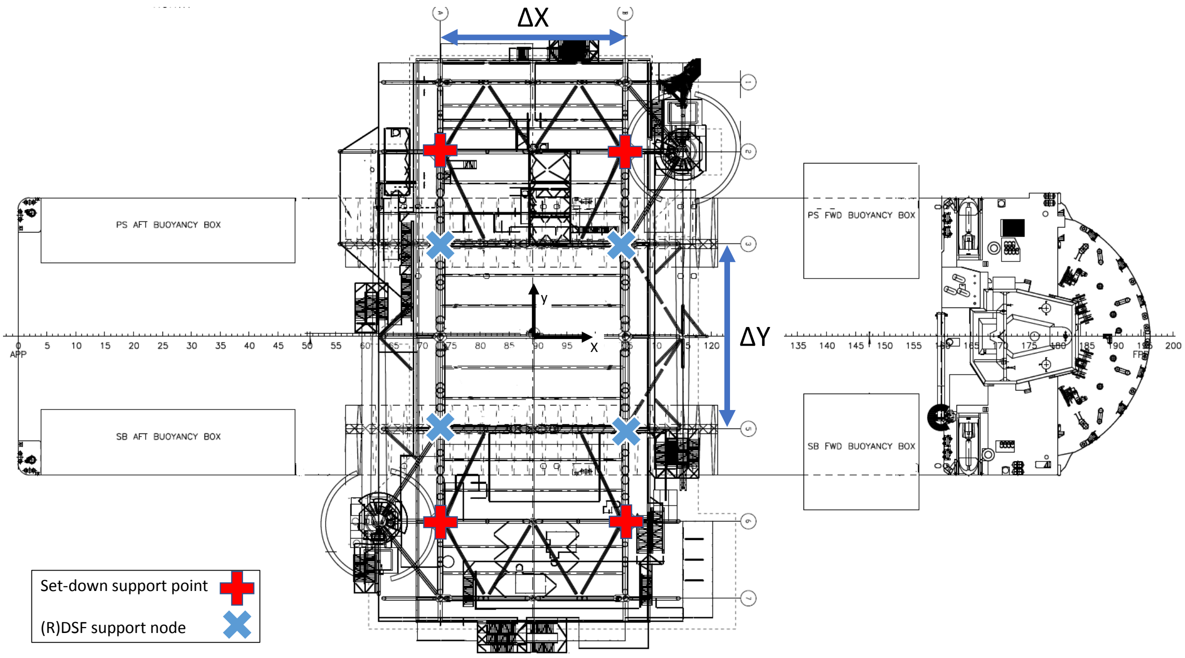


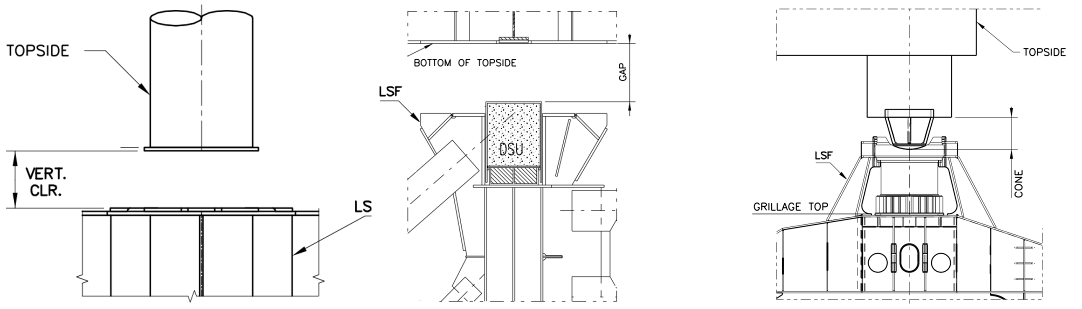
Figure 3.4: Top view of the layout of a topsides during voyage

SUPPORT NODE SPACING OF TOPSIDES

The (R)DSF support nodes (+) are an important input parameter for the design of the RDSF. The DSF is connected to the topsides at these points. The variation in the amount of nodes and in nodal spacing is shown in Table 3.3. It is seen that the number of topsides DSF support nodes varies from 4-8, with always 2 lines in longitudinal direction. Generally, heavier topsides have more DSF support nodes. The node spacing in x-direction (ΔX) decreases with more topsides nodes.

Table 3.3: Variation of node spacing of topsides (*based on 35 projects*)

	Topsides 4 nodes			Topsides 6 nodes			Topsides 8 nodes			
# Projects		18			2			15		
Spacing	Min	Max	Average	Min	Max	Avg	Min	Max	Avg	
TS_{mass}	5,329	25,000	13,000	13,599	23,500	18,500	7,715	26,000	18,000	[mT]
ΔX	18.0	32.0	25.2	17.0	24.0	20.5	10.7	20.0	15.8	[m]
ΔY	22.0	32.0	26.0	24.0	26.0	25.0	20.0	32.0	28.6	[m]



(a) Leg-Flat connection (Bongkot) (b) Flat-Flat connection (CMMP) (c) Pin-hole connection (Aasta Hansteen)

Figure 3.5: Topsides node connections

The DSF is connected with the topsides at the position of the DSF support nodes. A variation in connections between the DSF and topsides is seen, whereof three of them are shown in Figure 3.5. The scope of the project is not limited to one specific connection. However, since the dimensions of the connection points vary widely each project, the Bongkot leg-flat connection with $\oslash = 1500mm$ & $t = 60mm$ seen in Figure 3.5a is used as reference throughout the study. Consequences of this focus to other node connection layouts are expected to be limited. Modifications to the DSF node connection points are assumed to be foreseeable.

3.1.7. DECK SUPPORT FRAME

The deck support frame is different for every topsides installation project. The main parameters determining this geometry of the DSF are: the load-out operation, the grillage design and the type of structure.

THE LOAD-OUT OPERATION WITH THE DECK SUPPORT FRAME

The load-out operation determines for a major part the dimensions and shape of the DSF. As can be seen in Table 3.4, the load-outs of all projects are subdivided into longitudinal and transverse load-outs on barges or HTV's. The scope of the design is focused on HTVs and more particularly the Boskalis Black Marlin, therefore, all Black Marlin projects are listed in the table as well.

Table 3.4: Load-out operation characteristics (*based on 22 projects*)

Direction	Vessel	#Projects	Skid tracks per row	GSB $\overline{H}$ [m]	min GSB H [m]	max GSB H[m]
Longitudinal	Barge	8	no info	2.81	1.50	4.3
Longitudinal	HTV	3	1.00	2.14	1.75	2.87
Transverse	Barge	1	no info	2.79	2.79	2.79
Transverse	HTV	10	1.78	1.87	1.00	3.37
Transverse	Black M.	5	1.80	1.83	1.50	2.17

In general, longitudinal load-outs are preferred over transverse load-outs, the higher stability in this direction requires less ballast capacity. For barges this longitudinal load-out is generally the standard as can be seen in the table. The structural frames and bulkheads of barges running along the entire length, having full strength over this entire length. However, for HTV's this is not the case. HTV's have a decreasing section area due to the position of thrusters, engine rooms, and the drag reducing ship shape. This causes interruptions in bulkhead- and web frames that decrease the strength and buoyancy at the aft of the HTV. This makes longitudinal load-outs more difficult to perform on HTVs. For this reason, the vast majority of load-outs on HTV's is performed in transverse direction.

Therefore, the RDSF system must be able to handle transverse load-out operations. To have a more valuable design, the RDSF system is preferred to also be able to handle longitudinal load-out operations.

GRILLAGE DESIGN

The direction of the load-out operation has consequences to the grillage design. Grillage or grillage skid beam (GSB) is the steel framework of plates and beams used to spread and introduce heavy loads over large areas to the deck. Grillage is used into a number of concepts, which differ in the way of spreading loads. Often, the grillage concept spreads loads into one primary type of frame. The transverse web frames are most suitable carrying the topsides loads as they only have to endure small stresses during voyage. This in contrast to longitudinal bulkhead frames, which endures higher stresses during transport due to larger hydrodynamic loads in pitch direction (hogging and sagging).

The grillage design is not part of the scope of this study, but has to be sufficient to handle all loads. Therefore, a minimal grillage height is chosen as boundary for the RDSF system. Table 3.4 shows that a grillage height value of 1.5m is sufficient for heavy topsides until 16.734 tons (CPOC Muda project). If a coming project appears to lack on grillage height or strength, it is assumed that the capacity can easily be increased by enlarging the grillage or adding material.

TYPES OF DECK SUPPORT FRAMES

The single-use DSFs can be classified to four different DSF construction types. The types are divided on the method of supporting the topsides node and are listed below. Examples of the different DSF construction types can be found in Figure 3.6.

- **The individual DSF module**, connects to one single support node.
- **The transverse DSF module**, connects the support nodes in transverse direction only.
- **The longitudinal DSF module**, connects the support nodes in longitudinal direction only.
- **The full DSF construction**, connects all DSF support nodes with each other by a frame.

(a) Individual module (CKX)

(b) Full construction (Angel)

Figure 3.6: DSF construction types

The characteristics of the DSF construction types are shown in Table 3.5. It is observed that the topsides supported by individual DSF modules have the smallest average transportation height (H_{ad}) and topsides supported by full DSF constructions have by far the largest average H_{ad}. The full DSF constructions also have larger average footprints. Having therefore a larger resistance against moments created by the higher vertical centre of gravity.

Table 3.5: Topsides node types (*based on 18 projects*)

DSF (node) type	# Topsides	$\overline{\Delta X}[m]$	$\overline{\Delta Y}[m]$	$\overline{H_{ad}}[m]$
Individual DSF module	4	19.8	28.5	6.8
Longitudinal DSF module	5	18.4	29.8	8.5
Transverse DSF module	4	20.4	25.5	8.6
Full DSF construction	5	24.8	28.0	14.0

3.2. CONCLUSIONS OF THE MARKET ANALYSIS

Data of historic topsides float-over installations is collected and used to assess the most interesting range of topsides for repetitive installation. Out of data of over 95 float-over installations the following conclusions to the scope are drawn.

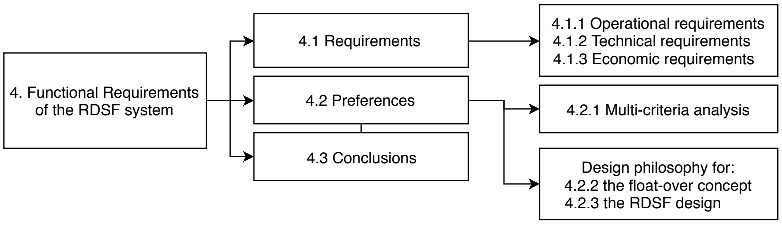
- It is seen that the majority of topsides installations is for fixed substructures with a slot. The topsides for these category are mostly installed by the typical float-over method. Float-over installations on floating structures are relatively easy operations and Smartleg structures not a future-proof concept. Therefore, only installations on fixed substructure are taken into account in the scope of the RDSF system.
- The majority of topsides weigh between the 5,000 and 20,000 tonnes. Less than one installation per year is performed for topsides with an heavier weight. This makes topsides above 20,000 uninteresting for repetitive installation with an RDSF. Therefore, the scope of the RDSF design is restricted to topsides of 20,000 tonnes.
- Transportation heights vary mostly between 5 and 15 meters. Although outliers up to 25 meters are seen. The requirement to handle topsides with transportation heights H_{ad} up to 15.0 is added to the scope. Additionally, the RDSF system is preferred to handle H_{ad} until 25.0 meters as this is the maximum height that is seen in this weight category.
- Main strength of Boskalis is to be competitive on long distance voyages with its HTVs, making it not appealing to only focus on several regions. Therefore, the scope of the RDSF system is not restricted to fabrication and installation locations. This consequently will lead to the toughest environmental conditions and therefore most heavy loads on the system.
- Boskalis has a typical range of heavy transport vessels (HTVs) capable of performing the float-over installation, named type IIa vessels. Preferably, the design of the RDSF is applicable to all type IIa vessels. However, to prove the feasibility of the RDSF system, only one vessel is required. Therefore, the RDSF system only must be applicable to the Black Marlin, the vessel with the largest track record.
- It is observed that the topsides layouts vary with 4, 6 and 8 support nodes and have always 2 lines in Y-direction. To not exclude any topsides on geometry, the scope is limited to the minimum and maximum values of node spacing seen in the historic data.

This market analysis has lead to a more focused scope of the RDSF design. This scope covers about 75% of the historic float-over installations on fixed substructures. In the next chapter, this scope is translated to a program of requirements to which the RDSF design must comply.

4

PROGRAM OF REQUIREMENTS AND PREFERENCES FOR THE REUSABLE DECK SUPPORT FRAME

The program of requirements of the RDSF system which is a result of the market analysis (chapter 3) is presented in this chapter. The program of requirements consists of a set of requirements, conditions and preferences to which the design of the RDSF system has to comply. These requirements will guide the generation and evaluation of the concepts. Both requirements (R) and preferences (P) for the RDSF design are presented. The design must comply with the requirements and is preferred to comply with the preferences to have a more valuable design.



4.1. REQUIREMENTS FOR THE REUSABLE DECK SUPPORT FRAME

The main requirements for the RDSF system are listed below and elaborated in the following sections. These requirements are related to the feasibility study according to Easterbrook [10].

R1. The RDSF system and all operations with the RDSF are feasible (Operational feasibility 4.1.1).
R2. The RDSF system is technically feasible (Technical feasibility 4.1.2).
R3. The RDSF system has a potential positive business case (Economic feasibility 4.1.3).

The following thresholds are secured in the requirements. These thresholds are based on the current single-use DSF solution.

- Usage of the RDSF has at least the same level of safety as the use of the single-use DSF.
- Usage of the RDSF has at least the same level of workability as the use of the single-use DSF.

4.1.1. R1. OPERATIONAL FEASIBILITY REQUIREMENTS

The operational feasibility requirements concern the topsides, vessel, yard and design environment aspects.

TOPSIDES SPECIFIC REQUIREMENTS

The RDSF must be able to handle all multiple topsides with the parameters given in Table 4.1. The topsides specification requirements are the result of the market analysis in chapter 3.

Table 4.1: Topsides specific requirements for the RDSF system

Topsides specific requirements		**Requirement**	**Preference**
Topsides weight	W	5.000t - 20.000t	5.000t - 25.000t
Rows (transversal)		2, 3 and 4	
Row spacing	ΔX	16m - 32m	
Lines (longitudinal)		2	
Line spacing	ΔY	23m - 32m	
# Nodes	n	4, 6 and 8	
Variation Height Above Deck	H_{ad}	5m - 15m	5m - 25m
Node connection type		Flat-Pin	All node types
No modifications to jacket and topsides			
Max. accelerations at CoG topsides	Longitidunal (a_l)	-0.2g / +0.2g	
	Transversal (a_t)	-0.5g / +0.5g	
	Vertical (a_v)	+0.7g / +1.3g	

VESSEL SPECIFIC REQUIREMENTS

The following RDSF requirements and preferences are related to the vessel:
Vessel Requirements

1. The RDSF must fit on Boskalis Black Marlin (see appendix Black Marlin).
2. The RDSF must be capable to perform a transverse skidded load-out.
3. The RDSF is intended for the typical float-over installations through jacket slots.
4. Load-out possible with 2 skid tracks per row.
5. Maximum distributed web frame load of 99 ton/m.
6. RDSF system has to fit on Black Marlin deck (Black Marlin = 178.2 x 42m).

Vessel Preferences

1. All Type IIa Boskalis vessels with frame spacing 2400mm and 2500mm.
2. Load-out possible with 1, 2, 3 or 4 skid tracks per row.
3. All Boskalis type 2A vessels and barges.
4. Additional longitudinal load-out for other vessels and barges.

Coordinate System Vessel
The right-handed global Cartesian coordinate system is used in this system. The orientation is picked with the +X axis as the centerline of the vessel, and the +Y-axis as the centerline of the topsides, SB towards PS and the +Z axis upwards from vessel's keel.

YARD SPECIFIC REQUIREMENTS

Since all yards use different approaches for the fabrication of topsides, it is hard to set yard specific requirements. Eventually, the design of the RDSF system results in a set of specifications to the yard. The following preferences are set to the RDSF design.

1. Limit the amount of required build-up space.
2. Limit the amount and capacity of build-up equipment (for example yard cranes and forklift trucks).

DESIGN ENVIRONMENT CONDITIONS PER OPERATION

The design environment is a specific set of criteria for the operations of the float-over installation. These criteria are set up by the classification society DNV [11] and are used to determine the loads on the RDSF. All environmental parameters are given for completeness of the table, also the ones that do not influence the RDSF system.

Table 4.2: Design Environment of float-over installation for the RDSF system

		Transport	**Stand-off**	**Entry, Mating & Exit**
Time window	Tr	Not applicable	16h	30h
Duration contingency	Tpop + Tc	Not applicable	12h + 4h	24h + 6h
Head waves height	Hs			1.0 m
Quartering waves height	Hs	9.5 m	1.75 m	0.75 m
Beam waves height	Hs			0.5 m
Wave period	Tp	9.1-13.1 s	4.5-8 s	4.5-8 s
Sheltered waves height	Hs	Not applicable	0.5 m	0.5 m
Swell waves height	Hs swell	Not applicable	0.5 m	0.5 m
Swell waves height	Tp swell	Not applicable	>8s	>8s
Wind (1h)	v_w	45 kn	30 kn	25 kn
Current	v_c	Not applicable	1 m/s	1 m/s

4.1.2. R2. TECHNICAL FEASIBILITY REQUIREMENTS

The technical feasibility is related to the structural integrity of the RDSF system. Therefore, the design of the RDSF system is carried out to meet the safety and design requirements stipulated in the industry standards:

- DET NORSKE VERITAS (DNV)
  - DNV-OS-H101 DNV's Marine Operations, General
  - DNV-OS-H101 DNV's Marine Operations, Design and Fabrication
- American Bureau of Shipping (ABS)
  - Guide for Buckling and ultimate strength assessment for offshore structures
- American Petroleum Institute (API)
  - RP2A – WSD Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms, Working Stress Design, 21st Edition
- American Institute of Steel Construction (AISC)
  - AISC Manual of Steel Construction, 13th Edition
- American Welding Society (AWS)
  - AWS D1.1/D1.1 Structural Welding Code – Steel

4.1.3. R3. ECONOMIC FEASIBILITY REQUIREMENTS

The following requirements ensure that the RDSF system is economically feasible. These requirements are a result of multiple interviews within Boskalis and Mammoet.

1. Minimal lifetime (depreciation time) of the RDSF system of 10 years.
2. The RDSF has to be cost reductive after minimal 5 projects.

4.1.4. TOPSIDES CASE STUDIES

The design of the RDSF must be technically, operationally and economically feasible to a range of future topsides installations. However, the parameters of future topsides are unknown. Therefore, the feasibility will be checked to four topsides cases. Each of these cases have an unique set of parameters and together form a good representation of the scope of the study. The cases are listed below.

- **Bongkot**: Heaviest topsides float-over installation with the Black Marlin, with $W = 19,500 mT$

- **CPOC Muda**: Widest DSF node spacing layout with $\Delta Y = 32m$.
- **Bokor**: Future float-over installation (2019).
- **Angel A**: Float-over installation with highest air gap of $H_{ad} = 20$.

The topsides cases do not differ in vertical centre of gravity from bottom of steel ($H_{TS} = 12m$, *reference Bongkot*).

4.2. PREFERENCES FOR THE REUSABLE DECK SUPPORT FRAME

In this section the preferences for the RDSF system are discussed. The preferences do not necessarily have to be fulfilled, but they do give additional desired value to the RDSF design. The preferences are acquired by performing a multi-criteria analysis (MCA) on all stakeholders of the float-over installation in 4.2.1. The MCA results in a design philosophy on two different levels: for the float-over installation method and for the RDSF design itself. Both design philosophies are kept in mind during the development of the RDSF system given in chapter 5 and 6.

4.2.1. MULTI-CRITERIA ANALYSIS ON STAKEHOLDER CRITERIA

The multi-criteria analysis is a method for decision making that evaluates multiple conflicting criteria [17]. It is a method to structure and value the preferences of the stakeholders. The input criteria are identified according to the goal tree method [17]. The resulting goal tree is shown in appendix E.2. All criteria are ranked on level of importance for the stakeholders individually, with zero to five points. The field operator (the owner of the topsides who pays for the installation) and the installation contractor (in this case a collaboration between Mammoet and Boskalis) are selected as most important stakeholders. Regardless of the allocation of activities between the installation contractors Mammoet and Boskalis.

The criteria list and the corresponding scoring of both stakeholders is given in Table 4.3. In total, eight persons participated in the criteria analysis. These participants are members of the TU Delft, Boskalis and Mammoet. The composition ensures for a wide range of knowledge. The addition of fabrication yards and classification societies in this analysis is omitted due to limited study time. It is recommended to involve them in future decision making processes.

Table 4.3: Criteria scoring by stakeholders

#	**Criteria**	**Field operator** (e.g. Shell)	**Installation contractor** (Boskalis & Mammoet)
1	Engineering costs	1.1	2.6
2	Steel fabrication costs	1.1	3.4
3	Drive and control costs	1.5	3.1
4	Project modification costs	1.6	3.4
5	Project mobilization costs	1.6	3.4
6	Periodic maintenance	0.8	3.1
7	Duration of operations on land	2.8	2.9
8	Limits of operations on land	1.9	2.9
9	Duration of operations at sea	4.4	3.9
10	Limits of operations at sea	4.5	4.5
11	Risks on delays	4.4	4.3
12	Number of topsides	1.4	4.6
13	Number of vessels/barges	1.3	3.3
14	Usage in other disciplines	0.9	2.8
15	Reliable design	4.0	3.4
16	Number of increased risk operations	4.3	3.9
17	Redundancy	3.1	2.8
18	Reversibility	3.6	3.3

Field Operator
For the field operator, one of the most important criteria is the total topsides installation time. The total time is affected by the (expected) duration and by the (unexpected) delays of all float-over operations. The total duration of an installation can be reduced by using shorter scheduled operations. It also can be reduced by eliminating delays by increasing the reliability of each operation. So by improving both reliability and duration of the installation method, cost savings can be obtained.

Installation contractor
Most important criterion for the installation contractors is the applicability of the RDSF to a wide variation of topsides and vessels. The reusability of the RDSF is the main pillar for the business case. Next to this, it is a plus for the installation contractor when the use of the RDSF decreases the response time. This strengthens its competitive position.

4.2.2. DESIGN PHILOSOPHY FOR THE DEVELOPMENT OF THE FLOAT-OVER OPERATION

The criteria analysis has lead to a design philosophy for the float-over operation. The following five statements will be taken into account during the development of the float-over operation in chapter 5.

1. **Increase reliability and safety.**
   The RDSF system must function according to its specifications. There is no room for any faults. Therefore all risky operations should be eliminated from the float-over installation process. Delays in the float-over installation are dominating the overall cost of an installation project. Therefore, it is preferred that the RDSF design makes use of existing methods and components to increase the reliability of the design.
2. **Decrease duration of onboard operations.**
   The duration of onboard operations must be decreased to a minimum level. The operational costs of the HTV have a large share in the total costs of a float-over installation.
3. **Ensure wide applicability of the RDSF.**
   A wide applicability of the RDSF is important to the installation contractors. This is to ensure that a wide range of topsides can be installed without having extensive modifications to the system. The wide applicability of the RDSF is captured in the functional requirements.
4. **Increase limits of operations at sea.**
   Increasing the limits of the operations at sea, decreases the probability of exceeding the time schedule. It may also enlarge the scope of the market that could be addressed.
5. **Restrain overall cost of RDSF.**
   The costs of the RDSF are to a lesser extent important, as the costs can be depreciated over multiple projects. However, the amount of expected float-over installations each year has influence on the payback period. Therefore, the initial costs to construct the RDSF is aimed to be no more than 2.5 times the costs to construct a DSF.

4.2.3. DESIGN PHILOSOPHY FOR THE DESIGN OF THE RDSF

The following preferences are related to fabrication of the RDSF. These preferences are taken into account during the development of the RDSF system in chapter 6.

Operational preferences

1. **Occupation time of the vessel should be kept to a minimum.**
   The heavy transport vessel is the main cost driver of a float-over installation. A quick and easy handling of the RDSF onto the vessel ensures a limited HTV demand.

Technical preferences

- **The amount of RDSF *components* should be kept to a minimum.**
  Fewer components reduces the amount of maintenance-sensitive connections.

- **The amount of temporary *welded connections* should be kept to a minimum.**
  Heat introduction due to welding causes the components to deform. These deformations may cause misfits between components resulting in the need of replacing parts.
- **The amount of *bolted connections* should be kept to a minimum.**
  Transport of heavy topsides results in high loads on the RDSF. Transferring these loads require many heavy bolts, which increase the operational time during build-up. Therefore, frequent use of bolted connections in tension members should be avoided.
- **The amount of *movable connections* should be kept to a minimum.**
  The offshore environment effects the degradation to the system. The degradation of the system causes misfits between (moving) connections. Therefore, these moving connections have to be avoided or specially treated to prevent degradation of the system.
- **The required RDSF *build-up space* should be kept to a minimum.**
  The space on the yard around the skid tracks is limited and yard specific. The less space the RDSF system takes, the higher the applicability to multiple fabrication yards.

4.3. CONCLUSIONS OF PROGRAM OF REQUIREMENTS

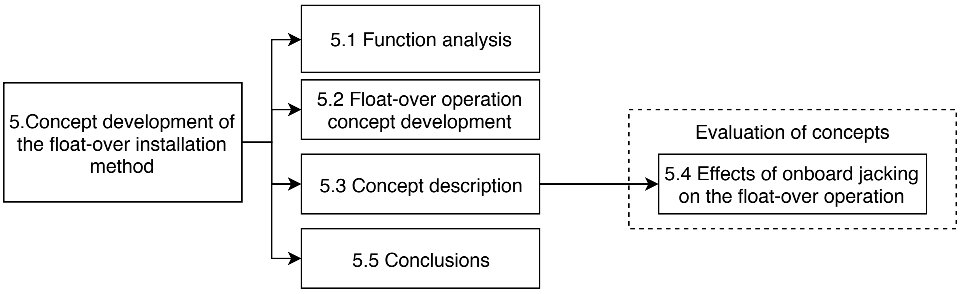
The program of requirements for the RDSF system defines the scope and provides guidance to the development of the design. The requirements are divided into operational, technical and economic requirements. The RDSF design will be validated on these requirements. The stakeholder analysis concluded into a number of preferences. This analysis included several sessions with experts within Boskalis, Mammoet and the TU Delft. It is seen that safety and reliability are the most important factors in the design. This translates into the preference to use of as little components as possible. The resulting preferences are taken into account during the development of both the float-over concept with the RDSF as well as the RDSF system itself.

5

CONCEPT DEVELOPMENT OF THE FLOAT-OVER INSTALLATION METHOD

The development of the design is divided into two parts, each part on a different level of detail. In this chapter, the first part, the concept development of the float-over installation operation involving the reusable deck support frame (RDSF) is described. The development of the RDSF itself is described in the second part in chapter 6.

Implementation of the reusable deck support must be a betterment to the float-over concept. The float-over operation is optimized to effectively integrate this support frame in the existing method. This is done by exposing the entire operation and eliminating superfluous operations. First, the main- and sub-functions of the installation method are defined. Individual solutions for these functions are generated, and a combination of these solutions form concepts. These solution combinations are described and evaluated at the end of this chapter. The result of this chapter is a description of the entire float-over operation with use of the RDSF system, where the RDSF is considered as a 'black box'. The RDSF system itself (the black box) is developed in chapter 6.



5.1. FUNCTION ANALYSIS OF THE FLOAT-OVER METHOD

By performing a function analysis of the entire platform installation operation, the essential parts of the design come to light [8]. Figure 5.1 shows all functions of the float-over installation process. All functions are evaluated on the requirements that are set up in the chapter 4. To see whether there is still room for improvement on the process. The functions that are included in the scope of the study are indicated in green and bounded with a dashed line. The excluded functions are indicated in red. The functions indicated with an orange colour are not included, but are preferable because they add value to the design.

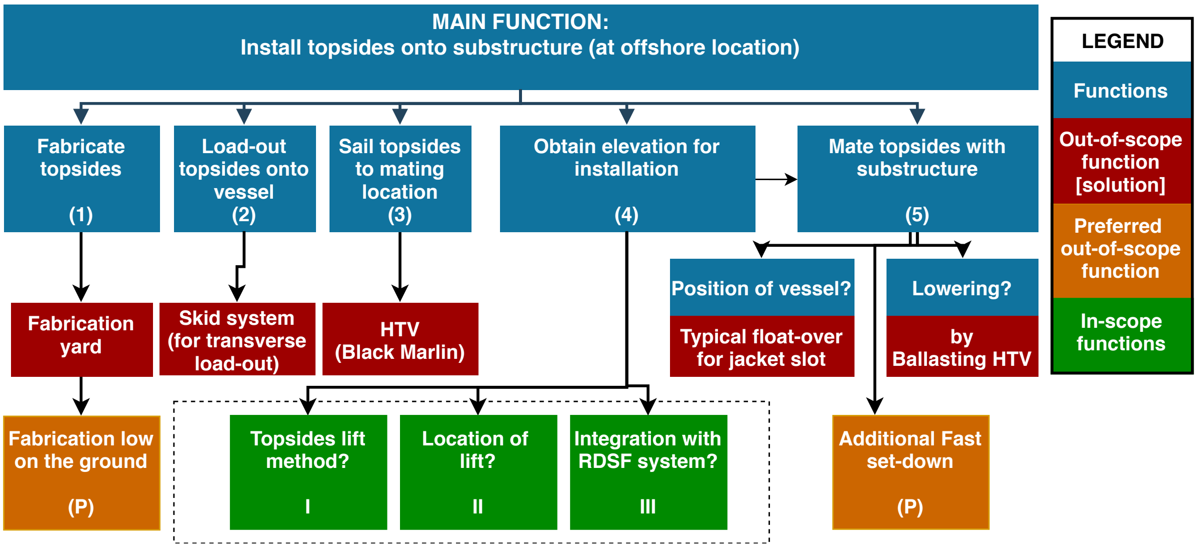


Figure 5.1: Function Tree RDSF

The main function of the float-over installation method is: *"to install the topsides on top of a substructure (at offshore location)"*. The sub-functions corresponding to the numbers in Figure 5.1 are described below:

1. **Fabrication of topsides**
   Improving the fabrication of topsides is not included in the scope of this study. For the installation contractor, the installation process starts when the fabrication of the topsides is finished. However, if an improvement of the topsides installation process could influence the way this topsides is fabricated, it could lead to cost reductions for the topsides fabricator. Which may lead to cost reduction for the entire installation process. A significant cost saving for the yard is for example the low positioning of the topsides during fabrication, instead of fabrication on top of the DSF. Therefore, it is preferred to build the topsides low to the ground. This preference needs to be taken into account during the development of the concept.

2. **Load-out topsides onto vessel**
   The load-out of the topsides is one of the critical processes of a float-over installation. The RDSF system is limited to a skidded load-out as is described in the vessel's functional requirements (chapter 4). This restriction makes that the concept development on the load-out operation is not taken into account.

3. **Sail topsides to location**
   The study is scoped by the requirement to use a heavy transport vessel and more specifically the Boskalis Black Marlin. Therefore, further development on the sea transport phase is at a halt.

4. **Obtain elevation for installation**
   The topsides has to be installed on top of the substructure at a safe elevation above the splash zone of the sea. The certain height needs to be obtained in order to perform the float-over installation. In the current float-over method, this height is obtained at the yard, before the load-out operation using a jacking system. This process is described in chapter 2.
   Optimization of the float-over operation can be achieved in changing the solution to this function. Changes in the method of obtaining the elevation, the moment when this elevation is obtained, and the possible integration of this elevating system in the RDSF could lead to a smarter system.

5. **Mating with substructure**
   As described in the program of requirements, the method of mating the topsides with the substructure is limited to typical single-vessel installation with the use jacket slots. The final lowering of the topsides is performed by ballasting the HTV. Therefore, further concept development on this sub-function is not performed. The additional preferred function "fast set down" of the topsides is not in the scope of this study. However, a fast set down system could increase workability a lot, which is preferred.

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5.2. CONCEPT DEVELOPMENT OF THE FLOAT-OVER OPERATION

In this section the concept development of the float-over operation involving the reusable deck support frame is described. It is seen that the only main in-scope function that can be improved is: *'obtain elevation for installation'*. The corresponding sub-functions are given in the dashed block in Figure 5.1. Different, solutions are developed for these sub-functions, where solution combinations form a concept described in the next section.

5.2.1. ELEVATING TOPSIDES

The function; *'obtain elevation for topsides'*, is subdivided into three sub-functions: the method, the location and the integration with the RDSF. The solutions to these sub-functions are listed below and illustrated in Figure 5.2.

METHOD OF ELEVATING TOPSIDES

The following methods of obtaining topsides elevation are found. Each solution is validated whether it fits the scope.

A **Crane lift.** Does not have the heavy lift capacity for target domain.

B **Jack system.** Most common in industry for extreme heavy linear lifting and a Mammoet solution.

C **Self-elevating vessel.** Expensive method for target and not a Boskalis solution.

D **Ballasting.** Limited variation of approximately 4.0 meters, which is not sufficient to cover requirements. The ballast capacity should also be reserved for float-over operations.

E **Piggy back & ballasting.** Highly reusable solution by using barges for different purposes. However, the solution requires additional heavy capacity barge which is perfectly aligned with HTV. Next to this, a structure or frame is required to introduce the heavy loads the piggyback barge.

Solution (B), the jack system, is chosen as solution to elevate the topsides. This method is most cost-effective to full fill the tasks.

LOCATION OF ELEVATING TOPSIDES

The topsides elevation can be obtained at the following locations.

(I) **Jacking at the yard.**
Jacking at the yard is currently the industry standard, an interesting method for the reusable frame. The operational and technical feasibility is already proved for this solution.

(II) **Jacking at the vessel.**
Jacking at the vessel is an interesting concept because it enables the option to transport the topsides low on deck. The jacking and stacking at sea method is not been done before and therefore comes with large risks, especially concerning failure of the jacking system. If this method however can be made safe and reversible, it could be a viable concept. A comparable patent is filed by McDermott in 2012 [US6347909B1], where a semi-submersible barge is lowered and the platform is lifted by a rack and pinion mechanism.

(III) **Jacking at substructure.**
The jacking at the substructure solution is used in Smartleg structures. This solution has three possible methods described in chapter 2. Structural weaknesses of this methods makes it not a future solution. A hot spot area is the connection between jacket and leg and between leg and platform, where cyclic loading makes the construction fatigue sensitive.

Solution (I), jacking at the yard and solution (II), jacking at the vessel are the most suitable solutions for the scope.

INTEGRATION WITH RDSF

The jacking system that obtains the elevation of the topsides is currently an external system that works individually of the deck support frame. Integrating the jack system in the RDSF could reduce the total amount of required material. The following two options are considered for the RDSF concepts.

1. No - External system.
2. Yes - Internal system.

5.2.2. CONCLUSIONS OF CONCEPT DEVELOPMENT PART A

The function and their corresponding solutions are given in Figure 5.2. The solution that are already chosen or discarded are given in green and red respectively. The solutions that are still in play are given blue.

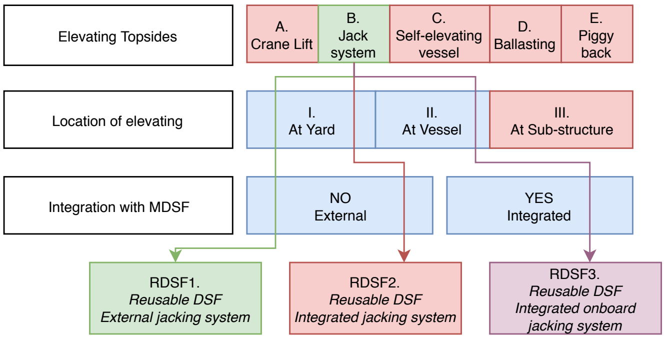


Figure 5.2: Solutions of obtaining elevation

The combinations of the potential solutions form concepts. These combinations are illustrated by the different lines in Figure 5.2. The concepts are listed below and individually described in the next section.

1. RDSF1 - RDSF with external on-land jacking system.
2. RDSF2 - RDSF with internal on-land jacking system.
3. RDSF3 - RDSF with external on-board jacking system.

5.3. DESCRIPTION OF THE FLOAT-OVER OPERATION CONCEPTS BY USING THE REUSABLE DECK SUPPORT FRAME

In this section, the installation operation of the previous concepts is described. The concepts are introduced individually by a step-by-step description of the working principles. All concepts are compared with each other to expose the strengths and weaknesses in order to form a weighed choice with a multi-criteria analysis (MCA). The functional preferences are the basis of the MCA, as all concepts already comply with the functional requirements set up in chapter 4.

In this chapter, the 'black box' is assumed to consist out of multiple parts which are transported in an efficient way. The assemblage of the RDSF starts at the yard. Here it transforms to its float-over configuration in order to act as a deck support frame. The mobilization of the RDSF assembly is not taken into account as it is assumed to be similar for all concepts. This also applies to the operations that happen after installation of the topsides: the return voyage, the disassembly and the storage.

5.3.1. RDSF1 - RDSF WITH EXTERNAL ON-LAND JACKING SYSTEM

The sequence of the topsides installation process using the RDSF1 is similar as the use of a standard DSF. A step-by-step description of the RDSF1 is given in Table 5.1 and is illustrated in Figure 5.3.

Table 5.1: Step-by-step topsides installation process RDSF1

	Operation	Description
1	Assemble RDSF	After arrival of the RDSF assembly, the assembling of the RDSF is performed by yard cranes with a capacity of at least the weight the heaviest RDSF component.
2	Jack-up topsides	The standard jack-up operation uses an external jack-up system placed on the set-down support nodes.
3	Installation RDSF	The installation of the RDSF under the topsides is done by SPMT's or a skid system depending on the yard's preferences.
4	Load-out	Standard transverse load-out using a heavy skid-system.
5	Voyage	Standard voyage by a HTV.
6	Float-over	Standard float-over by ballasting a HTV.

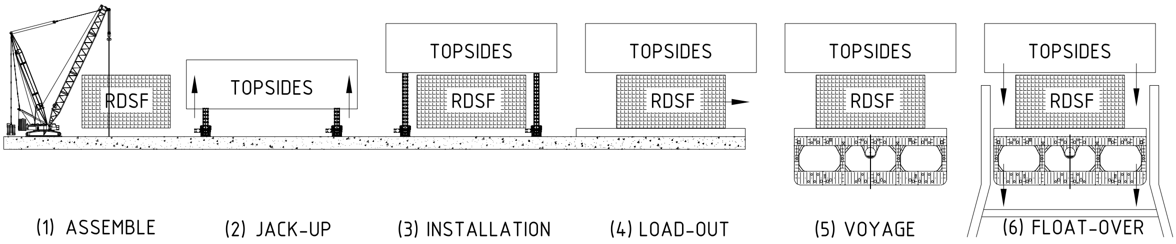


Figure 5.3: Concept RDSF1

Pros of concept:

- RDSF1 uses existing jack-up equipment which has a long track record.
- RDSF1 has no moving components subjected to heavy loads as it only supports the topsides in float-over configuration (fully assembled).
- RDSF1 has only two offshore operations.

5.3.2. RDSF2 - RDSF WITH INTERNAL ON-LAND JACKING SYSTEM

The RDSF2 has an additional function to the RDSF1, because of the integrated jacking capability. The external jacking equipment which is normally necessary is therefore superfluous. The assembly of the RDSF happens simultaneously with the jacking of the topsides. The float-over installation with the RDSF2 eliminates therefore one operation. A step-by-step description of the RDSF2 is given in Table 5.2 and related to Figure 5.4.

Table 5.2: Step-by-step topsides installation process RDSF2

	Operation	Description
1	Installation RDSF	Directly after arrival of the RDSF assembly the start components of the RDSF will be installed under the topsides.
2	Jack-up & Assemble	During the jacking operation the topsides is elevated and the RDSF is assembled simultaneously.
3	Load-out	Standard transverse load-out using a heavy skid system.
4	Voyage	Standard voyage by a HTV.
5	Float-over	Standard float-over by ballasting a HTV.

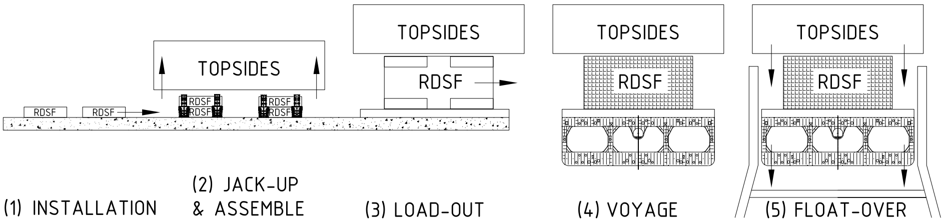


Figure 5.4: Concept RDSF2

Pros of concept:

- RDSF2 eliminates one operation by combining the jack-up and assemble operation.
- RDSF2 does not require heavy on-land crane capacity as it is self installing/erupting.
- RDSF2 has only two offshore operations.

5.3.3. RDSF3 - RDSF WITH EXTERNAL ON-BOARD JACKING SYSTEM

The RDSF3 uses an integrated jacking system just like the RDSF2. However, the assembling and jacking operation of the RDSF3 takes place onboard the HTV. This enables the jack-up operation to be performed at a freely chosen offshore location, resulting in flexibility improvements. However, this comes at a cost, as the RDSF has to be able to withstand larger loads on the system during the on-board jacking operation due to vessel's motions. Therefore the jacking equipment and the RDSF frame is expected to be much heavier and therefore more costly. A step-by-step description of the RDSF3 is given in Table 5.3 and is illustrated in Figure 5.5.

Table 5.3: Step-by-step topsides installation process RDSF3

	Operation	Description
1	Install RDSF	Directly after arrival of the RDSF, the first components of the RDSF assembly will be installed under the topsides. Therefore, no heavy on-land crane capacity is needed.
3	Load-out	Transverse load-out with a low topsides centre of gravity by using a heavy skid system.
4	Voyage	Voyage with a low topsides centre of gravity by a HTV.
5	Jack-up & Assemble	Offshore jack-up operation and simultaneous assembling of the RDSF system.
6	Float-over	Standard float-over by ballasting a HTV.

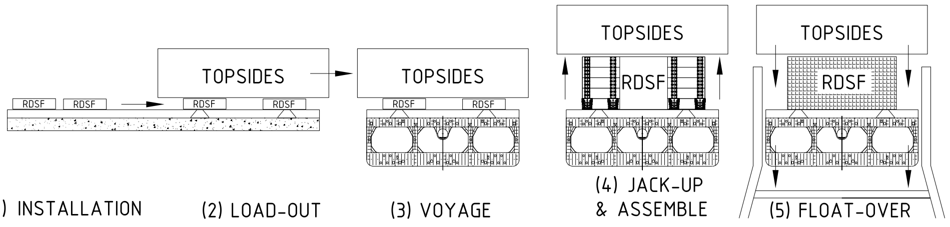


Figure 5.5: Concept RDSF3

Pros of concept:

- Little space and time required at the yard.
- RDSF3 eliminates one operation by combining the jack-up and assemble operation.
- RDSF3 gains flexibility for the voyage operation by tuning the topsides centre of gravity during voyage.

5.3.4. COMPARISON OF CONCEPTS

A comparison between the process in not easily made when considering the RDSF as black box. Nevertheless, the duration of each operation can be estimated first qualitatively, as the completion of the RDSF is not required yet. The total estimated operational time is divided into on-land operations and offshore operations and can be seen in Table 5.4. This rough time estimation is compared on projects with the standard DSF. The operations with the standard DSF are scored as average with '+-'.

Table 5.4: Time estimation of operations of concepts

	DSF	RDSF1	RDSF2	RDSF3
On-land operation	+-	+-	+	++
Offshore operations	+-	+-	+-	- -
Total	+-	+-	+	+-

To find the most promising concept, the concepts are reviewed based on the list of design philosophy criteria in Table 5.5. The design philosophy criteria are a result of the stakeholder preferences, see chapter 4. For example, the estimated duration of the operations is used as input for this assessment. The assessment does not present a clear winner and therefore the differences need to be further investigated.

Table 5.5: Concept development assessment based on design philosophy

	Design philopsophy criteria	RDSF1	RDSF2	RDSF3
1	Increase reliability and safety	+	+-	+-
2	Decrease duration of onboard operations	+	+	-
3	Increase limits of operations at sea	+-	+-	++
4	Ensure wide applicability of the RDSF	+-	+	++
5	Restrain overall costs	+-	+	-
All		++	+++	++

In the following list, an explanation of the most striking values of the concept design philosophy assessment are highlighted. The numbers in the list correspond to the numbers in Table 5.5.

1. The more uncertainties in the design, the lower the expected reliability and safety. The required innovation on the integrated jacking system brings uncertainties for the RDSF2 and RDSF3. However, the onboard jacking capability introduces more reversibility for RDSF3 resulting in a slightly safer system.

2. The RDSF3 has an additional onboard operation: the jack-up & assemble operation which increases the HTV standby time.
3. The RDSF3 enables tuning of the vertical centre of gravity during voyage which could decrease the loads on the system and therefore increases the limits of sea operations.
4. The RDSF2 and RDSF3 do not require a large space at the yard, therefore more topsides fabrication yards are expected to be applicable to the system.
5. The RDSF2 and RDSF3 both eliminate one operation by combining the jack-up and assemble operation. This makes them more cost efficient. However, the RDSF3 requires probably a heavy onboard jacking system which drives up the price again.

5.3.5. CONCLUSIONS OF THE RDSF-OPERATION CONCEPTS

As is mentioned in the comparison of concepts, although all concepts show promising outcomes, there is no clear concept winner. Therefore, additional research on the differences between the concepts is necessary to make an improved judgment. The main differences between all 3 concepts are the effects of onboard jacking and the capability of integrated jacking.

- **ONBOARD JACKING**
  The onboard jacking operation is the main pillar of the RDSF3 concept. More flexibility and reversibility in the float-over process can be acquired with the use of the onboard jacking operation. However, the RDSF3 does require the most amount of offshore time which has to be kept to a minimum, as the offshore time is the most important project cost driver. Therefore, the advantages and disadvantages of the effects of the onboard jacking operation on the total float-over operation are investigated in section 5.4.
- **INTEGRATED JACKING**
  The application of an integrated jack system, as described in concepts RDSF2 and RDSF3, elinates the need of the current external jack system. It is expected that the equipment mobilization costs can therefore be reduced significantly. Also, the required space to perform a on-land jack up and load-out reduces significantly. However, the integrated jacking in the RDSF is not an existing solution. Therefore, feasibility of the integrated jacking operation needs to be investigated. The possibility of integrated jacking is considered during the design of the RDSF in chapter 6.

The consequences of onboard jacking are elaborated first because the outcome is of high importance for integrated jacking. If onboard jacking improves the installation overall, it changes the input of the RDSF design drastically.

5.4. EFFECTS OF ONBOARD JACKING ON FLOAT-OVER INSTALLATIONS

In this section, the effects of onboard jacking on float-over installations are evaluated, which is the main principle of concept RDSF3. The capability of onboard jacking in RDSF3 causes changes to the typical float-over process. Main change created by onboard jacking is the possibility to postpone the jacking operation to a later point in time. This enables for reordering the phases of the float-over installation (see chapter 2 for the phases). The topsides can therefore be transported low on deck to the installation location before the jacking operation, where normally the topsides is already at the high position for installation during load-out and voyage operations. The possibility of varying the topsides height during transportation causes different motions and loads on the system. In this section, these effects of the vertical position of the topsides on the entire float-over installation is analysed. The decision, if concept RDSF3 with onboard jacking is interesting, is given in the conclusion.

However, an onboard jacking system has a number of disadvantages compared to an on-land jacking system.

- The double systems that are required (the jacking system and the RDSF system) are causing a higher cargo weight on the vessel. This reduces the capacity of the vessel.
- The current jacking systems have insufficient side load capacity to perform the jacking operation at sea.
- The vessels have a limited available space on deck causing the supply of the jacking components to be a logistical challenge.

The disadvantages mentioned above, demand for a new onboard jacking system. The first requirements of this new system are listed below.

1. Onboard jacking system must be lockable during every jacking step to assure a certain safety level.
2. The side load capacity of the onboard jacking system system must be at least 20% (corresponding with a roll trim angle of 10 degrees).
3. Weight of onboard jacking system plus RDSF should be in the same order of magnitude as the current DSF system.
4. Onboard jacking system needs to spread loads during all phases of the jacking operation (jacking and stacking mode), to stay within deck capacity limits.

These mentioned criteria are expected to come with at a high price, therefore, the flexibility advantages have to outweigh these disadvantageous before commencing the design of a integrated onboard jacking system. In the following sections the potential flexibility gain is investigated.

5.4.1. EFFECT OF VARIATION IN HEIGHT ABOVE DECK ON THE FLOAT-OVER OPERATIONS

Two different scenarios are given in Table 5.6, wherein the sequence of the float-over phases is presented. Scenario 1 makes use of the current on-land jacking operation. Scenario 2 makes use of the offshore onboard jacking operation. For clarification, the vertical position of the topsides during the phases is given between brackets.

Table 5.6: Order of float-over phases for on-land and offshore jacking

	1. Current float-over scenario: *On-land jacking operation*	**2. Onboard jacking scenario:** *Offshore onboard jacking*
1	On-land jacking (low>high)	Load-out (low)
2	Load-out (high)	Voyage (low)
3	Voyage (high)	Offshore onboard jacking (low>high)
4	Float-over (high)	Float-over (high)

As can be seen in the table, the postponement of the jacking operation in scenario 2 has influences on the load-out operation and the voyage operation. The influence of the variable transportation height above deck (H_{ad}) on the load-out and voyage operation is described in the following subsections.

EFFECTS OF H_{ad} ON THE LOAD-OUT OPERATION

During the load-out operation, the topsides is moved gradually in horizontal direction from the quay to the vessel. The main factors that affect the load-out operation are the weight distribution of the topsides, the tidal changes, the vessel draught level and stability of the vessel [18]. The variation in topsides height (H_{ad}) has no impact on the tidal chances and vessel draught level, but does influence the dynamic weight distribution of the topsides and stability of the vessel.

- The vertical position of the topsides (H_{ad}) influences the stability of the system. By positioning the topsides as low as possible onto the HTV deck, a decrease of the vertical center of gravity of the topsides is obtained which increases the overall stability of the system. A more stable system has a positive influence on the load-out operation, because smaller relative motions between quay side and vessel are expected.
- The lower position of the topsides influences the weight distribution negatively. The lower the topsides position to the ground is, the smaller the distance to distribute the topsides loads which eventually yields into higher ground/deck reaction forces. There is a limit to the ground/deck reaction forces, therefore a preliminary threshold of 5 meters to the minimal H_{ad} is introduced.

The differences between a low and high load-out operation are not expected to be significant. Thresholds in stability requirements and ground reaction forces maintain the quality of the load-out for both scenarios. Therefore, the consequences of onboard jacking on a low load-out operation are not further investigated.

EFFECTS OF H_{ad} ON THE VOYAGE OPERATION

The loads occurring due to motion of the vessel during the voyage operation are leading the design of both the topsides and the DSF. With the onboard jacking system, the topsides Height Above Deck (H_{ad}) during voyage can be tuned, so that the most ideal situation is obtained in order to have the smallest loads on the system. The effects of an increased H_{ad} are analysed by the motion analysis in subsection 5.4.2.

EFFECTS ON THE ONBOARD JACKING OPERATION

The vessel motions are expected to be the main bottleneck for the onboard jacking operation. According to DNVGL-ST-N001-2.6.1 [11], when performing the mooring, jacking and float-over operation in maximal 96h, the design environments of this operation may be chosen as restricted. With a restricted design environment, conditions such as wind and waves may be selected instead of having to design for conditions with a 10 year return period. If the environmental conditions at the installation site are too severe to perform the jacking operation, the onboard jacking operation could be moved to an inshore/sheltered location like the Norwegian fjords.

Only the effects of onboard jacking are described in the following motion analysis. The description of the process of onboard jacking requires a design of the onboard jacking system. The development of this design is only considered if the effects of onboard jacking are promising.

5.4.2. MOTION ANALYSIS FOR VOYAGE OPERATION

The loads due to the motion of the vessel are dominating the design of the (R)DSF. In this motion analysis, the effects of varying the H_{ad} are investigated. The largest changes in accelerations and motions are expected to be in roll direction, because in this direction the system (vessel and topsides) has the least resistance due to the smallest damping. For less time consuming calculations, the analyses of the systems motions and accelerations are limited to two-dimensional YZ-plane (Roll plane). The motions of the vessel are limited to sway, heave and roll. The effects of surge, pitch and yaw are not taken into account. For this analysis, the fixed vessels coordinate system is considered.

The following parameters influence the RDSF design. These parameters are resulting from the motion analyses. The equations of these parameters are given in Appendix G.

1. Loads on the RDSF system
    - Normal loads (F_N)
    - Transverse loads (F_T)
    - Moments (M)
2. Size of the RDSF system
    - Length (L)
    - Breadth (B)
    - Height Above Deck (H_{ad})

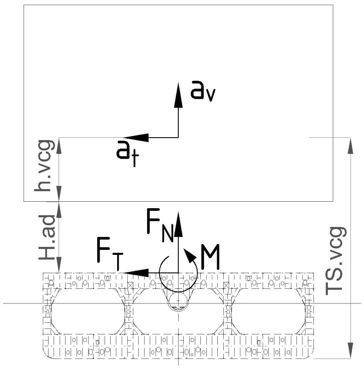


Figure 5.6: Sketch of loads on RDSF

The design of the RDSF depends for the major part on the loads resulted by the transverse accelerations, which is recurring seen in old projects. In this motion analysis the transverse accelerations are found for the multiple vessel-topsides configurations. This is done according to the the DNVGL-ST-N001 11.1.2.1 approval process of voyage design [11]. The process is given in the following list:

1. Determine topsides, vessel, weights and system CoG.
2. Determine route options and seasons, restrictions & met design criteria.
3. System stability check.
4. Motion response analysis.
5. Load response analysis

The motion analysis is split up into two different analyses shown in Table 5.7, where the effects of H_{ad} and the effects of the topsides weight are analysed in analysis 1 and analysis 2 respectively.

Table 5.7: Settings fro oll motion analysis 1 and 2

Analysis	Voyage	Vessel	Weight	H_{ad}
1. H_{ad}-analysis	Hs = 9.5m & Tz = 10.97s	Black Marlin	19,500 mT	0 - 25 m
2. Weight-analysis	Hs = 9.5m & Tz = 10.97s	Black Marlin	5,000 - 25,000 mT	10 m

In analysis 1, H_{ad}-analysis, the effects of the topsides height above deck during transport (H_{ad}) on the DSF loads are investigated. The H_{ad} is varied from 0 meter to 25 meters. With the results of this analysis, conclusions can be drawn for the onboard jacking concept in RDSF3.

In analysis 2, the Weight-analysis, the influence of the topsides weights is added. This analysis captures the effects of varying the vessel. Increasing the weight of the topsides increases the topsides-vessel-weight ratio. This applies for changing the vessel as well, where a smaller vessel for the same topsides increases the topsides-vessel-weight ratio. Therefore, conclusions of the weight-analysis can be drawn wider for both topsides weight and vessels breadths. The processes of both analyses are fully explained in Appendix G.

1. DETERMINE TOPSIDES, VESSEL, WEIGHTS AND SYSTEM COG

The recent Bongkot topsides is chosen as reference project, which is the heaviest topsides transported by the Boskalis Black Marlin vessel. The transportation height of the topsides (H_{ad}) and therefore the vertical centre of gravity is changing in this analysis from 0 m to 25 m. In appendix Table G.1 the characteristics of the Bongkot topsides and Black Marlin vessel are shown.

In Table 5.8 and Table 5.9 the input characteristics for both motion analyses are shown. Where the variation in system vertical centre of gravity and natural roll period is a good indicator of the behaviour of the vessel.

Table 5.8: System characteristics for H_{ad}-analysis (Analysis 1)

Topsides transportation height	H_{ad}	[m]	0	5	10	15	20	25
Topsides VCG	TS_{vcg}	[m]	25.9	30.9	35.9	40.9	45.9	50.9
System VCG	sys_{vcg}	[m]	13.0	14.5	16.1	17.6	19.1	20.7
Natural roll period	T_n	[s]	12.8	15.2	18.6	25.4	33.4	62.7

Table 5.9: System characteristics for weight-analysis (Analysis 2)

Topsides Weight	TS_{mass}	[mT]	5,000	10,000	15,000	20,000	25,000	30,000
Topsides VCG	TS_{vcg}	[m]	31.6	31.6	31.65	31.6	31.6	31.6
System VCG	sys_{vcg}	[m]	9.2	11.1	13.1	15.0	16.9	18.8
Natural roll period	T_n	[s]	8.8	10.4	12.2	14.5	17.8	23.8

In the tables is seen that the natural roll period increases for a larger H_{ad} and a larger TS_{mass}. As Appendix G mentioned, this natural roll period increase is a result of a more unstable system. The same behaviour is seen for in an increasing weight of the topsides. This higher natural period will shift the excitation peak period to the lower peak frequencies causing different responses to be expected.

2. DETERMINE ROUTE OPTIONS AND SEASONS, RESTRICTIONS & MET DESIGN CRITERIA

The RDSF is to be designed for every worldwide sea. The highest probable worldwide environmental conditions are taken as input for the motion analysis. Global Wave Statistics (GWS) provides nearly worldwide coverage of wave climate in 104 sea areas [19]. According to GWS, the highest sea states are to be found in 'area 90' which is close to the Cape of Good Hope. The highest 1% waves of Hs = 9.5m and a Tz = 9s - 13s. Sea states with longer periods (Tz > 13s) occur less than 0.5% with a maximum Hs of 8m [19]. The four most heavy sea states which occur in Area 90 are given in Table 5.10.

Table 5.10: Spectrum variation

		1	2	3	4
Significant wave height	Hs	9.5 m	9.5 m	9.5 m	8.0 m
Zero-crossing period	Tz	9.0 s	11.0 s	13.0 s	15.0 s
Mean-crossing period	T1	9.8 s	11.9 s	14.1 s	16.3 s
Peak period	Tp	12.7 s	15.5 s	18.3 s	21.1 s

A real sea can be described as a superposition of series of regular sinusoidal waves, whereof a wave spectrum on radial frequency can be expressed via a Fourier series analysis. The wave spectrum for fully developed seas is best approached by the Pierson Moskowitz (PM) spectrum [20]. The PM-spectra for the most severe conditions of area 90 are illustrated in Figure 5.7.

$$S(\omega) = \frac{1.25}{4}\frac{\omega_p^4}{\omega^5} H_s^2 exp(-1.25(\frac{\omega_p}{\omega})^4) \tag{5.1}$$

Where ω_p is the peak frequency and H_s is the significant wave height.

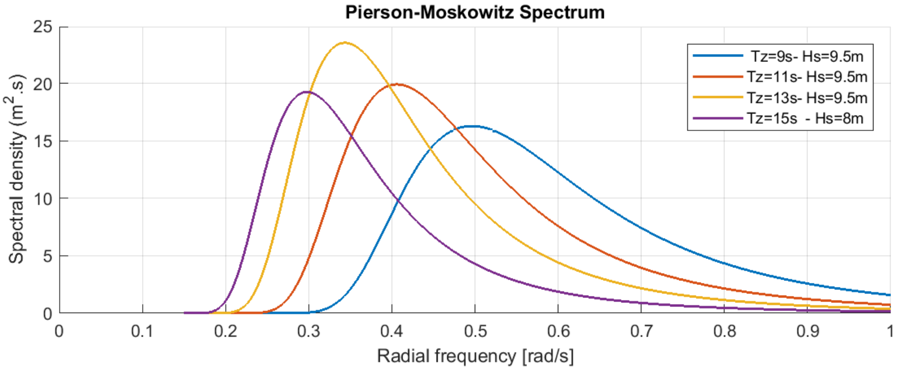


Figure 5.7: Pierson Moskowitz spectrum for different Tz

All variations of the Pierson-Moskowitz spectra do not have energy at the frequencies smaller than 0.2 radians per seconds, and therefore the system is not excited around the lower frequencies. Consequently this leads to the little to none accelerations responses.

5.4.3. 3. SYSTEM STABILITY CHECK

To perform the voyage, the system is to be checked on stability criteria of classification societies given in Table 4.1.1. The stability checks for this analysis are only limited to criteria 1: The upright GM (or meta-centric height) shall not be less than 1.0 meters.

The stability checks for H_{ad}-analysis (Analysis 1) and weight-analysis (Analysis 2) are combined in Table 5.11. The table gives the values for upright GM for the combinations of topsides weights ($W = 5,000 - 30,000 mT$) horizontally and the Height Above Deck range of ($H_{ad} = 0 - 25m$) vertically.

Table 5.11: GM upright stability analysis for combination of weight and H_{ad} of topsides

	Weight of topsides [mT]					
H_{ad} [m]	5,000	10,000	15,000	20,000	25,000	30,000
0	12.7	11.2	9.8	8.3	6.8	5.4
5	12.3	10.4	8.6	6.7 [3,4,5]	4.9	3.0
10	11.9	9.7	7.4 [2]	5.1	2.9	0.6
15	11.5	8.9	6.2	3.6	0.9	-1.7
20	11.1	8.1	5.0 [1]	2.0	-1.1	-4.1
25	10.7	7.3	3.9	0.4	-3.0	-6.5

The configuration with red values in Table 5.11 do not comply with the GM upright stability rule of minimal 1.0 meter. The superscript numbers 1-5 show the succeeded projects performed with the Black Marlin ([1]*Angel*, [2]*Muda MDPP CPOC*, [3]*Bongkot (GM= 5.89)*, [4]*Tapis R*, [5]*Vyborg Semisub*). The values of GM of the succeeded topsides installations vary around 5.0 m to 7.4 m. Configuration with a comparable topsides weight and H_{ad} parameters will most likely meet all stability rules.

To support this statement, other succesfull reference projects are given: Heera (GM = 5.18m), Ofon (GM = 4.48m), Aasta Hansteen (GM = 24.2m), SHWE (GM=19.1m). For the Ofon project however, buoyancy tanks were required to enhance the wind and stability range criteria.

4. MOTION RESPONSE ANALYSIS

The load responses of both motion analyses are calculated using the following method:

1. Calculating the RAO spectra for all different system configuration using in-house DOSUITE software. $RAO = \frac{a_T}{\zeta_a}$
2. Calculating the acceleration response spectra for each Pierson-Moskowitz Hs&Tp combination. $S_{a_T}(\omega) = |\frac{a_T}{\zeta_a}|^2 * S_\zeta(\omega)$
3. Calculating maximum accelerations of all spectra. $a_T = max(S_{a_T}(\omega))$

Acceleration responses analysis 1: Varying: Height Above Deck
In the first analysis, the height of the topsides during transport (H_{ad}) is varied from 0 - 25 meters. For a increasing H_{ad} a decreasing RAO peak values are calculated, as can be seen Figure 5.8. The transport of the topsides with a large H_{ad} causes therefore longer natural periods as the energy shifts to smaller radial frequencies. The acceleration responses of the four different Pierson-Moskowitz spectra are combined in Figure 5.9 to show the effects of changing H_{AD}.

For the acceleration responses for all Pierson-Moskowitz spectra see Appendix G.4.

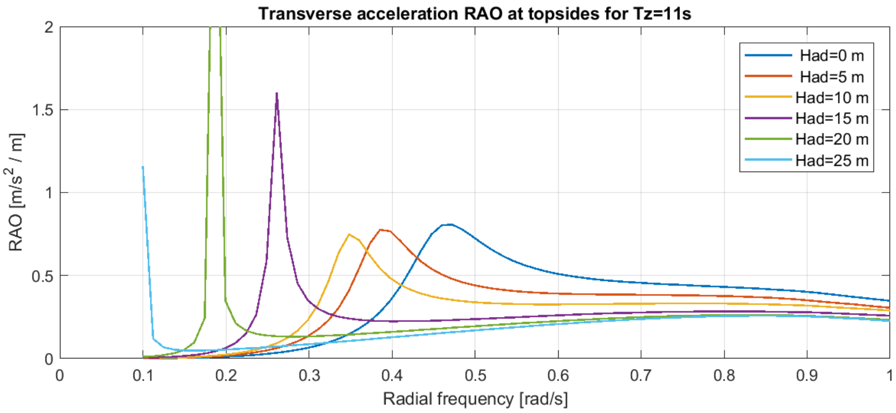


Figure 5.8: RAO H_{ad}-analysis (Analysis 1)

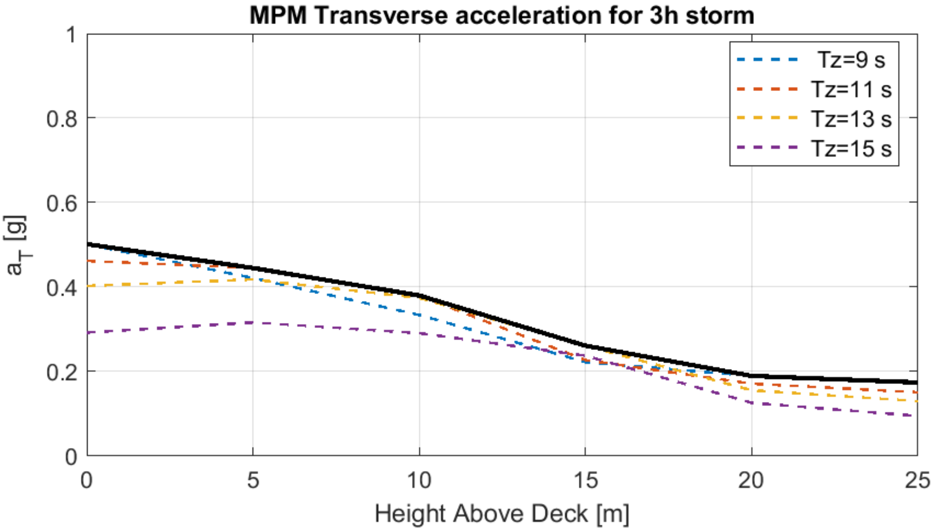


Figure 5.9: Most probable maximum (MPM) transverse acceleration of H_{ad}-analysis (Analysis 1)

The transverse accelerations for every configuration are below the 0.5g requirement, which is set for the design of the RDSF (see Table 4.1).

Acceleration responses analysis 2: Variation in weight of topsides
In the second analysis, the topsides weight varies from 5,000 - 25,000 mT. The trend of decreasing RAO outputs for increasing natural roll periods is also seen in Figure 5.10 by increasing the topsides weight. The responses for the different Pierson-Moskowitz spectra are combined in Figure 5.11 to show the effects of a changing the weight of the topsides.

For the acceleration responses for all Pierson-Moskowitz spectra see Appendix G.4.

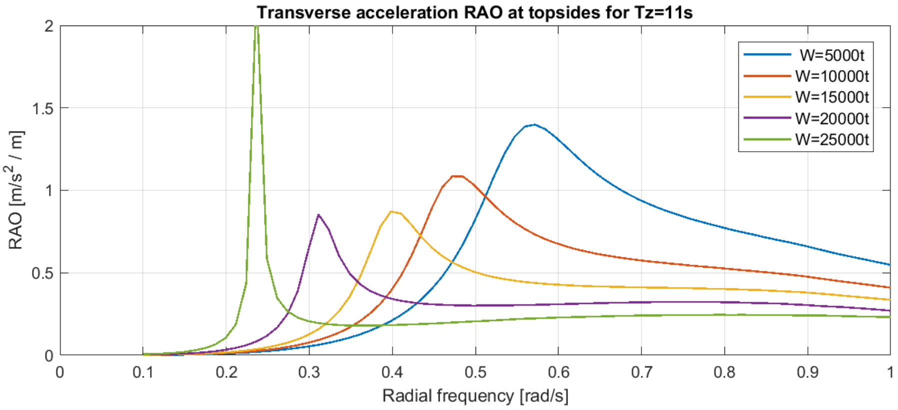


Figure 5.10: RAO weight-analysis (Analysis 2)

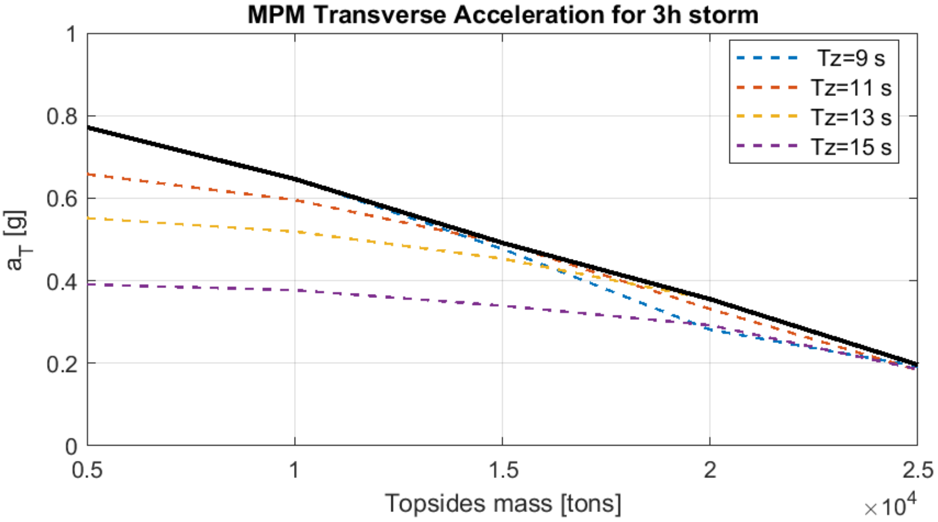


Figure 5.11: Most probable maximum (MPM) transverse acceleration of weight-analysis (Analysis 2)

The transverse accelerations for the configurations until 15,000 tonnes are above the 0.5g requirement, which is set for the design of the RDSF (see Table 4.1). However, ballast tuning which improves the behaviour in not considered during this analysis. Therefore, the 0.5g requirement is still expected to be valid for most light configurations.

5. LOAD RESPONSES ANALYSIS

The load response for both analyses is calculated according to the following formulas:

- Transverse loads: $F_T = TS_{mass} * a_T$
- Moment loads: $M = F_T * (H_{ad} + H_{TS})$

Load response analysis 1: Varying the transportation height of the topsides

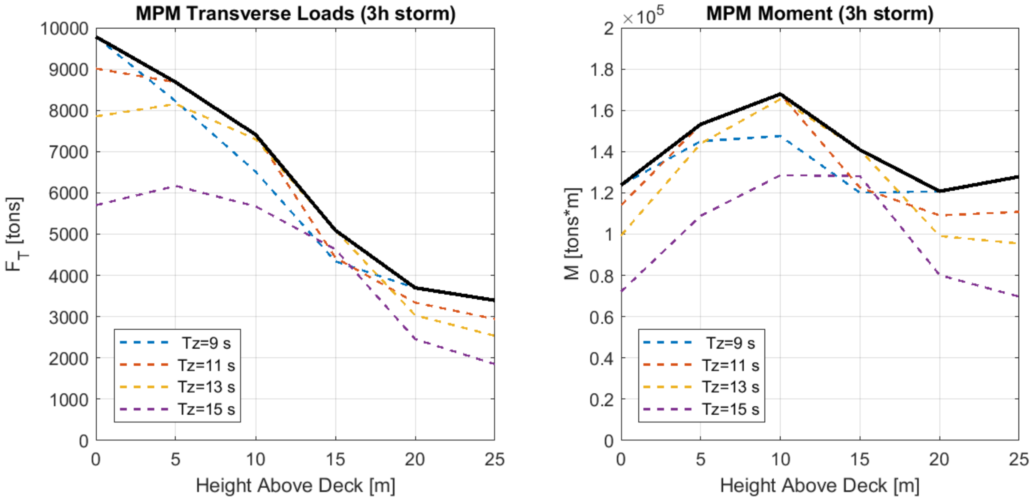


Figure 5.12: Load response analysis 1

For a decreasing topsides H_{ad}, from 25m - 5m, the behaviour of the system has:

- Increasing transverse loads with a ratio of around 2.5, from 4,000 - 10,000 tonnes-force.
- More or less constant moment, varying around 140,000 mT*m.

The tuning parameter in analysis 1 is the H_{ad} which varies from 5m to 25m. Hereby, the maximum transverse loads (F_T) vary with 66% between 4,000 and 10,000 ton-force. The maximum moments vary with 40% between 120,000 mT*m and 170,000 mT*m.

Load response analysis 2: Varying the weight of the topsides

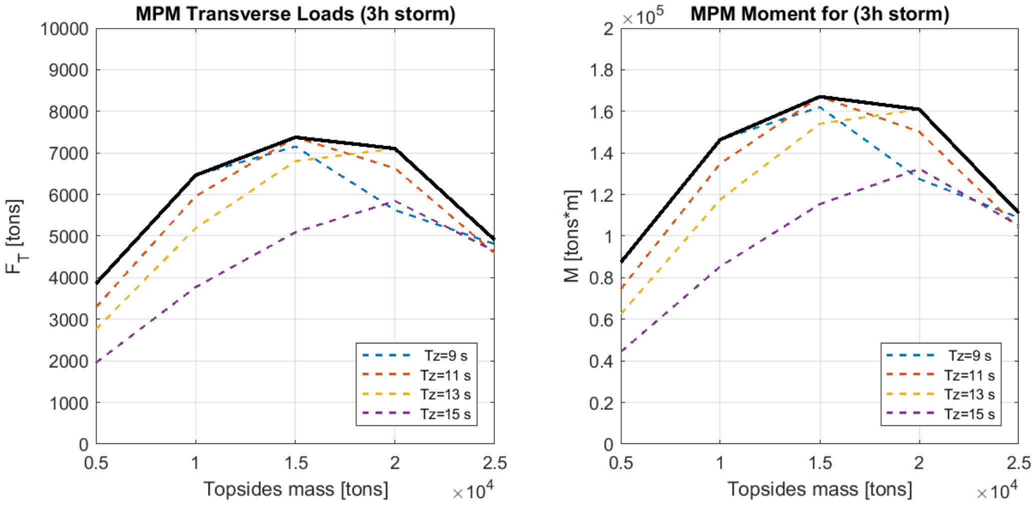


Figure 5.13: Load response weight-analysis (Analysis 2)

For a increasing topsides weight, from 5,000 - 25,000 tonnes, the behaviour ot the system has:

- Increasing transverse loads for light to medium topsides (5,000-10,000 tonnes)
- Heaviest transverse loads for topsides of 10,000-20,000 tonnes.
- Decreasing transverse loads for topsides from 20,000 tonnes.
- Exactly equal behaviour for the moment as for transverse loads (because of constant H_{ad}).

The topsides weight, the tuning parameter of the weight-analysis, varies from 5,000 - 25,000 tonnes, which is a difference of 500%. The maximum transverse loads (F_T) hereby vary with 90% between 4,000 and 7,500 ton-force. This applies for the maximum moments (M) as well, which vary with 90% between 90,000 and 170,000 mT*m.

5.4.4. CONCLUSION OF THE MOTION ANALYSIS

The main principle of concept 3, the onboard jacking operation, is analysed to find out if the advantages for the entire float-over process could be achieved. The onboard jacking operation enables reordering the float-over operations, which enables the topsides H_{ad} during voyage to be variable. Currently, the topsides are transported high on deck to enable installation at the substructure. With onboard jacking this H_{ad} could be decreased for voyage.

Analysis 1: Varying the transportation height of the topsides
The first analysis considers a voyage configuration consisting of the Black Marlin vessel and a 19,500 tonnes topsides (Bongkot). It is seen that for a decreasing H_{ad}, there is an increase in transverse loads and a relatively constant moment. The increase in loads is due to the fact that the system stability increases together with the natural frequency of the system. The systems transverse acceleration response shifts therefore to the more energy dense frequencies of the Pierson-Moskowitz spectrum which in their turn excites the system more. This is resulting in higher transverse accelerations and thus larger loads on the system.

It can be concluded that, a lower H_{ad} during transport causes higher loads to the DSF. Therefore, the onboard jacking operation does not cause an improved system behaviour.

Analysis 2: Varying the weight of the topsides
This first analysis is extended with the variation of topsides weights in the second analysis. This analysis shows both the consequences for increasing the weight of the topsides as for decreasing the breadth of the vessel. The following is observed:

- It is seen that for the low weight category (5,000 - 10,000 tonnes), the transverse acceleration are extremely high even above 0,7g, but are resulting in small loads on the system due to the small topsides weight.
- The medium weight category topsides (10,000 - 20,000t), medium accelerations are seen giving the highest loads on the system.
- For the heaviest topsides (> 20,000t), low accelerations are observed causing medium heavy loads on the system.

Most interesting result of the weight-analysis is the drop in accelerations and loads for the most heavy topsides. However, topsides installations with these configurations have never been done before. The main reason for this is that the remainder stability criteria are violated, and therefore approval for the voyage can not be issued.

Although the lightest topsides have the largest accelerations, the resulting loads still remain small. Therefore, the RDSF designs for heavier topsides are always able to install the lighter topsides.

General discussion of the motion analysis

- The step size of the both the topsides transportation height above deck (H_{ad}) and weight(W) is large. For both analyses only 5-6 points per measurement are taken into account, which is resulting in rough outcomes. The results still show a trend however, making the analysis valuable.
- The accelerations and therefore loads and moments depend for the vast part on the chosen environmental conditions. The choice to model the most severe conditions, so the highest significant wave heights with their corresponding long periods, lead to extreme high responses. The extreme

design conditions of Hs of 9.5m has for the chosen area (area 90) with South-West heading waves a probability of exceedance of only 1.5%. The responses are calculated in this design environment for beam seas with a 3-hour long period. In reality, the vessel will never experience these harsh conditions, because activities like like weather routing and heading changes prevent these conditions from happening.

- To make a fair comparison, the draught level for both analyses is kept constant on 8.55 meters. Therefore, the ballast of the system varies for different topsides weights in the weight-analysis (Analysis 2). This causes unrealistic ballast conditions for the lightest topsides which is resulting in unrealistic high accelerations.
  In reality, the vessel's behaviour is improved by tuning the ballast conditions, where the fill rate of the ballast tanks are reconfigured to move the system's vertical centre of gravity. This tuning of the system's behaviour with ballast, is left out of consideration during this motion analysis.
- There must be noted that a minimal H_{ad} is required to ensure for load introduction in the vessel's deck. The analysis with the smallest H_{ad} ($H_{ad} = 0m$) is therefore infeasible. The minimal required H_{ad} for load introduction is however strongly depended on the deck, grillage and topsides and is therefore incomparable for multiple projects.
- The remainder stability criteria as wind angle and stability range are not taken into account for this motion analysis. To have a better view on the feasibility of the configurations, the stability rules need to be further investigated.

5.4.5. GENERAL CONCLUSIONS OF THE EFFECTS OF ONBOARD JACKING

To make the onboard jacking operation an success, a lot of investigation has to be done. However, it is seen that the gain in flexibility does not outweigh the disadvantages. In general, the loads on the RDSF do not decrease by decreasing the topsides height during voyage. Next to this, the most challenging part of the onboard jacking concept, is to design a jacking system which can safely operate under high side loads due to vessel's motions. Additionally, the RDSF with onboard jacking system may not weigh much more than a standard single-use DSF in order to not influence the HTV capacity to much. The conclusion can be drawn, that the onboard jacking operation concept (RDSF3) is not the most effective solution for the RDSF.

Nevertheless, for the topsides that are beyond the scope of the study, it is seen that the onboard jacking system could still be an interesting method. Especially, for extreme heavy topsides that momentarily do not comply with the stability rules. These stability criteria could be met when transporting the topsides low on deck. With the use of onboard jacking, the topsides can be lowered during voyage to meet the stability requirement. When arrived at the installation site, the required height will be achieved by the onboard jacking operation, causing the stability criteria to be potentially violated. However, the float-over operation is performed in a weather restricted time window, where relaxation of stability criteria may be applied. Relaxation of stability criteria is often done in consultation with warranty surveyors. These relaxation may be issued when special conditions apply, for example for short voyages or in sheltered waters. This analysis is however limited to the upright stability criteria only. Therefore, more research on the stability criteria and the relaxation of these is recommended. This to determine the technical feasibility of heavy topsides installations on relatively small vessels with the use of onboard jacking.

5.5. CONCLUSIONS OF THE CONCEPT DEVELOPMENT OF THE FLOAT-OVER INSTALLATION METHOD

The concept development of float-over operation with the use of the RDSF has concluded in three concepts which are presented below. The main differences between the concepts are the location and the moment of the jacking operation.

1. RDSF1 - RDSF with external on-land jacking system.
2. RDSF2 - RDSF with internal on-land jacking system.
3. RDSF3 - RDSF with external on-board jacking system.

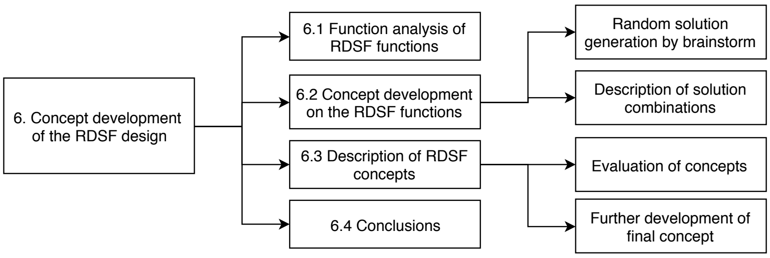
The main feature of concept RDSF3, is the onboard jacking operation. In this concept, the jacking operation is postponed to a later moment in time, which enhances the flexibility during the voyage. This concept has a high potential for the most heavy topsides that do not comply with the stability criteria for regular voyages. For the scope of this study however, the advantages do not outweigh the disadvantages that turn up by designing a new and stronger onboard jacking system. Therefore, concept RDSF3 is rejected and not further investigated in this study.

It is seen that, an integrated jacking system of concept RDSF2, brings advantages to the float-over operation by eliminating one operation. However, more detail is required to make an educated decision about concept RDSF1 and RDSF2. The RDSF design itself (the 'black box' at this stage), is developed in the next chapter (chapter 6). After concluding the next chapter, a decision on these concepts can be made.

6

CONCEPT DEVELOPMENT OF THE RDSF SYSTEM

Tthe concept development of the RDSF system itself is described in this chapter. The function analysis has divided the main function of the system into smaller sub functions. Multiple solutions are presented for these functions. Combinations of the solutions form concepts which are described and evaluated at the end of this chapter. The result of this chapter is a final concept of the reusable deck support frame, wherefore the feasibility is checked in chapter 7.



6.1. FUNCTION ANALYSIS OF THE REUSABLE DECK SUPPORT FRAME

The sub functions of the RDSF are analysed in the function analysis. The main function of the RDSF is to support the topsides during all phases of a float-over installation. The resulting sub functions are shown in the function tree in Figure 6.1. Multiple solutions, for the lowest level sub functions, are presented in the next section.

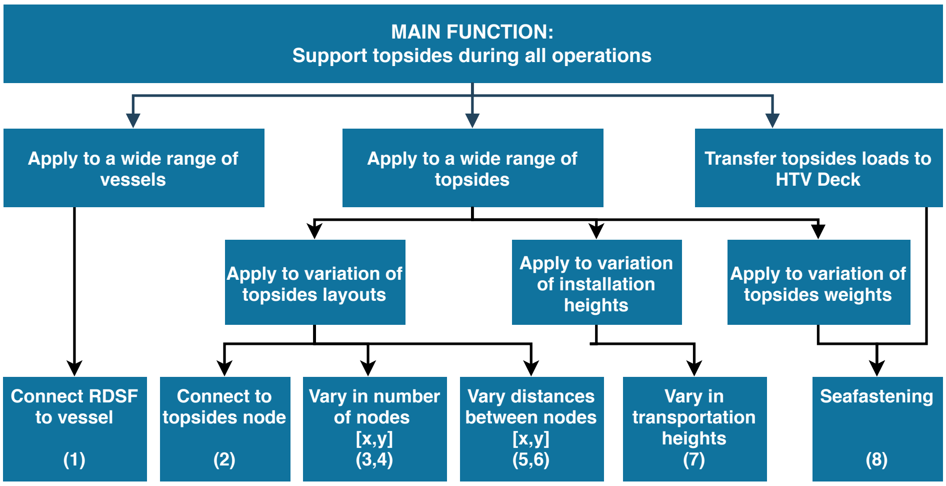


Figure 6.1: RDSF function tree

Description of functions for the RDSF design

The solutions are restricted, these boundaries are given in Table 6.1. The relations between the functions are visualized in Figure 6.2. The full list of restrictions can be found in chapter 4.

Table 6.1: Restrictions to functions

	Functions	Restrictions
1	Connect RDSF to vessel	For 2 transverse skid tracks per row Supported by 2 web frames
2	Connect RDSF to topsides node	For a Leg-Flat connection (Bongkot, Figure 3.5a)
3	Connect with vessel in X-direction	
4	Connect with vessel in Y-direction	
5	Vary distances in Y-direction	
6	Vary distances in X - direction	
7	Vary in Heights	
8	Sea fastening (transfer horizontal loads)	

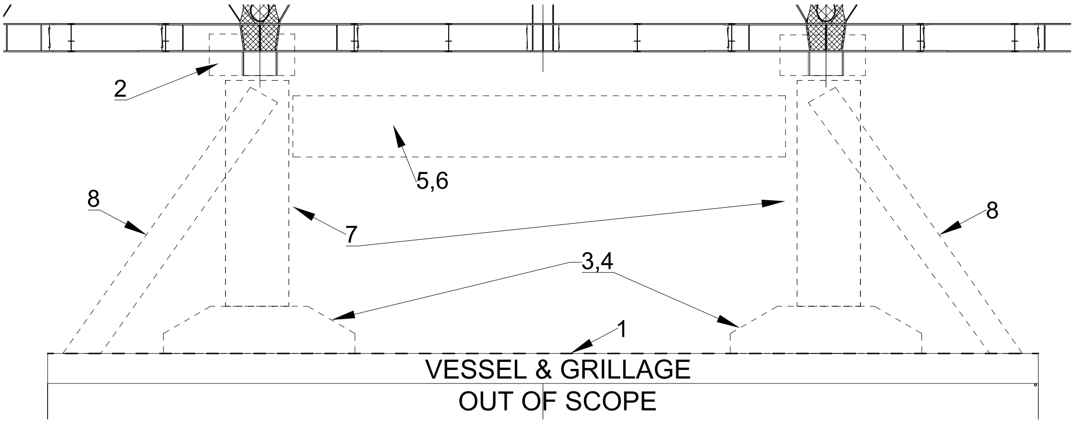


Figure 6.2: Schematic representations of the RDSF functions

6.2. RDSF CONCEPT DEVELOPMENT FOR THE RDSF FUNCTIONS

In this section the development of the RDSF concepts is given. The concept development is described in two parts. A random set of solutions is generated in the brainstorm sessions first, and then these solutions are categorized based on the functions earlier described in a morphological overview.

6.2.1. RANDOM SOLUTION GENERATION BY BRAINSTORM SESSIONS

The following design layouts shown in Table 6.2 are used to frame the design process by representing the geometrical limits of the requirements. If the operational feasibility is viable for these extreme layouts, expected it that is also complies with the ones in-between. The layouts give boundaries to the design in terms of weight, height, number of nodes and node spacing.

Table 6.2: Design layout parameters for brainstorm sessions

	Weight [mT]	Height [m]	Nodes (X x Y)	Spacing X [m]	Spacing Y [m]
Heavy & Low	25,000	5	4x2	24-24	27
Medium & Mid	15,000	15	3x2	1-20-18	32
Light & High	8,000	25	2x2	32	30

The design layout drawing (see section E.2) is used in multiple brainstorm sessions among students and employees of both Boskalis and Mammoet. The goal of this method is to find solutions for the problem without any prior knowledge. The different perspective of both experienced employees and inexperienced students helps to generate a wide range of solutions. The generated solutions generated are processed after the function analysis of the system. An impression of the result of the brainstorm sessions is shown in Figure 6.3. The solutions are categorized based on all sub functions of the RDSF. The categorization and function analysis is given in the next section.

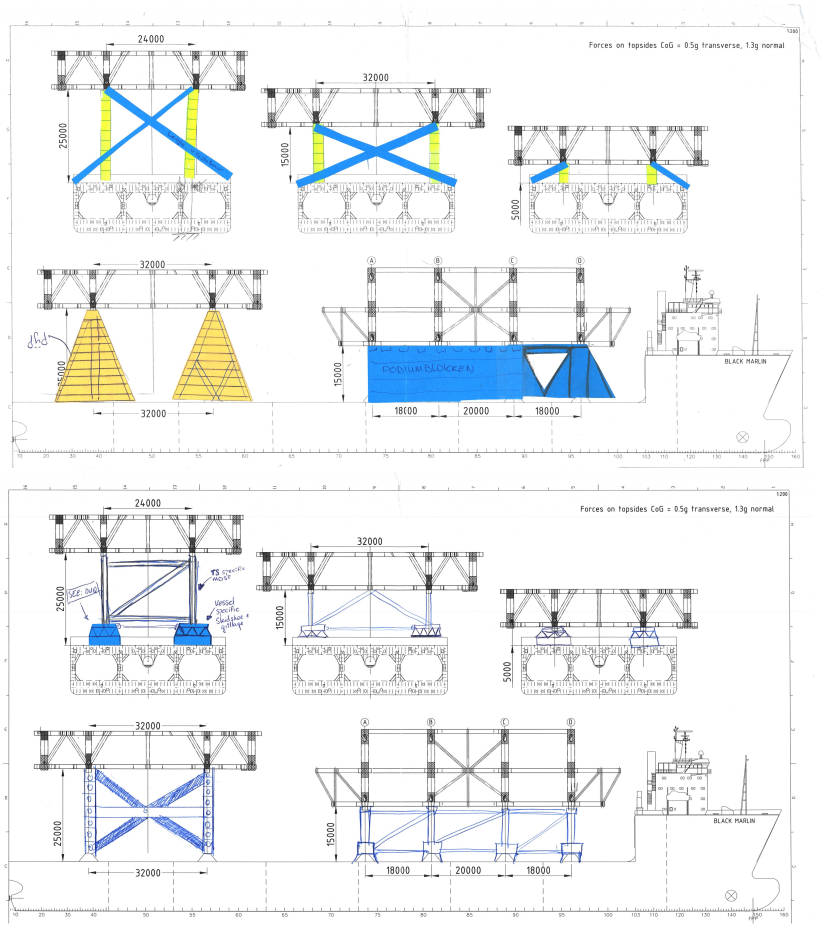
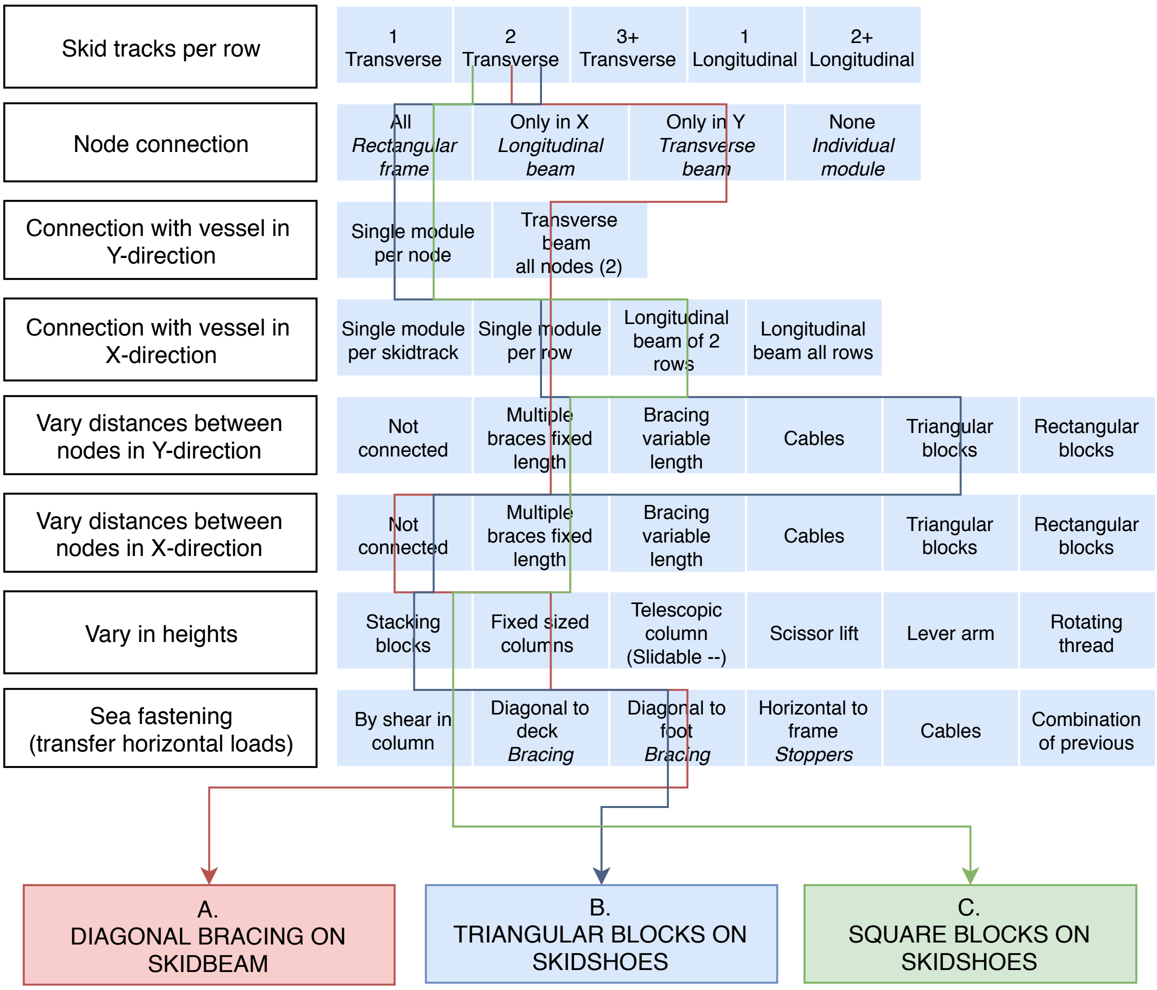


Figure 6.3: Impression of brainstorm sessions

6.2.2. MORPHOLOGICAL OVERVIEW

The RDSF concept development is performed by the building blocks method. First, the solutions that are generated during the brains storm sessions are categorized for the different individual functions. This can be seen in Figure 6.4 in the morphological overview, where on the left (white boxes) the functions and on the right (blue boxes) the solutions are listed.

Different combinations of solutions form preliminary concepts. Three different solution combinations are generated which are visualized by the coloured lines in Figure 6.4. These solution combinations are described in the next section.



Skid tracks per row	1 Transverse	2 Transverse	3+ Transverse	1 Longitudinal	2+ Longitudinal	
Node connection	All *Rectangular frame*	Only in X *Longitudinal beam*	Only in Y *Transverse beam*	None *Individual module*		
Connection with vessel in Y-direction	Single module per node	Transverse beam all nodes (2)				
Connection with vessel in X-direction	Single module per skidtrack	Single module per row	Longitudinal beam of 2 rows	Longitudinal beam all rows		
Vary distances between nodes in Y-direction	Not connected	Multiple braces fixed length	Bracing variable length	Cables	Triangular blocks	Rectangular blocks
Vary distances between nodes in X-direction	Not connected	Multiple braces fixed length	Bracing variable length	Cables	Triangular blocks	Rectangular blocks
Vary in heights	Stacking blocks	Fixed sized columns	Telescopic column (Slidable --)	Scissor lift	Lever arm	Rotating thread
Sea fastening (transfer horizontal loads)	By shear in column	Diagonal to deck *Bracing*	Diagonal to foot *Bracing*	Horizontal to frame *Stoppers*	Cables	Combination of previous

Figure 6.4: Morphological overview of solutions for RDSF functions, with solution combinations (concepts)

6.3. DESCRIPTION AND EVALUATION OF THE RDSF CONCEPTS

In this part the description of the preliminary RDSF concepts is given. The pros and cons of every concept are eventually used to develop the final concept which is described in the next section.

A: HORIZONTAL BEAMS WITH DIAGONAL BRACING ON SKID BEAM

Solution combination A (Figure 6.5) consists of two main transverse beams that are connected by diagonal bracing pipes. The lower beam stretches over the entire width of the vessel which is 42 meters for the Black Marlin. The bottom of the lower beam is able to slide over the skid tracks during the load-out operation. The upper beam is also pointed in transverse direction and is slightly smaller than the lower one. The upper beam is able to connect to the topsides support nodes at multiple positions. The topsides will not be mounted to the middle part of the upper beam as it is therefore slightly smaller. The upper beam and the lower beam are connected to each other by means of diagonal bracing. Different bracing lengths, positions and angles enables the upper beam to vary in height. The bracing can be mounted step-wise to the different holes on the beams, to vary these angles.

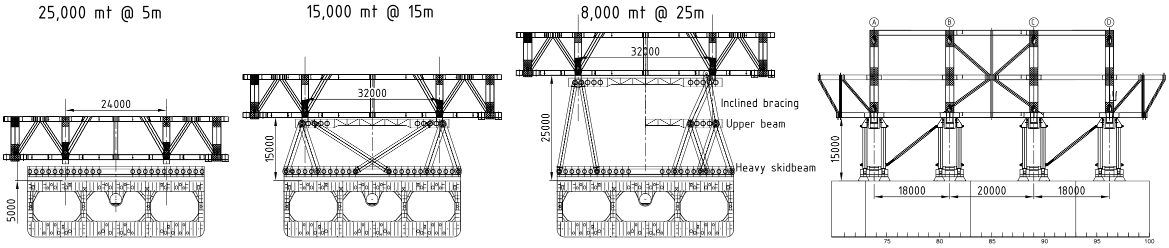


Figure 6.5: A. Horizontal beams with diagonal bracing on skid shoes

Pros of A: Horizontal beams with diagonal bracing on skid beam:

- Fully variable in heights by interchangeable pipes.
- Able to integrate existing jack systems.

Cons of A: Horizontal beams with diagonal bracing on skid beam:

- Inefficient use of steel in lower en upper beam due the high number of mounting points.
- Replacement of different sized pipes brings additional project-specific costs.
- Lower beam is not compatible for other vessel with different deck layouts.

B: TRIANGULAR BLOCKS ON SKID SHOES

Solution combination B (Figure 6.6) can be seen as an assembly of many triangular blocks or 'Lego pieces'. All blocks have the same shape and can be assembled freely to each other. All sorts of RDSFs can be created by varying the positions of the pieces. At the bottom of the frame, multiple skid shoes are positioned which slide over the grillage during the load-out operation.

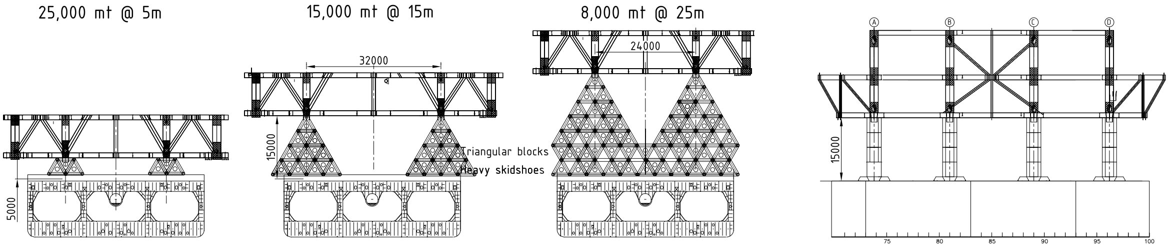


Figure 6.6: B: Triangular blocks on skid shoes

Pros of B: Triangular blocks on skid shoes:

- A lot of geometrical freedom.
- Interchangeable blocks (Lego pieces).
- Triangular shape assures high stability.
- Very scalable (for 4, 6, 8, ... nodes) due to individual modules per node.

Cons of B: Triangular blocks on skid shoes:

- Many fragile connection points.
- Fixed blocks geometry may cause misalignments with some topsides-deck configurations.
- Unable to integrate existing jack systems.

C: SQUARE BLOCKS ON SKID SHOES

Solution combination C (Figure 6.7) consists of square heavy corner blocks under each topsides support node. These corner blocks are connected with each other by horizontal beams which alternate in longitudinal and transverse direction. Each corner block is positioned on top of a set skid shoes, which enable the load-out of the topsides with the concept. After the load-out, the skid shoes are removed and the main DSF frame is sea fastened to the HTV.

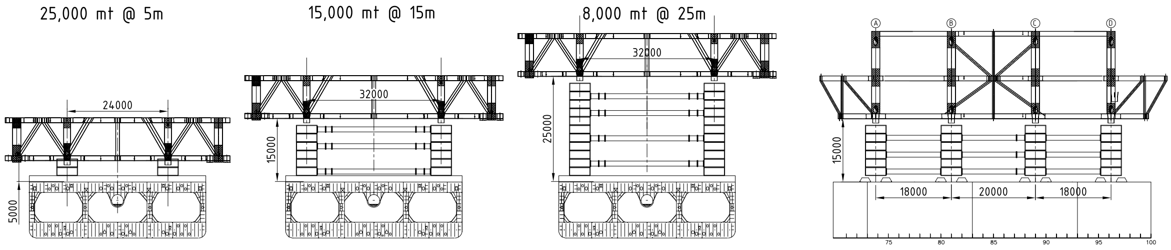


Figure 6.7: C. Square blocks on skid shoes

Pros of C: Square blocks on skid shoes:

- Easily varying the nodes spacing by changing length between towers.
- The use of existing skid shoes for the load-out.
- Possibility to integrate existing jack systems.

Cons of C: Square blocks on skid shoes:

- No load spreading due to constant footprint of the vertical corner tower structures.
- Additional external skid system required.

6.3.1. EVALUATION AND FURTHER DEVELOPMENT ON FINAL CONCEPT

The above presented solution combinations have been evaluated during several individual and group discussions with experts within Mammoet. These experts have a lot of knowledge about the design of heavy equipment. During these meetings, the pros of the solution combinations above are collaborated to one final concept using the building blocks method [21]. The selection of the building blocks of the final concept are described below and shown in Figure 6.8.

Selection of main building blocks of the final concept.

1. Individual module per topsides DSF node.
   The basis of the RDSF is design is chosen to be an individual module per topsides node. As noticed in the the market analysis (chapter 3), low topsides transposition makes often use these individual modules. Individual modules are highly adjustable in spacing and scalable to more nodes compared to full constructions. This makes the individual module suitable for repetitive installation for a wide variation of topsides layouts.

2. Upper-block.
   The individual module consist of one upper-block that functions as the connection between the RDSF module to the topsides. It is able to handle a wide variation of node interfaces and is therefore reusable in multiple projects.

3. Triangular framing.
   The individual module uses a triangular shape to spread the loads in order to remain within the limitation of the HTV deck.

4. Skid shoes for load introduction and the load-out operation.
   The skid shoe has predictable load introduction during the load-out operation. The skid shoes automatically stabilize by finding its optimal balance and therefore cause a more equal load distribution than the alternative skid beam concept. Additionally, skid shoes are very suitable for load spreading. Using them for both load introduction during voyage and the load-out operation eliminates the need for two individual systems.

5. Grillage support.
   The grillage is not part of the scope of this study, however, it is important for the technical feasibility of the concept. The grillage concept needs to be designed for two skid tracks per topsides node. The corresponding grillage capacity can be enlarged by increasing the number of web frames per skid track.

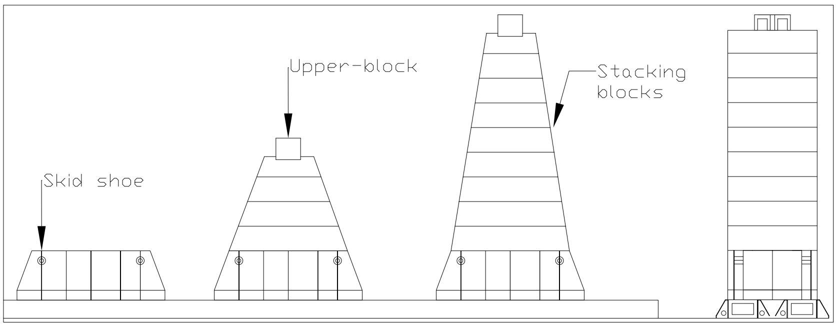


Figure 6.8: Individual module including its building blocks

DEVELOPMENT OF THE DESIGN

The stacking blocks for the higher configurations are not steel-efficient and consist a high number of connections. First optimization is achieved by replacing the stacking blocks with long pipes (Figure 6.9, a). In this new configuration the concepts of load spreading is still preserved, but with less required steel and connections. However, the pipes/legs of the unit are not modular any-more, and will therefore have to be replaced if a different configuration (with different dimensions) comes around.

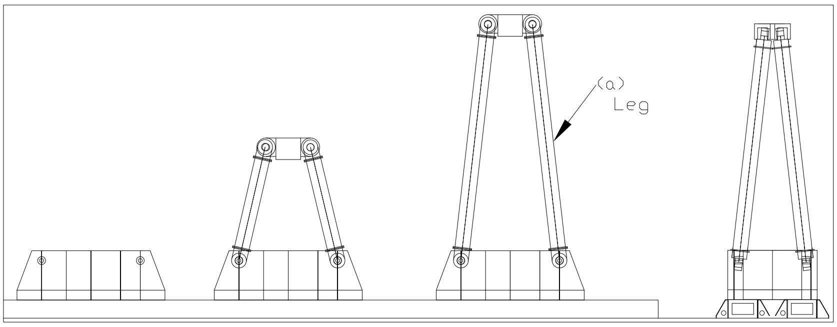


Figure 6.9

The high topsides voyages require a wider footprint than the low voyages due to the larger overturning moments. Contradictory to this, topsides for high transports are less heavy and require thus a smaller footprint for load spreading. In the second optimization this problem is tackled by splitting the skid shoe. This enables the distance between them to be variable leading to a larger triangular shape (Figure 6.10, b). Now, the footprint can be chosen ideally for every future configuration. Another optimization is achieved to the legs by positioning the mounting points of the legs in line with the skid tracks (Figure 6.10, c). This enables the RDSF unit to be erected under the topsides without sticking outside the skid tracks. Eventually, the upper connection position (axis) of the legs and the upper-block needs to positioned so that the axes geocentrically coincide around one rotation point. This makes the RDSF unit stable without having a moment-fixed topsides connection (Figure 6.10, d).

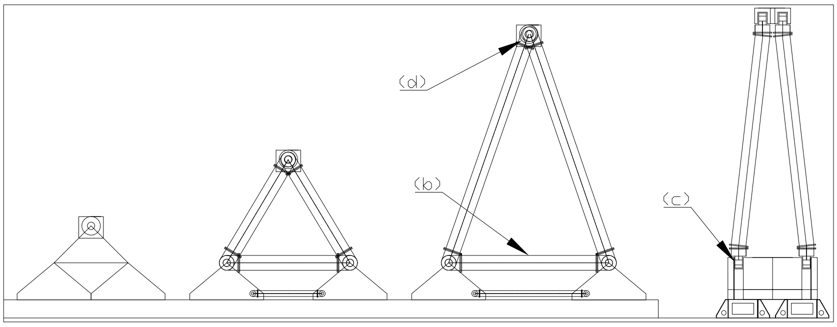


Figure 6.10

There is a lower limit to the topsides configurations due to the most efficient load spread angle (of 45 degrees). This minimal required height causes the RDSF unit to be inapplicable for the low topsides configurations (below $H_{ad} = 6.0m$). This problem is overcome by introducing a flexural bending beam (or bogie) to spread loads over longer distance (Figure 6.11, e). The previous optimization by positioning the legs in line with the skid tracks has as consequence that the legs cannot vary in length. This problem is overcome by placing the legs in line with the skid track. The resulting loss in stiffness is captured by introducing horizontal and diagonal bracing (Figure 6.11, f). Also the skid shoes modules are split in longitudinal direction, which enables the applicability to vessels with a deviant frame spacing distance (Figure 6.11, g).

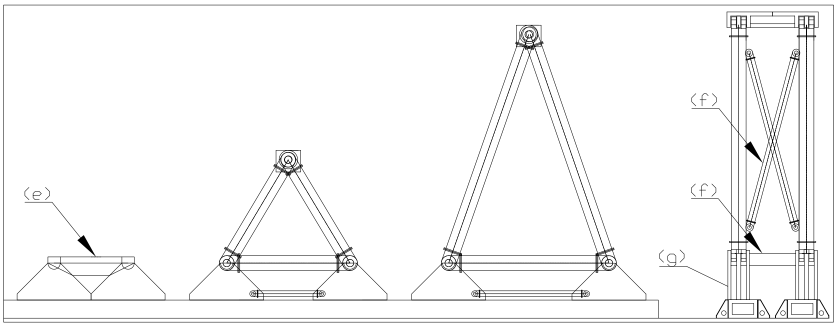


Figure 6.11

6.3.2. ADDITIONAL INTEGRATED JACKING BY EXISTING JACKING SYSTEM

The RDSF is way more valuable if the jacking systems could be integrated to the RDSF system, as mentioned in the development of the float-over method. The resulting elimination of one operation by combining the jacking and assemble operation (by integrated jacking) reduces the need of space, heavy equipment, amount of systems, and time.

This preferred function is taken into account by integrating an existing jacking system to the RDSF. The jacking system type or manufacturer is not important in this case. As an example, the implementation of the Mammoet JS2400 in the RDSF is shown in Figure 6.12.

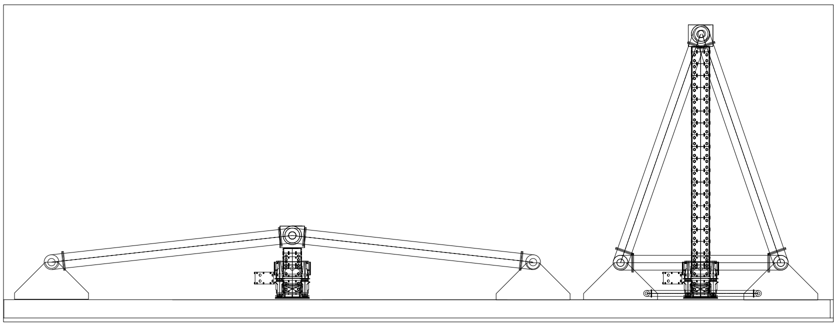


Figure 6.12

The following advantages of using an existing jacking system instead of designing a new integrated jacking system come to light:

1. There is no need for additional investment and further research. The proof of concept of an existing jacking system ensures for a short time-to-market (TTM), which is important for making innovation profitable.
2. The RDSF system and jacking system are independently usable. Future projects that require only the RDSF system or the jacking system are therefore be adequately addressed. Independent use of both systems makes the innovation more versatile, applicable and cost-effective.
3. The jacking system stays onshore, making it less subjected to the harsh offshore environment.

Jacking systems are limited mainly on the side load capacity in combination with the jacking height. For example, the JS2400 has only a side load limit of 2% at 12 meters height. These limited specifications make the system incapable of performing most topsides' jack-ups. With the use of the RDSF design the side loads can be taken away at the top of the jacking tower. Because of this, the jacking system will not experience any side loads. This causes the system's capacity to be independent of the jacking height, enlarging the capacity envelope of jacking systems.

6.4. CONCLUSIONS OF THE CONCEPT DEVELOPMENT OF THE REUSABLE DECK SUPPORT FRAME

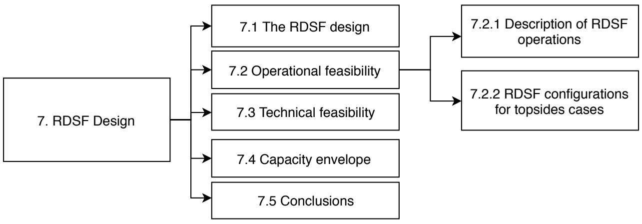
Multiple solutions are generated in order to come up with a targeted reusable deck support frame design. The (stakeholder) preferences play a major role in the design choices. It is seen that the most important preferences are the high degree of flexibility with a minimum level of temporary connections. Given these preferences, an RDSF system with an individual module per topsides DSF node is found most suitable. The modules have a triangular shape that ensure an excellent load distribution for a wide variation of transportation heights. Furthermore, the different interchangeable pipe sections ensure for a minimal use of steel and connections. However, this design comes with a disadvantage, since the different pipe/leg sections are not reusable on different projects, making this concepts not fully reusable. The base of the system consists of four skid shoes and is able to move individually in horizontal direction. This to enlarge the applicability on multiple vessels with different frame spacing.

In chapter 7, 'the RDSF system' is described in more detail. Also, the technical and operational feasibility of the system is validated.

7

RDSF DESIGN

This chapter elaborates on the RDSF concept chosen in the previous chapter. First the design of the RDSF system is presented and all main components are introduced in 7.1. The feasibility of this RDSF system is examined on operational and technical feasibility. The operational feasibility of the RDSF is examined by describing all operational steps in 7.2. Hereafter, the technical feasibility is demonstrated by checking the global strength of all RDSF components in 7.3. Eventually, the RDSF system capacity envelope is presented in 7.4. This envelope is used as basis for the business case in the next chapter.



7.1. THE RDSF SYSTEM

The main principle of the RDSF system are the independent units per topsides node. Every 'RDSF unit' supports one topsides' node individually. The distances between the RDSF units can be chosen freely. This acquires a high applicability of the system. The entire RDSF system is a composition of 4, 6 or 8 RDSF units. The amount of units depend on the number of support nodes of the topsides. The RDSF system is illustrated in Figure 7.1 in the 4 RDSF unit configuration. The general arrangement drawing of the RDSF system is given in Appendix B.

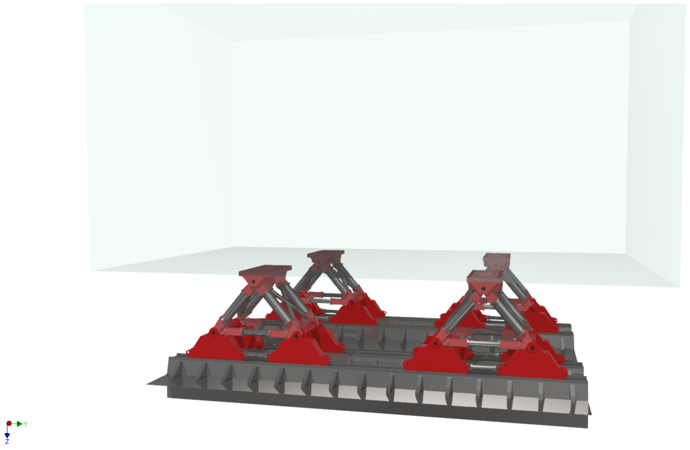


Figure 7.1: Render of RDSF system

7.1.1. THE RDSF UNIT

The RDSF unit is able to shape to any configuration within its geometrical limits. The system is able to cope with all different topsides configuration by the extension or shortening of the main legs. The RDSF unit is shown in Figure 7.2 indicating all its the main components. The distinction between the reusable and the project-specific components is given in the colours red and grey respectively. This distinction is important for the economic feasibility which is reviewed in chapter 8. The reusable parts are called CAPEX-parts and the project-specific parts are called OPEX-parts. This terminology is used throughout this report. The drawing of the CAPEX-parts and OPEX-parts is given in Appendix C.

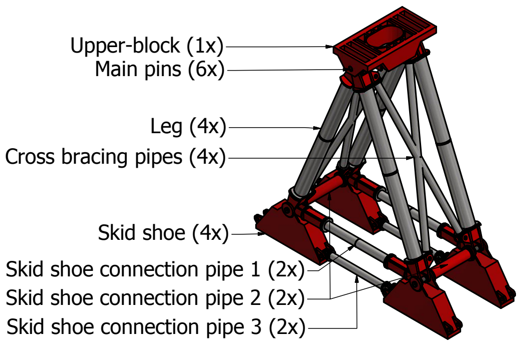


Figure 7.2: The RDSF unit

1. **Upper-block (1x per RDSF unit)**
   The upper-block is the interface of the RDSF system with the topsides and is illustrated in Figure 7.3. The upper-block has a horizontal surface with a hole in the middle. Topsides with protruding legs stick through this gap. The main deck of the topsides is supported by the horizontal surface of the upper-block. The topsides can be positioned slightly asymmetrical (± 625 mm) in longitudinal direction to cope in the varying web frame spacing of the different vessels. The legs are connected on the sides of the upper-block between the plates. Each leg of the RDSF unit can be mounted to the upper-block in two positions, 2400mm and 2500mm from the centre of the upper-block. This distance difference enables the RDSF system to be applicable for HTVs with a frames spacing of 2400mm and 2500mm. The upper-block is a reusable CAPEX part.

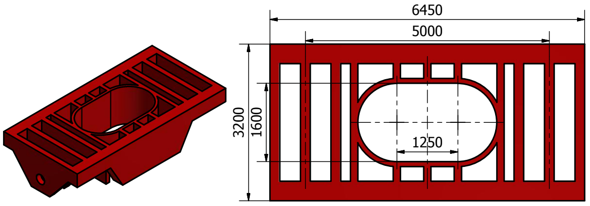


Figure 7.3: Upper-block

2. **Main legs (4x per RDSF unit)**
   At both ends of the main legs connection forks are bolted which mount the legs with the upper-block and skid shoes by a pin-hole link. In-between these connection points the interchangeable pipe is positioned. The lengths depend on the projects specifications. The connection forks at the sides are reusable CAPEX parts and the pipe in between is a project-specific OPEX part. However, when projects with similar geometry specifications reoccur, the project-specific pipes can still be reused. The legs and forks are shown in Figure 7.4.
   For the low RDSF configurations the legs become too small, making low configurations technical infeasible. For these configurations, an intermediate piece between the skid shoes is placed, creating a fixed connection between the upper-block and the skid shoes.

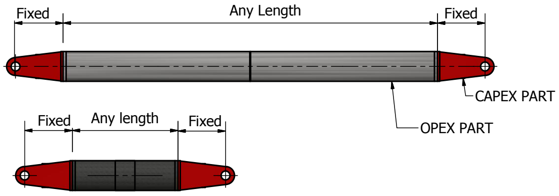


Figure 7.4: Legs

3. **Skid shoes (4x per RDSF unit)**
   The legs are connected to the skid shoes by the same pin-hole connection used in the upper-block. Via the skid shoes, the incoming load is introduced to the grillage at the bottom of the skid shoe. The skid shoes are connected to each other by two interchangeable connection pipe, one to the upper hole and the other to the lower hole. The skid shoes are reusable CAPEX parts.

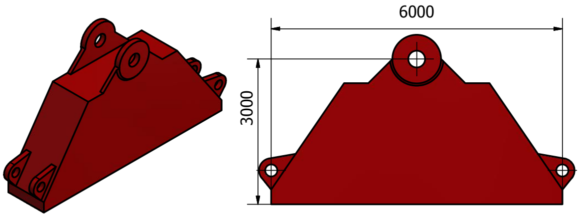


Figure 7.5: Skid shoe

4. **Secondary construction components**
   The RDSF unit consists out of the following secondary construction components. These components can be found in Appendix C:
   - The 'skid shoe connection pipe 1' is the main horizontal pipe in y-direction. The pipe ensures a closed triangle which prevents the skid shoes from slipping. The fork connection is a reusable CAPEX part and the pipe in-between belongs to the project-specific OPEX parts, which is similar to the main legs.
   - The 'skid shoe connection pipe 2' connects the skid shoes in x-direction and prevents the skid shoes from toppling. This pipe is a reusable CAPEX part.

- The ’skid shoe connection pipe 3’ connects ’pipe 1’ and the skid shoes with each other. However, this smaller pipe is positioned lower to skid shoes and ensures for an evenly horizontal load introduction during the load-out operation. The distance between the skid shoes is variable for every project. This pipe is a project-specific OPEX part.
- The ’cross bracing pipes" connect the legs with each other and ensure for longitudinal stability. The cross bracing pipes belong to the project-specific OPEX parts.
- The ’Main Pins’ connect the legs with the skid shoes and the upper-block. The main pins belong to the reusable Capex parts.

5. **(Grillage)**
   The grillage is not part of the RDSF unit. It is an important component however. The grillage interfaces the RDSF system by supporting the skid shoes. The RDSF system requires a minimal grillage capacity to function. This required grillage capacity differs for every project and is very dependent on the structural strength of the vessel. The grillage capacity for the RDSF is assumed to have a value of 150 tonnes per meter web frame. The calculation of this capacity is given in Appendix H .

RDSF SYSTEM WEIGHT INDICATION

The component list of the reusable Capex components including the weights and materials is given in Table 7.1.

Table 7.1: Approximate weight of Capex components

Capex component	Amount[x]	Approx mass [mT]	Material	Total mass [mT]
Skid shoe	4	26	S355	104
Interface upper-block	1	55	S355	55
Pins	6	1.2	34CrNiMo6	7
Main leg forks	8	6.7	S355	54
Horizontal pipe fork	4	5.2	S355	21
Horizontal pipe (X)	2	4.4	S355	6
RDSF unit				250 mT

7.2. OPERATIONAL FEASIBILITY

The operational feasibility is examined in two parts. First, a description of the operations of the RDSF system during the lifespan is given. And second, the operational feasibility is further demonstrated by showing the configurations for the four topsides cases described in 4.1.4.

7.2.1. DESCRIPTION OF RDSF OPERATIONS

The operations during the lifespan of the RDSF are listed below in Table 7.2. Most operations are exactly similar to the use of the DSF. The operational feasibility for these similar operations is not further elaborated.

Table 7.2: Operations of the RDSF system in total lifetime

	Operation	RDSF	DSF
1	Fabrication of (R)DSF components	Indoor (worldwide)	Outdoor (at yard)
2	Storage of (R)DSF CAPEX parts	Outdoor (worldwide)	Not required
3	Mobilization of CAPEX parts to yard	By vessel (worldwide)	Not required
4	Assembling of (R)DSF at yard	By small cranes (55 mT)	Not required (included in fabrication)
5	Installing (R)SDF under topsides	By existing skid system	Requires additional SPMT's
6	Jacking of topsides	On DSF nodes	On jacket support nodes
7	Lock (R)DSF system	By forklift trucks	Not required
8	Remove jacking system	Similar for RDSF & DSF	
9	Load-out of topsides onto HTV	Similar for RDSF & DSF	
10	Voyage to float-over location	Similar for RDSF & DSF	
11	Float-over installation	Similar for RDSF & DSF	
12	Return voyage	Similar for RDSF & DSF	
13	Removal (R)DSF from HTV	Similar for RDSF & DSF	
14	Discard (R)DSF	After all cycles	After one cycle

The operations: Fabrication, Storage, Mobilization, Assembling, Installing and Jacking are unique for the RDSF system and are discussed below. The operations Load-out, Voyage, Float-over, Return Voyage and Removal are exactly similar to the use of the DSF are therefore not further elaborated.

OPERATIONAL SEQUENCE OF THE RDSF SYSTEM

The RDSF operations at the yard from assembling (4) to locking (7), are elaborated thoroughly in Table 7.3. This is done for both the situations, with an internal jacking system and with an external jacking system. The operational sequence is also illustrated in Figure 7.6 with a front and side view. From step A2 & B2 onwards, all operations are executed under the topsides. A render illustration of the operational sequence with internal jack system is given in Figure 7.7.

Table 7.3: Operational sequence of the RDSF at the yard

	A: RDSF System with internal jack system		B: RDSF system with external jack system
A1	Pre-assemble the RDSF system	B1	Assembling entire RDSF system
A2	Positioning of the RDSF system under topsides	B2	Positioning of jacking system under topsides
A3	Positioning of jacking system between the RDSF	B3	Jack-up of the topsides
A4	Jack-up of the topsides and the RDSF system	B4	Positioning of the RDSF system under topsides
A5	Lock RDSF system system by horizontal pipes	B5	Set-down topsides on the RDSF
A6	Remove jacking system	B6	Remove jacking system

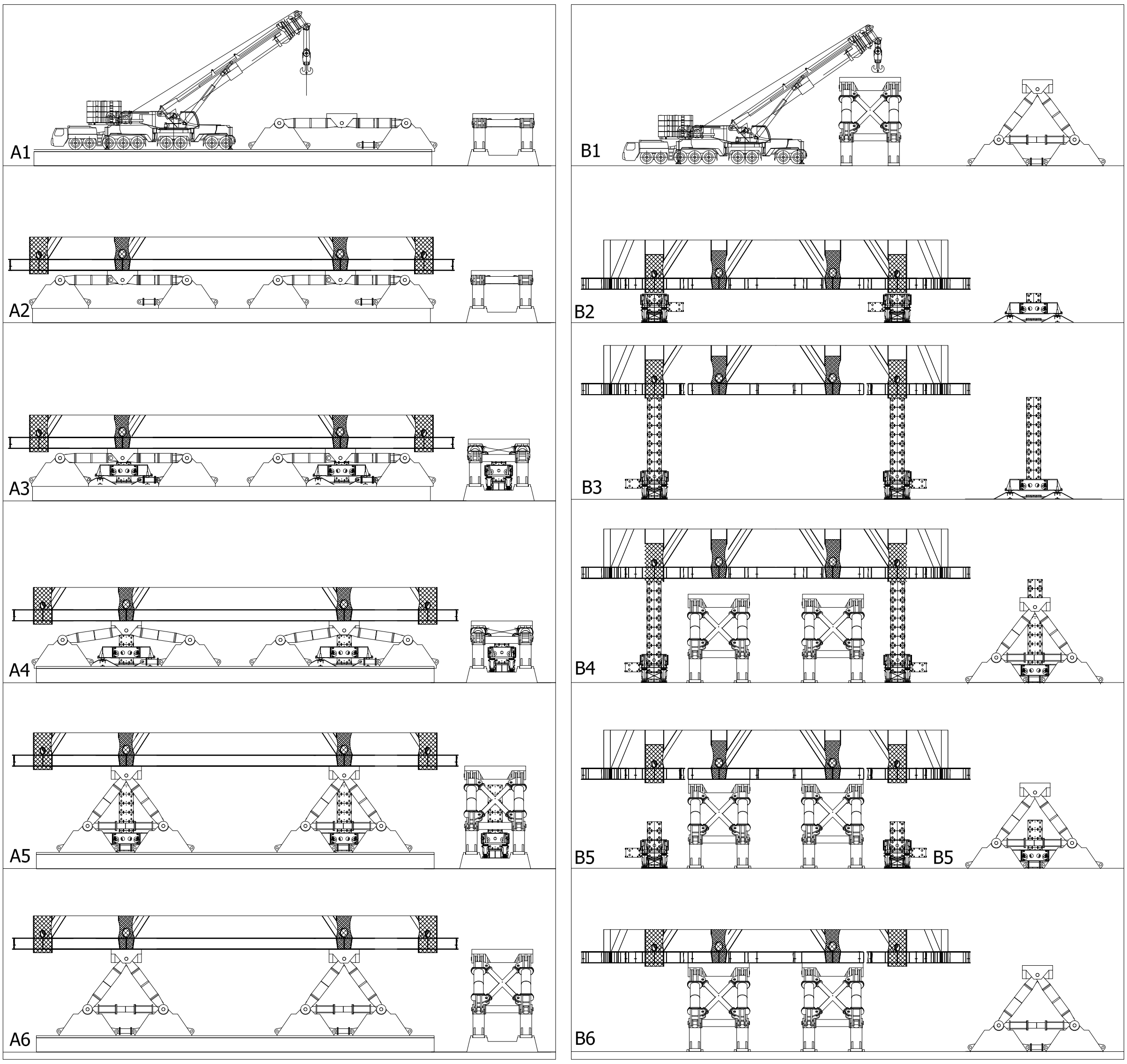


Figure 7.6: Operational sequence of the RDSF

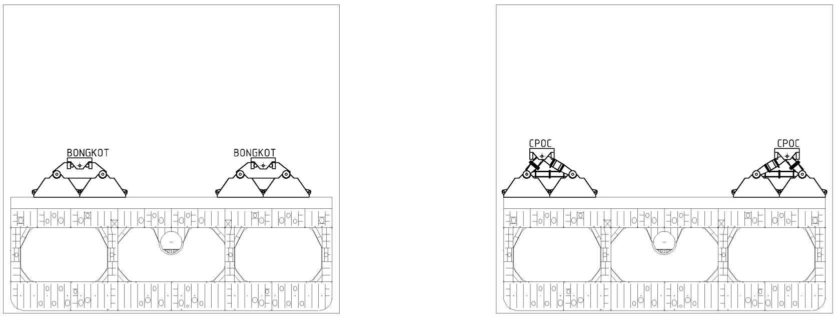
Figure 7.7: Internal jacking with the RDSF system

7.2.2. RDSF CONFIGURATIONS FOR CASES

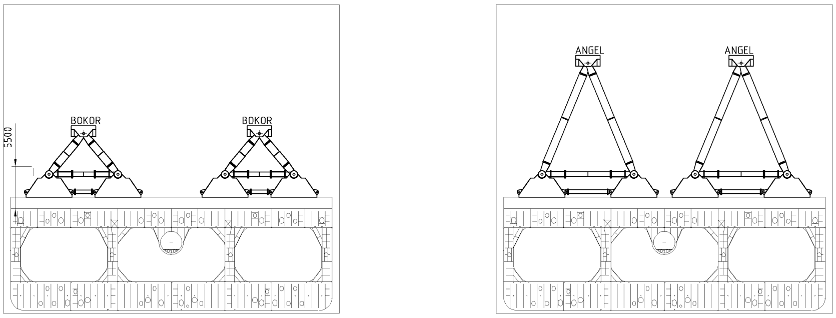
The operational feasibility is demonstrated for the four topsides cases set up in the functional requirements (subsection 4.1.4). The geometry parameters of these cases are given in Table 7.4. The four configurations of the RDSF system for the four cases are shown in Figure 7.8. All figures show the mid section of the Black Marlin including a 1.5 meter high grillage structure.

Table 7.4: Topsides cases with geometry characteristics for the feasibility checks

CASES		Bongkot	CPOC	Bokor	Angel A
Weight [mT]	W	19,500	16,734	11,500	7,568
Topsides VCG [m]	H_{TS}	12.0	12.0	12.0	12.0
Height Above Deck [m]	H_{ad}	6.62	7.85	10.83	20.0
Nodes (X x Y)	n	8 (4x2)	8 (4x2)	4 (2x2)	4 (2x2)
Node spacing X [m]	ΔX	18-20-18	16-16-16	20	23
Node spacing Y [m]	ΔY	24	32	23	20



(a) Bongkot (b) CPOC

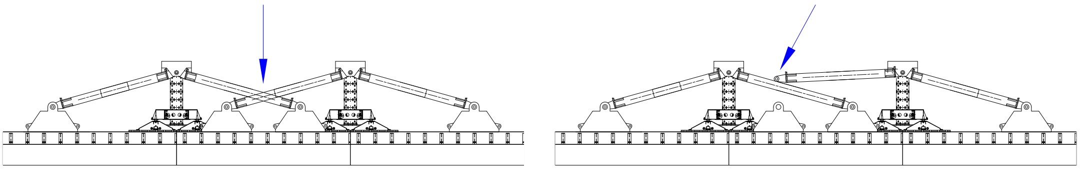


(c) Bokor (d) Angel

Figure 7.8: The operational envelope of the RDSF system

As can be seen in figure Figure 7.8, the configuration of the RDSF can differ strongly depending on the topsides characteristics. The following remarks are seen for the four cases.

- The RDSF configuration of Bongkot case does not include legs. The horizontal leg orientation for low topsides transports (H_{ad}) results in an inefficient loading condition. The legs of these low configurations are replaced by a flexural beam, which spreads the loads evenly over the two skid shoes. The allowable range of minimum leg angles (α) is determined in the technical feasibility section (7.3).
- The asymmetrical configuration for CPOC Muda topsides is a result of the wide nodal spacing in transverse direction ($\Delta Y = 32$). A symmetrical configuration would have extended over the side of the vessel. A asymmetrical shape by using different leg dimensions prevents this problem.
- For high topsides, like Angel A in Figure 7.8d), the RDSF legs intersect during the internal jacking operation. The interference is countered by disconnecting the inner legs. This enables the legs to slide over the other RDSF unit during jacking of the topsides. This problem and solution are sketched below in Figure 7.9.



Problem: Intersection of legs

Solution: Leg sliding connection

Figure 7.9: Leg sliding connection for high topsides

RDSF OPERATIONAL ENVELOPE

The previous RDSF configurations of the topsides cases are combined in Figure 7.10. In this figure, the difference in topsides node positions is shown. The thick black lines represent the operational envelope. The topsides that fall in the envelope are operationally feasible. The operational envelope has a lower boundary of 4.0 meters (minimal height on top of the grillage). The horizontal node spacing distance depends on the vessel. For the Black Marlin, the transverse distance (ΔY) is minimal 6.0 meters and maximal 36.0 meters. The minimum distance in longitudinal direction is 7.5 meters, which is three times frame spacing distance. The longitudinal direction is not restricted in maximum dimensions. The restrictions are given in Table 7.5 for the Black Marlin.

Table 7.5: Operational envelope of the RDSF system for Black Marlin

Restrictions		min	max	
Row spacing	ΔX	7.5	-	[m]
Line spacing	ΔY	6.0	36.0	[m]
Height above deck	H_{ad}	Hg + 4.0	-	[m]

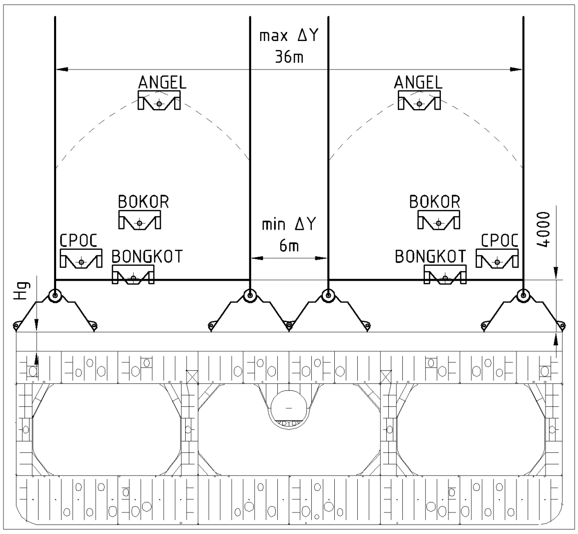


Figure 7.10: Operational envelope of the RDSF system for the Black Marlin

The operational envelope of the RDSF system for the Black Marlin covers 100% of all past float-over projects. It can be concluded that the RDSF system is operationally feasible.

7.3. TECHNICAL FEASIBILITY

In this section, the technical feasibility of the RDSF is examined by a strength check for all components. It is seen that the loads during the voyage are leading in the design. This analysis results in unity check values for every element. These values provide insight in the overall strength of the system. These unity check values are used to evaluate the critical elements of the RDSF system.

OPERATIONS WITH THE RDSF SYSTEM

The influence of all parameters on the strength of the RDSF system is discussed below. The fabrication of the topsides phase is excluded as the RDSF system is not involved during this operation.

- **Loads on RDSF during the jack-up operation.**
  The RDSF system does not support the topsides during the jack-up operation. The system does not experience loads during this operation. Therefore, the jack-up operation is only limited by the capacity of the jacking system. The design of the jack-up system is not included in the scope of this study. the jack-up operation is therefore not considered during the strength check analysis.
- **Loads on RDSF during the load-out operation.**
  Permanent loads (gravity), environmental loads (wind) and deflection loads are present during the load-out operation. These loads are expected to less than the loads on the RDSF during the voyage operation. The load-out operation is therefore not further discussed in this study.
  However, extreme deflections due to misalignments of the skid track and/or vessel may become an issue. It could cause losses of an RDSF supports that increase the loads to the other support points. This can be mitigated by introducing active hydraulic skid shoes which ensure a limited stiffness interaction between the RDSF and the grillage. The skid shoes will distribute the loads evenly over the hydraulic group and mitigate the deflections of the skid track and vessel.
- **Loads on RDSF during the voyage.**
  The RDSF is designed to handle transportation loads. During the voyage the largest loads will act on the support structure. The loads that are considered for the design of the RDSF are:
  - Permanent loads (G).
  - Environmental loads (E).
    For simplicity, only the most severe translational accelerations due to waves are considered.
    Wind loads are assumed not to be decisive. Current, tidal and ice loading do not have effect on the RDSF system.

  The topsides and vessel are assumed to be infinitely stiff. This is not the case in reality. The vessel will encounter small deflections in the longitudinal plane due to hogging and sagging caused by wave loading. The resulting horizontal loads on the RDSF can be prevented by fastening the system only at one row, allowing the other nodes for unrestricted positioning. The small vertical deflections do not have influence on the RDSF for topsides with two rows. It does have effects on topsides with three or more rows. However, because the topsides are in general less stiff than the 'closed box' HTV, the topsides will follow the deflection of the vessel, resulting in negligible additional loads. Therefore, the loads excited by vessel deflections are not taken into account in this study.
- **Loads on RDSF during mating operation.**
  The transfer of the topsides is assumed not to be decisive for the RDSF and GSB design. The horizontal and vertical loads are assumed to be lower than during the voyage, as seen for comparable projects as for example White Rose.

As mentioned above, the grillage and RDSF will be designed to fulfil its tasks during the jacking, load-out, transport and float-over operations of the topsides. As is described, only the voyage operation is considered as this is the dominating operation for the RDSF. For simplicity, only the translational accelerations due to the vessel motions are considered. The strength check of this voyage operation for all components is described in the following sections.

The design will be made in accordance with the international codes for ultimate limit state (ULS), among which: The Specification of Steel Structures (AISC-360-10) and the Marine Warranty Survey (DNVGL-ST-N001

[11]). The allowable stresses used are according API-RP-2A and given in Table 7.6. The intended steel to be used for GSB and RDSF is a high tensile steel with a minimal yield stress of 345 MPa (σ_{yield}).

Table 7.6: Allowable stresses API-RP-2A

Tension/Compression	$\sigma_{max} =$	0.60 $*\sigma_{yield}$
Shear	$\tau_{max} =$	0.53 $*\sigma_{yield}$
Bearing	$\sigma_{max} =$	0.90 $*\sigma_{yield}$
Combined (von Mises)	$\sigma_{max} =$	0.93 $*\sigma_{yield}$

The following assumptions are taken into account during the strength calculations of these cases.

- Topsides and vessel are infinitely stiff.
- Topsides has no horizontal centre of gravity offsets (LCG & TCG).
- No rotational accelerations are considered.
- Uniform grillage capacity.
- No RDSF self weight.

7.3.1. LOADS ON RDSF DURING VOYAGE OPERATION

In this section the strength check of the RDSF system is given. The check is examined on the four reference cases given in Table 7.4, which are Bongkot, CPOC Muda, Bokor and Angel A. The build-up of the strength check is given below. This technical feasibility assessment is modelled for four cases in this chapter, but can be remodelled for every possible topsides configuration with the RDSF configuration tool described in Appendix D.

1. Determine the loads on topsides support nodes (on RDSF unit).
2. Determine the loads on RDSF legs.
3. Determine the loads on RDSF connection pins and holes.
4. Determine the loads on skid shoes.
5. Determine the loads on HTV's web frames.

1. LOADS ON TOPSIDES' SUPPORT POINTS

The incoming topsides' loads are set according to the specifications in chapter 4. A snapshot of the maximum accelerations of the topsides is given in Table 7.7. Two load combinations are applied to the system to determine the maximum node forces; 'heave + roll' and 'heave + pitch'. These load cases are according to the DNV standards [11].

Table 7.7: Accelerations on topsides centre of gravity for strength check cases

Longitudinal acceleration	a_L	+0.5 / -0.5	[g]
Transverse acceleration	a_T	+0.2 / -0.2	[g]
Vertical acceleration	a_V	+0.3 / -0.3	[g]

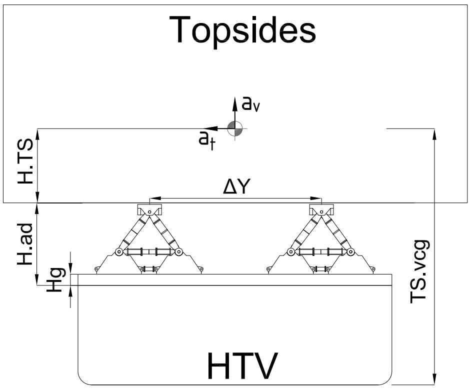


Figure 7.11

Horizontal loads on RDSF support node.

The maximum dynamic horizontal loads on the topsides nodes are calculated in longitudinal direction (F_X)

and transverse direction (F_Y) below.

$$F_X = TS_{mass} \cdot a_L \cdot 1/n \tag{7.1}$$

$$F_Y = TS_{mass} \cdot a_T \cdot 1/n \tag{7.2}$$

where TS_{mass} is the weight of the topsides and n the amount of DSF support nodes.

Vertical load for Heave+Roll.

The maximum dynamic vertical forces on the topsides nodes for the 'Heave+Roll' load combination are calculated in Equation 7.3 and is visualized in Figure 7.12. F_{Z-A} is the heaviest node force at the side where the acceleration is pointing to and F_{Z-B} is the node force on the other side. Pay attention, the transverse accelerations are cyclic (-0.5g to +0.5g) and thereby the F_{Z-A} and F_{Z-B} forces change in time as well. The less loaded side (F_{Z-B}) needs to be calculated to determine the inner leg forces.

$$\begin{aligned} F_{Z-A} &= \frac{W}{n} \cdot (1 + a_V) + TS_{mass} \cdot a_T \frac{(H_{TS} + H_{up})}{2 \cdot \Delta Y} \\ F_{Z-B} &= \frac{W}{n} \cdot (1 + a_V) - TS_{mass} \cdot a_T \frac{(H_{TS} + H_{up})}{2 \cdot \Delta Y} \end{aligned} \tag{7.3}$$

where:
$H_{TS} = 12m$ is the vertical distance between the centre of gravity and the bottom of the topsides.
$H_{up} = 1.0m$ is the vertical distance between the top and the rotation point of the RDSF unit.
ΔY is the spacing between the nodes in Y-direction.

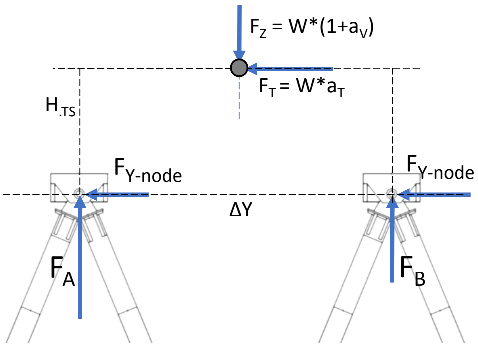


Figure 7.12: Node forces in transverse plane

Table 7.8: Dynamic loads on the RDSF unit for the heave-roll load combination

Dynamic load on nodes (Heave+Roll)		Bongkot	CPOC	Bokor	Angel	
Transverse	F_Y	1,219	1,046	1,438	946	[mT]
Vertical A max	F_{Z-A}	4,489	3,569	5,363	3,529	[mT]
Vertical B max	F_{Z-B}	1,848	1,870	2,113	1,390	[mT]
Vertical B min	F_{Z-B}	3,027	2,314	3,638	2,394	[mT]
Vertical B min	F_{Z-A1}	386	614	388	255	[mT]

Vertical load for Heave+Pitch.

The maximum dynamic vertical forces on the topsides nodes for Heave+Pitch are calculated according to Equation 7.4 for the 4-node and in Equation 7.5 for the 8-node topsides configurations. The schematic visualization of the 8-node topsides is shown in Figure 7.13. Only the maximum loads on the RDSF are considered and therefore the less loaded F_{Z-A2} and F_{Z-B2} are not presented.

For 4 node topsides:

$$F_{Z-A} = \frac{W}{n} \cdot (1 + a_V) + TS_{mass} \cdot a_L \frac{(H_{TS} + H_{up})}{2\Delta X}) \tag{7.4}$$

For 8 node topsides:

$$F_{Z-A1} = \frac{W}{n} \cdot (1 + a_V) + TS_{mass} \cdot a_L \frac{(H_{TS} + H_{up})}{\frac{20}{3}\Delta X} \tag{7.5}$$

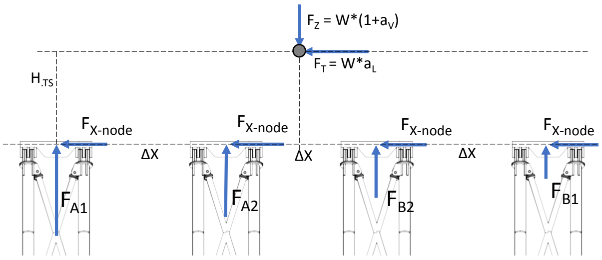


Figure 7.13: Node forces in longitudinal plane

Table 7.9: Dynamic loads on the RDSF unit for the heave-pitch load combination

Dynamic load on nodes (Heave+Pitch)		Bongkot	CPOC	Bokor	Angel	
Longitudinal max	F_X	1,219	1,046	1,438	946	[mT]
Vertical A1 max	F_{Z-A1}	3,591	3,127	4,485	2,952	[mT]
Vertical B1 max	F_{Z-B1}	2,746	2,311	2,990	1,968	[mT]
Vertical A1 min	F_{Z-A1}	2,129	1,872	2,760	1,816	[mT]
Vertical B1 min	F_{Z-B1}	1,284	1,056	1,265	832	[mT]

The most severe vertical loads on topsides DSF nodes are seen by applying the load combination: Heave + Roll. However, the Pitch + Roll load combination will still play a role by checking the strength of the RDSF for certain cases.

2. FORCES ON RDSF LEGS

The incoming forces on the RDSF units are introduced to the skid shoes via the legs. The leg force depends on the configuration geometry. The configuration of the RDSF is illustrated in Figure 7.14.

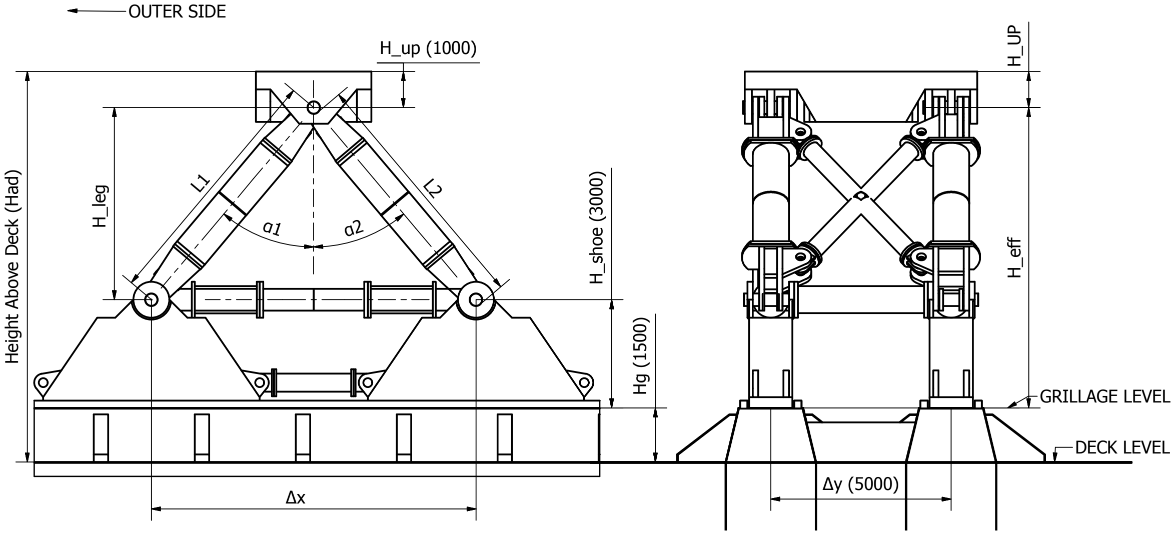


Figure 7.14

The legs of the RDSF consist of a pipe section with fork connection points on both sides. The pipe has a diameter of 1500mm, a thickness of 40mm and a S355 steel quality (S355, D1500, t40). The legs of the RDSF for the cases have different dimensions and orientations. The parameters of the four cases are given in Table 7.10. The heaviest loaded outer legs are indicated with number 1 and the inner legs with number 2.

The RDSF configuration of Bongkot project does not include legs because of the large leg angle. These calculations are therefore indicated as not applicable (NA*). The maximum allowed leg angle is set on α_{max} = 50 degrees. Exceeding this limit causes structural failure of the leg member.

Table 7.10: Geometry of the RDSF system for the topsides cases

INPUT		Bongkot	CPOC	Bokor	Angel	
Distance between shoes	Δy	6.0	6.0	9.0	12.0	[m]
Diameter-thickness leg	D-t	NA*	D1000 t40	D1000 t40	D1000 t40	[mm]
Length leg 1	L_1	NA*	3.1	7.0	15.7	[m]
Length leg 2	L_2	NA*	4.6	7.0	15.7	[m]
Angle leg 1	α_1	NA*	40.4	40.2	22.5	[deg]
Angle leg 2	α_2	NA*	59.6	40.2	22.5	[deg]

The legs are both checked on normal stress as on buckling strength. The allowable stress factor of $y_s = 0.80$ is used for both calculations. The incoming force in line with the legs is calculated according to formula 7.3. A visual representation of the situation is given in Figure 7.15 and the resulting unity checks for the cases are given in Table 7.11.

$$
\begin{aligned}
F1 &= \frac{F_Y \cdot cos(\alpha_2) + F_{Z-A} \cdot sin(\alpha_2)}{sin(\alpha_2) \cdot cos(\alpha_1) + cos(\alpha_2) \cdot sin(\alpha_1)} \\
F2 &= -\frac{F_Y \cdot cos(\alpha_1) - F_{Z-B} \cdot sin(\alpha_1)}{sin(\alpha_2) \cdot cos(\alpha_1) + cos(\alpha_2) \cdot sin(\alpha_1)}
\end{aligned}
\tag{7.6}
$$

Where:
$F1$ is the force in the outer legs and
$F2$ is the force in the inner legs

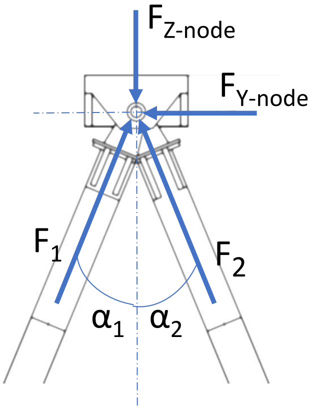


Figure 7.15

Table 7.11: Loads on RDSF legs for topsides cases

		Bongkot	CPOC	Bokor	Angel	
Max normal force outer legs	F_1	NA*	1,831	2,312	1,573	[mT]
Max normal force inner legs	F_2	NA*	1,320	2,094	1,515	[mT]
Unity check leg 1	UC1	NA*	0.54	0.70	0.55	[-]
Unity check leg 2	UC2	NA*	0.39	0.62	0.45	[-]

3. Forces on pins and holes

The pins connecting the legs with the upper-blocks and skid shoes are made of a 34CrNiMo6 alloy steel and have a diameter of 350mm (D). Pins with a diameter over the 300mm have 650 MPa yield stress capacity σ_{max} and the maximum shear capacity amounts $\tau_{max} = \sigma_{max} \cdot 0.4$ [22]. The 150mm thick skid shoe plates support the pin loads running through the legs. The pins are checked with a bearing stress factor of $y_s = 0.9$. The resulting unity check factors are given in Table 7.12.

$$\begin{aligned} UC1 &= \frac{F1}{\tau_{max} \cdot \frac{\pi}{4} D^2} \\ UC2 &= \frac{F1}{2D \cdot t \cdot \sigma_{yield} \cdot y_s} \end{aligned} \tag{7.7}$$

Table 7.12: Loads on pen hole connection for topsides cases

		Bongkot	CPOC	Bokor	Angel	
Max force pins	max(F_1,F_2)	1,273	1,831	2,312	1,573	[mT]
Unity check pins	$UC1$	0.38	0.54	0.68	0.47	[-]
Unity check bearing	$UC2$	0.38	0.55	0.70	0.47	[-]

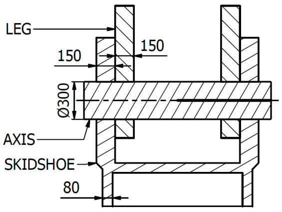


Figure 7.16

4. FORCES ON SKID SHOE

The function of the skid shoe is to spread the load from the legs to the grillage. The skid shoe needs a certain length to spread these loads because of the limited grillage capacity. The bottleneck of the skid shoe is at the transition of the thick plates near the pins towards the smaller plate. The skid shoe plates have a thickness of $t_s = 80mm$ and the diameter of the thick plates at the transition is $D = 1200mm$. The normal stress in the skid shoe is calculated with a stress reduction factor of $y_s = 0.8$. The resulting unity check factors are given in Table 7.13. The skid shoe to leg connection is illustrated in Figure 7.16.

$$UC = \frac{F1}{2D \cdot t_s} \cdot \sigma_{yield} \cdot y_s \tag{7.8}$$

Table 7.13: Loads on skid shoes for topsides cases

		Bongkot	CPOC	Bokor	Angel	
Max load skid shoe	$F1$	1,273	1,395	1,766	1,454	[T]
Unity check plating	UC	0.24	0.26	0.33	0.27	[-]

5. FORCES ON GRILLAGE AND WEB FRAMES

The incoming force originating from the legs is introduced in the grillage through the skid shoe. The maximum capacity of a 1.5-meter high grillage structure on the Black Marlin is set on 150 mT/m (Fg_{max}). The calculation of this grillage capacity can e found in Appendix H. The stress reduction factor for the grillage is set on $y_s = 1.0$ because for the grillage capacity the safety factors are already taken into account. The skid shoe is 6.0 meters long and introduces the loads into two web frames. The grillage load is calculated for both load combination: the transverse plane (heave+roll) and the longitudinal plane (heave+pitch).

Transverse plane (heave + roll)
The grillage load and corresponding unity checks due to 'heave+roll' load combination are calculated according to Equation 7.9 and is illustrated in Figure 7.17. The resulting grillage unity check factors for both the outer and inner skid shoe are given in Table 7.14.

$$Fg_n = \frac{F_1 \cdot cos(\alpha_1)}{w \cdot L_{shoe}} \tag{7.9}$$
$$UC_n = \frac{Fg_n}{Fg_{max}}$$

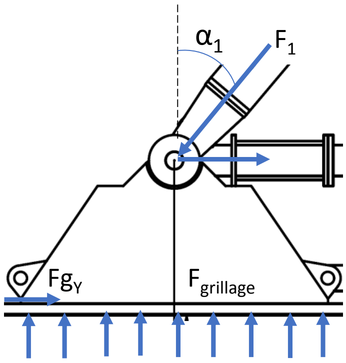


Figure 7.17

where,
w is the amount of web frames per skid track which is 2.
L_{shoe} = the length of the skid shoe which is 6.0 meters.

Table 7.14: Load on grillage and web frames for heave-roll load combination

HEAVE+ROLL		Bongkot	CPOC	Bokor	Angel	
Max web frame load outer skid shoe	Fg_1	103	116	147	121	[mT/m]
Unity check	$UC1$	0.69	0.77	0.98	0.81	[-]
Max web frame load inner skid shoe	Fg_2	42	16	38	53	[mT/m]
Unity check	$UC2$	0.56	0.22	0.51	0.35	[-]
Min web frame load inner skid shoe	Fg_{min}	10	3	-14	-38	[mT/m]
Unity check	$UC3$	0.07	0.02	-0.09	-0.25	[-]
Horizontal load skid shoe	Fg_Y	305	261	359	237	[mT/shoe]

Longitudinal plane (heave + pitch)
The grillage load due to heave+pitch load combination is calculated according to Equation 7.10 and is illustrated in Figure 7.18. The legs have the same loading condition because the configuration is symmetric in XZ plane. The resulting grillage unity check factors for both the outer and inner skid shoe are given in Table 7.15.

$$Fg_1 = \frac{1}{s \cdot L_{shoe}} \cdot (F_{Z-A1} + \frac{2 \cdot F_X \cdot H_{eff}}{\Delta x}) \tag{7.10}$$
$$Fg_2 = \frac{1}{s \cdot L_{shoe}} \cdot (F_{Z-A1} - \frac{2 \cdot F_X \cdot H_{eff}}{\Delta x})$$
$$UC1 = \frac{Fg_1}{Fg_{max}}$$
$$UC2 = \frac{Fg_2}{Fg_{max}}$$
$$Fg_X = F_X \cdot \tfrac{1}{s}$$

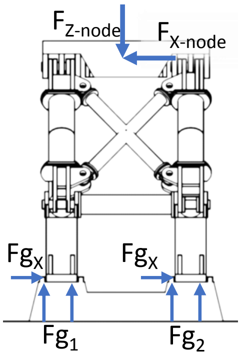


Figure 7.18

where,
s = number of skid shoes is 4.
L_{shoe} = length shoe is 6.0 meters.
Δx = distance between skid shoes is 5.0m.
$H_{eff} = H_{ad} - Hg - H_{up}$ = distance between grillage and rotation point.

Table 7.15: Load on grillage and web frames for heave-pitch load combination

HEAVE + PITCH			Bongkot	CPOC	Bokor	Angel	
Maximal loads	Grillage load	Fg_1	92	84	133	117	[mT/m]
	Unity check	$UC1$	0.61	0.56	0.89	0.78	[-]
Minimal loads	Grillage load	Fg_2	4	-2	-21	-43	[mT/m]
	Unity check	$UC2$	0.03	-0.01	-0.14	-0.28	[-]
Horizontal grillage load		Fg_X	122	105	144	95	[mT/shoe]

The skid shoe for Angel topsides is case subjected to a significant amount of negative grillage load (uplift or tension). In general, uplift in the deck has to be avoided. However, the deck and grillage capacity calculations in Appendix H show that uplifts up to 125 mT/m will not be destructive. However, this tension capacity cannot be guaranteed and should therefore be determined on a project basis.

SEA FASTENING

The resulting horizontal and uplift loads are introduced in the vessel by sea fastening. It exists of two different components. The sea fastening concepts are shown in Figure 7.19. The strength check of the sea fastening components is planned for detailed design.

- X-direction The skids shoes are locked up in longitudinal direction by a gutter.
- Y-direction A small stopper welded onto the skid track prevents the shoe to move in Y-direction.
- Z-direction The y-direction stopper includes an overhanging clamp preventing for uplift.

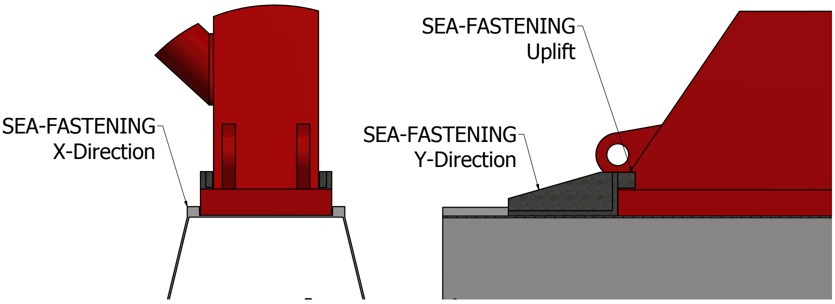


Figure 7.19: Sea fastening concept

7.3.2. CONCLUSIONS OF TECHNICAL FEASIBILITY

The technical feasibility of the RDSF is checked for four topsides cases (4.1.4), where all cases meet the structural requirements. It is seen that the voyage operation causes the largest loads on the system. During this voyage operation, the total capacity of the RDSF system is limited by the amount and capacity of the supporting web frames. The RDSF system has more capacity for topsides with more RDSF support nodes, because more web frames are being addressed. This technical feasibility assessment is now modelled for four cases, but can be remodelled for every possible topsides configuration with the RDSF configuration tool described in Appendix D.

7.4. CAPACITY ENVELOPE OF THE RDSF

The strength is proved the technical feasibility for four topsides cases. In this section, this capacity envelope of the RDSF system is presented, to see what the total applicability of the RDSF system is. The build-up of the envelope is presented first by giving the limiting parameters of the RDSF system step by step. After that, the combination of the single limitations form three RDSF envelopes for 4, 6, and 8 RDSF units. Eventually, the influence of the scoping choices to the capacity envelope is reviewed by comparing them with old projects. This review exposes the differences between typical and unusual topsides float-over projects. In the next chapter, the RDSF capacity envelope is the used to model the business case.

7.4.1. LIMITATIONS TO RDSF ENVELOPE

The main limitations to the RDSF envelope are listed below. In the following sections, these limitation are elaborated.

1. **Vessel selection**
   The vessel determines for the major part the envelope of the RDSF system. The following vessel parameters will be discussed:
   (a) Vessel's dead weight capacity
   (b) Vessel's stability limit
   (c) Vessel's load introduction capacity
2. **RDSF Geometry**
   The following geometry parameter that is discussed is:
   (a) Installation dimensions
   The RDSF geometry is influenced by the height of the grillage. This height is influenced by the vessel load introduction capacity and thus indirectly by the vessel selection.

VESSEL'S DEADWEIGHT CAPACITY

As described in the functional requirements, the RDSF has to be applicable on the Boskalis Black Marlin. Which means the topsides' weight must not exceed the Black Marlin's deadweight capacity of 57,021 mT. This high vessel's deadweight will not decisive for the RDSF system, and is therefore not taken into account in the RDSF capacity envelopes.

VESSEL'S STABILITY

The vessel's stability is mainly determined by the vessel geometry, cargo weight and system's centre of gravity. As in section 5.4 is described, the system's upright stability is calculated according to the IMO A749 intact criteria, where the GM-Upright is maximum 0.15 meters. Given this GM-Upright criteria, the combination of maximum displacement and vertical centre of gravity is given in the Black Marlin Stability Booklet ([23]). The regular Black Marlin voyage draft of 8,5 meters (ref. Bongkot T&I) causes a 62,856 mT displacement (∇) which is taken as input for the stability calculations. This booklet states, that under these conditions, the vessel is stable until a system's vertical centre of gravity (sys_{vcg}) of 17.9 meters. Given this relation, the topsides weight limit can be described according the following formula 7.11.

$$\begin{aligned} sys_{vcg} \cdot \nabla &= V_{vcg} \cdot V_{mass} + TS_{vcg} \cdot TS_{mass} \\ TS_{mass} &= \nabla - V_{mass} \\ TS_{mass} &= -\nabla * \frac{V_{vcg} - sys_{vcg}}{TS_{vcg} - V_{vcg}} = -\nabla * \frac{V_{vcg} - sys_{vcg}}{(V_H + H_{ad} + H_{TS}) - V_{vcg}} \end{aligned} \tag{7.11}$$

The resulting stability limit for the Black Marlin vessel is shown in Figure 7.20.

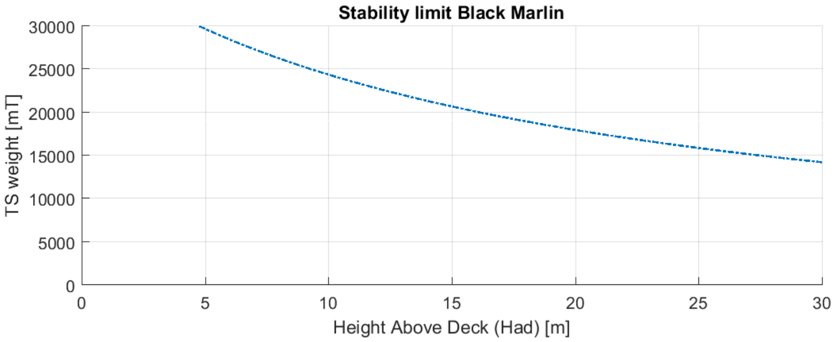


Figure 7.20

VESSEL'S LOAD INTRODUCTION

All loads need to be introduced into the deck. The HTV deck has a limited capacity which can be enlarged by an additional grillage. A grillage height of 1.5m is used as reference, as it is used in several installation projects of the Black Marlin. Both the deck and grillage capacities are presented in Table 7.16. In appendix H a elaborated deck and grillage capacity calculation are executed, resulting in a maximum grillage capacity of 150 mT/m per web frame.

Table 7.16: Grillage capacity of Black Marlin

Capacity of grillage on Black Marlin			
Height grillage	H	1500	mm
Max load per web frame	q_{max}	150	mT/m

The maximum load on the grillage for a single skid shoe is:

$$FA_{max} = q_{max} \cdot wf \cdot L_{shoe} = 150 \cdot 2 \cdot 6.00 = 1800[mT] \tag{7.12}$$

where,
wf is the amount of web frames that is addressed by the grillage and is 2.

The maximum vertical load on the single outer skid shoe determines the maximum leg load. The total legs running through one side (=2 legs) is to be calculated according to the following formula:

$$F1_{max} = 2 \cdot \frac{FA_{max}}{cos(\alpha_1)} \tag{7.13}$$

This maximum force depends on the geometrical configuration of the RDSF. Causing the RDSF capacity to differ for varying heights. The maximum topsides weight is calculated according the following formulas, that indicate a static equilibrium around the rotation point of the upper-block:

$$\begin{aligned} \sum F_y = 0 \quad &= F1 \cdot sin(\alpha_1) - F2 \cdot sin(\alpha_2) - TS_{mass}\frac{a_t}{n} \\ \sum F_z = 0 \quad &= F1 \cdot cos(\alpha_1) + F2 \cdot cos(\alpha_2) - (\frac{W}{n}(1+a_v) + TS_{mass}\frac{a_t \cdot (H_{TS}+H_{up})}{2 \cdot \Delta Y}) \\ \sum M_x = 0 \quad & \end{aligned} \tag{7.14}$$

The above formulas are rewritten in the following form in Equation 7.15. This formula is plotted together with the stability limit in Figure 7.21. In the figure, the multiple lines present the RDSF system with 4, 6 and 8 RDSF units.

$$TS_{mass} = \frac{F1_{max} \cdot 4 \cdot sin(\alpha) \cdot cos(\alpha)}{((1+a_v) + \frac{(H_{TS}+H_{up})}{2\Delta Y} \cdot a_t) \cdot sin(\alpha) + \frac{a_t}{n} \cdot cos(\alpha)} \tag{7.15}$$

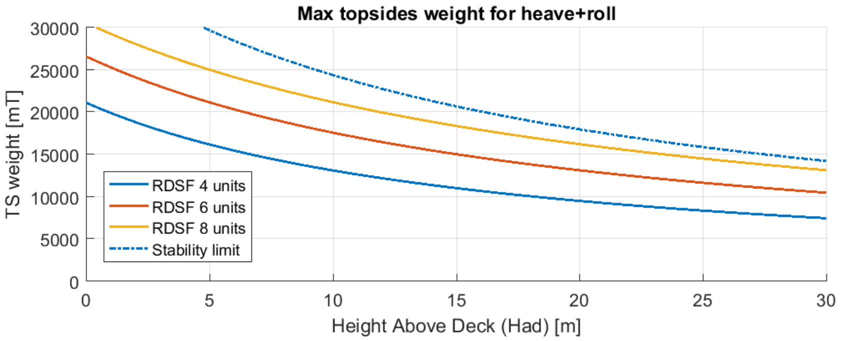


Figure 7.21

LONGITUDINAL PLANE (HEAVE + PITCH)

The same approach is used for the maximum capacity in longitudinal plane. Where the formulas below indicate the force equilibrium at the grillage surface.

$$\begin{aligned} \sum F_x = 0 \quad &= -\frac{TS_{mass}}{n} a_l + Fg_x \\ \sum F_z = 0 \quad &= FA + FB - F_{Z-An} \\ \sum M_y = 0 \quad &= FA\frac{\Delta x}{2} - FB\frac{\Delta x}{2} - \frac{TS_{mass}}{n} a_l \cdot (H_{ad} - H_g - H_{up}) \end{aligned} \tag{7.16}$$

The formulas for the force-equilibrium in Z-direction (F_{Z-An}) are depending on the amount of topsides nodes (n):

$$\begin{aligned} F_{Z-A4} &= \frac{TS_{mass}}{n_4} \cdot (1 + a_V) + TS_{mass} \cdot a_L \frac{(H_{TS} + H_{up})}{2\Delta X}) \\ F_{Z-A6} &= \frac{TS_{mass}}{n_6} \cdot (1 + a_V) + TS_{mass} \cdot a_L \frac{(H_{TS} + H_{up})}{4\Delta X}) \\ F_{Z-A8} &= \frac{TS_{mass}}{n_8} \cdot (1 + a_V) + TS_{mass} \cdot a_L \frac{(H_{TS} + H_{up})}{\frac{20}{3}\Delta X} \end{aligned} \tag{7.17}$$

The above formulas are rewritten in the following form. Resulting in the multiple lines for the RDSF systems with 4, 6 or 8 DSF support nodes.

$$TS_{mass-4} = -\frac{4 \cdot FA \cdot \Delta X \cdot \Delta x \cdot n_4}{(4 \cdot a_l(H_g - H_{ad} + H_{up}) - 2 \cdot \Delta x \cdot (1 + av)) \cdot DX - n_4 \cdot al \cdot \Delta x \cdot (H_{TS} + H_{up})} \tag{7.18}$$

$$TS_{mass-6} = -\frac{8 \cdot FA \cdot \Delta X \cdot \Delta x \cdot n_6}{(8 \cdot a_l(H_g - H_{ad} + H_{up}) - 4 \cdot \Delta x \cdot (1 + av)) \cdot DX - n_6 \cdot al \cdot \Delta x \cdot (H_{TS} + H_{up})} \tag{7.19}$$

$$TS_{mass-8} = -\frac{40 \cdot FA \cdot \Delta X \cdot \Delta x \cdot n_8}{(40 \cdot a_l(H_g - H_{ad} + H_{up}) - 20 \cdot \Delta x \cdot (1 + av)) \cdot DX - 3 \cdot n_8 \cdot al \cdot \Delta x \cdot (H_{TS} + H_{up})} \tag{7.20}$$

The maximum capacity due to heave+pitch are added to the envelope in Figure 7.22. In this envelope is seen that only the 4-unit RDSF system does not meet the vessel stability limit.

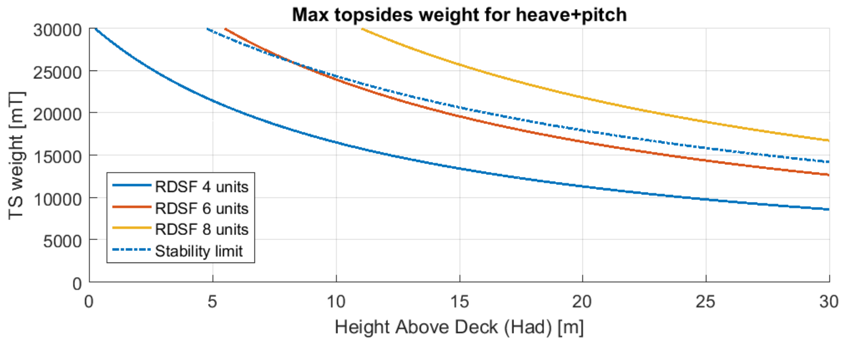


Figure 7.22

RDSF GEOMETRY

The RDSF system has a minimal installation dimension caused by its geometry shown in Figure 7.23.

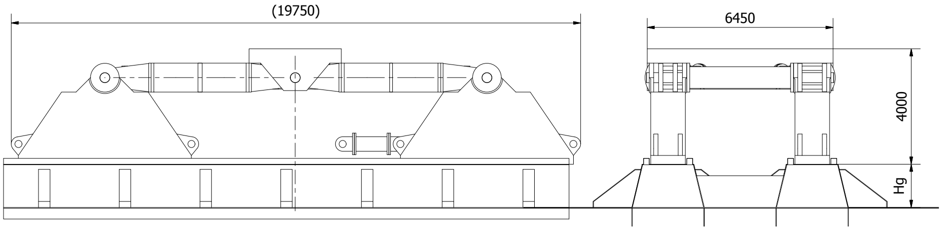


Figure 7.23: RDSF Installation dimensions

The installation height of the RDSF system amounts 4.0 meter. Together with the grillage height (1.5 meter), the minimal height boundary of the capacity envelope is 5.5 meter. The RDSF geometry envelope limitation is shown in Figure 7.24. This lines should be interpreted as lower limits, so all topsides with starting heights higher than 4.0 (and 5.5) meters can be installed.

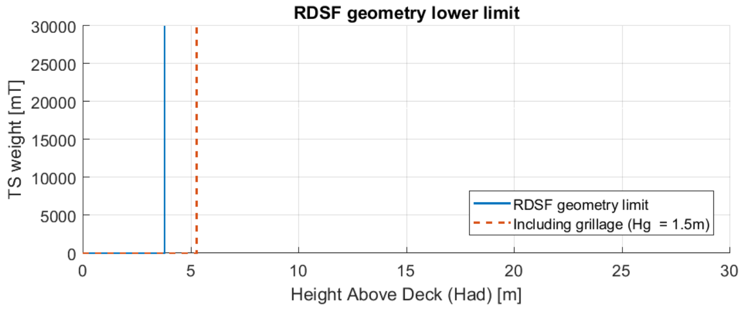


Figure 7.24: Geometry limits

7.4.2. RESULTING RDSF CAPACITY ENVELOPES

The combinations of all previous limitations form the RDSF capacity envelope. The RDSF system envelope is shown as a thick black line in the following figures. The capacity envelope is divided into the 3 sub-envelopes, for the RDSF systems with 4, 6 and 8 units. The red crosses, within the envelope plots indicate the past projects. When the red cross falls within the RDSF envelope, the system is able to handle this topsides float-over.

Initial settings of envelopes
The following settings shown in Table 7.17 are used to model the RDSF capacity envelope. Changes in these parameters cause changes to the RDSF envelopes.

Table 7.17: Initial settings for capacity envelopes of RDSF system

Topsides characteristics			
H_{TS}	12	[m]	Topsides' VCG (ref. Bongkot project)
ΔX	25.2; 20.5; 15.8	[m]	Average node spacing in X-direction for 4; 6; 8 nodes
ΔY	26.0; 25.0; 28.6	[m]	Average node spacing in Y-direction for 4; 6; 8 nodes
Vessel characteristics: Black Marlin			
V_{vcg}	7.3	[m]	Vessel VCG at 8.5m draft (ref. Bongkot project [F])
H_g	1.5	[m]	Grillage height
q_{max}	150	[mT/m]	Web frame capacity including grillage
wf	2	[-]	Amount of web frames per skid track
RDSF configuration			
Δx	5.0	[m]	Space between skid shoes in x
Δy	12	[m]	Space between skid shoes in y (variable between 6m and 15m)
c	0	[m]	Symmetrical position of skid shoes (c=0)

ENVELOPE WITH 4 RDSF UNITS

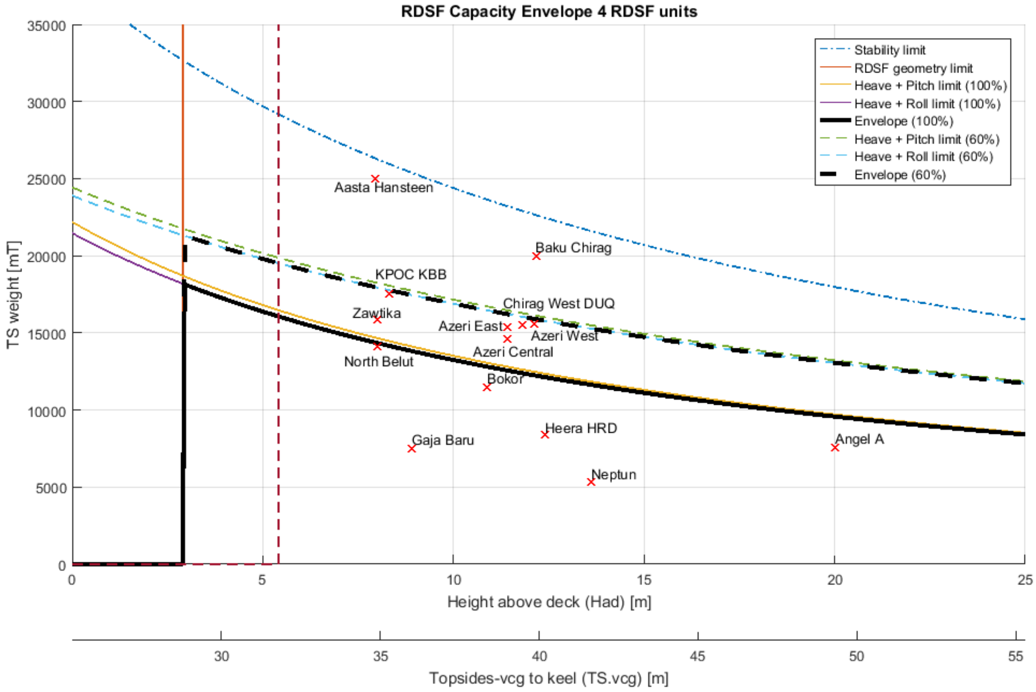


Figure 7.25: Capacity envelope of the RDSF system with 4 units

In Figure 7.25, the envelope of the RDSF system with 4 units is shown. It is seen that the limiting parameter of the envelope is the maximum load introduction due to the heave and roll motions. From the figure, it is seen that the RDSF system with 4 units, is able to install about half of the past projects (6 out of 14 projects).

The remainder projects, which fall outside the envelope of the RDSF, are summed up below. A short description of these projects is given as well.

1. Aasta Hansteen SPAR - Different dual vessel float-over concept where the voyage is performed on 62m wide vessel: the White Marlin.

2. Baku Chirag PDQ - Very calm voyage within Caspian Sea on high capacity barge.
3. KPOC KBB - Short voyage within South-East Asia on Cosco XRK.
4. Chirag West DUQ - Very calm voyage within Caspian Sea on Intermac 650 barge.
5. Azeri West - Very calm voyage within Caspian Sea.
6. Azeri East - Very calm voyage within Caspian Sea.
7. Zawitka - Calm voyage within South-East Asia on the Saipem S45 barge.

Most of the remainder float-over projects are performed during short and calm voyages, for example on the Caspian Sea. The accelerations of these voyages, will never come close to the initial accelerations set for this capacity envelope in Table 7.7. Therefore, a reduction to the accelerations is introduced in Figure 7.25 by means of the 'black dashed line'. This line indicates the capacity envelope with 60% of the initial accelerations. Considering this new RDSF capacity for short voyages, there can be concluded that most remainder projects now fall within the capacity (12 out of 14 projects). The properties of the RDSF system with 4 units are therefore chosen correctly.

ENVELOPE WITH 6 RDSF UNITS

The RDSF system envelope with 6 units is shown in Figure 7.26 and is limited grillage capacity due to the heave+roll motion. Two projects with 6 topsides support nodes are seen in the past, where the RDSF system can install only 1 of them. The other one, 'North Rankin B', is a very unique installation project and cannot be installed with the Black Marlin because it lacks stability. No conclusions can be made to the RDSF system with 6 units on basis of only 2 historic projects.

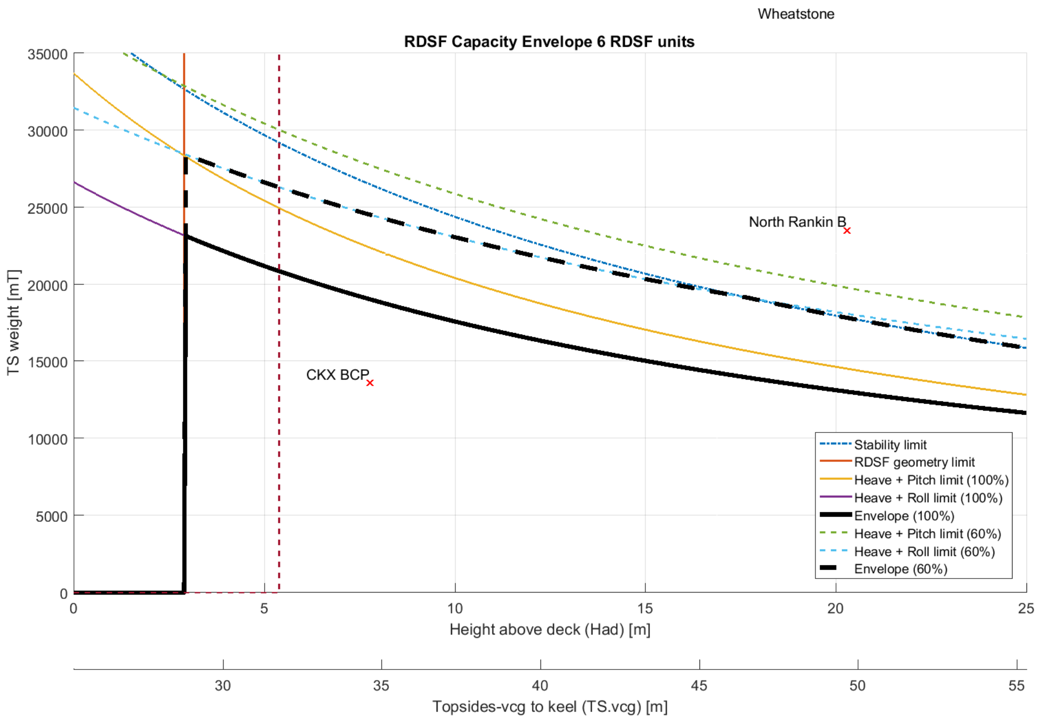


Figure 7.26: Capacity envelope for the RDSF system with 6 units

ENVELOPE WITH 8 RDSF UNITS

The 8 unit RDSF system envelope shown in Figure 7.26 almost meets the Black Marlin stability line. Therefore, the RDSF system is able to install all projects that can be installed with the Black Marlin. The remainder projects which falls outside the 8-unit RDSF envelope are 'White Rose' and 'Shwe'.The 'White Rose topsides' will be installed using the Allseas Pioneering Spirit, a catamaran vessel. The 'Shwe project' is installed using a heavy capacity barge. Both projects do not match the capabilities of the Black Marlin. It is concluded that the RDSF system with 8 units is correctly targeted.

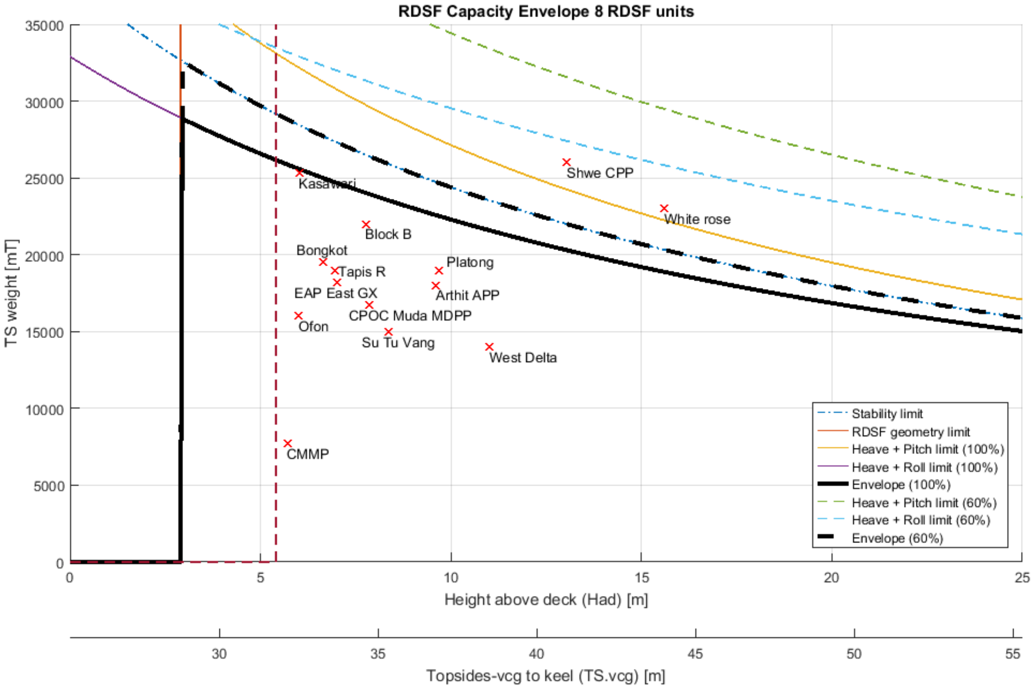


Figure 7.27: Capacity envelope for the RDSF system with 8 units

7.4.3. SENSITIVITY OF INPUT PARAMETERS

The RDSF capacity envelope is determined for the initial setting earlier mentioned in Table 7.17. However, future installation projects will not have identical input settings. The influences of varying these input settings is given in Table 7.18. The tuning parameters are divided into four main categories: the vessel selection, the topsides, the transportation route and the RDSF configuration.

The starting point of this sensitivity analysis, is a topsides with an average node spacing and transportation height above deck (H_{ad}) of 10 meters. The sensitivities are calculated for RDSF systems with 4, 6 and 8 nodes.

Table 7.18: Sensitivities of parameters of the RDSF system

Category	Parameter		Sensitivity	Effects on TS_{mass} for		
				n=4	n=6	n=8
	RDSF capacity at H_{ad}=10m	TS_{mass}	Initial settings	13,250 mT	17,600 mT	22,300 mT
Vessel	Deck/Grillage capacity	σ_{max}	150 -> 200 $\frac{mT}{m}$	+33%	+33%	+9%
Topsides	Transportation height	H_{ad}	10m -> 20m	-28%	-25%	-24%
	Vertical centre of gravity	H_{TS}	12m -> 6m	+8%	+17%	+19%
	Number of DSF nodes	n	4 - 6 - 8	0%	+33%	+68%
	Nodes spacing in X	ΔX	ΔX_{min} ->ΔX_{max}	+9%	+2.5%	+6.5 %
	Nodes spacing in Y	ΔY	ΔY_{min} -> ΔY_{max}	+6%	+3%	+20 %
Route	Accelerations	a_l,a_t,a_v	-50%	+36%	+40%	+44%
RDSF	Layout of configuration	Δy	12m-> 6m	-5.5%	-5.0%	-4.5%
	Distance between skid tracks	Δx	5.0m -> 4.8m	0%	0%	0%
	Length of skid shoes	L_{shoe}	6.0m -> 7.0m	+17%	+17%	+9%

The sensitivity table gives insight in the input parameters, which is helpful to improve the system. Relatively cheap solutions can increase the RDSF capacity significantly. For example by decreasing the accelerations or changing the layout of the RDSF configuration. Improving the RDSF capacity by tuning the input parameters may cause cost savings on the expensive parts of the RDSF system. For example, the required grillage capacity could be decreased by optimizing the RDSF system. These optimization come in play when the details about the specific projects are known.

7.5. CONCLUSIONS OF THE RDSF DESIGN

In this chapter a detailed design of the RDSF system is presented. The conceptual design of the RDSF system is composed of either four, six or eight RDSF units that support one single topsides node. Each unit consists of a set of key reusable components: one topsides interface block and four skid shoes. The components are connected by interchangeable legs which enable the system to adjust for differences in the layout of topsides. This design is examined on operational and technical feasibility using four topsides cases that represent the scope (4.1.4).

Operational feasibility of the RDSF system
The RDSF system is found operationally feasible for all topsides within the scope. The operational feasibility is mainly limited on the combination of the node positions and the geometry of the HTV, in this case the Black Marlin. The topsides nodes spacing is limited between 6.0 and 36.0 meters in transverse direction (Y), and unrestricted in longitudinal direction (X). The RDSF system has a minimal installation dimension of 4.0 meters.

The RDSF system is able to operate according to the following main options:

1. RDSF with external existing jack system (on jacket support nodes).
2. RDSF with internal existing jack system (on DSF support nodes).

The external jacking option differs from the original float-over operation only during the build-up operation. The internal jacking option, slightly differs in the sequence of the operations and requires less preparations. Less time and space is required using this option, which is expected to lead to a more cost-effective installation than with the use of the single DSF.

Technical feasibility
The RDSF system is found technical feasibility based on the four topsides cases. The following conclusion can be drawn regarding the technical feasibility:

- Strength checks on the main components of the RDSF have demonstrated that the overall strength of the system approves to the requirements. This is shown by the unity check values, which are for all four cases within the 1.00 limitation. However, the RDSF system is not checked on local structural strength, which is a recommended for detailed design.
- It is seen, that the grillage endures uplift for topsides with a large transportation heights (H_{ad}). A basic calculation shows that the vessel's uplift capacity is sufficient.
- During the strength check calculations, the topsides structures are assumed to be symmetric with a 100% proportional distribution of loads on the nodes. Potential offsets in the centre of gravity could influence the RDSF envelope negatively, causing the technical feasibility to be unsatisfied. Further research is recommended, to see what the influences of the overcapacity of the RDSF is to the envelope regarding the topsides offset.

Capacity envelope
The capacity envelope is divided into the three sub-envelopes, for the RDSF systems with 4, 6 and 8 units. The following conclusions regarding the RDSF capacity envelope are drawn:

- RDSF system envelopes are mainly limited by the maximum web frame capacity.
- RDSF 4 has a limited capacity of 13,000 mT covering 6 out of 14 projects. When applying reductions on accelerations for calm voyages, it is seen that the RDSF system covers 12 out of 14 projects.
- RDSF 8 has a high capacity over the full range meeting the stability line of the Black Marlin. The system covers all projects that are applicable on the Black Marlin.

This chapter has concluded into specification of the RDSF system that is shown in Table 7.19. In addition to the feasibility checks for the topsides cases, a configuration tool is developed to assess the feasibility and estimate the weight of the RDSF configurations of future projects. The knowledge about the applicability and capacity of the RDSF system is used in the next chapter to develop a business case.

Table 7.19: RDSF system specifications

RDSF System:	RDSF 4 Units	RDSF 6 Units	RDSF 8 units
Capacity @10m heavy conditions	13,000 mT	17,500 mT	22,500 mT
Capacity @10m mild conditions	17,500 mT	22,500 mT	25,000 mT
Required skid track capacity	300 mT/m	300 mT/m	300 mT/m
Installation height	4 m	4 m	4 m
Final heights	25+ m	25+ m	25+ m
Required skid tracks	8 skid tracks	12 skid tracks	16 skid tracks

8

ECONOMIC FEASIBILITY OF THE RDSF SYSTEM

In this section the economic feasibility of the RDSF is discussed. A business case is presented which is based on a cost comparison between the use of the standard single-use DSF and the RDSF system. This business case leads to a break-even points for 4, 6 and 8 RDSF units. This break-even point is eventually used to assess the economic feasibility of the RDSF system.

8.1. SCOPE OF COST COMPARISON

The life span operations of the RDSF and DSF are described earlier in Table 7.2. Only the ones that differ are considered in the scope of this business case. The life span costs are given for both the standard single-use DSF and the new RDSF in Table 8.1.

Table 8.1: Operational cost differences between DSF and RDSF

Operation	Standard DSF	RDSF	Comments
Fabrication	4,500 $\frac{USD}{mT}$	6,000 $\frac{USD}{mT}$	See fabrication costs in Appendix I.3.
Mobilization	No costs	255,000-475,000 USD	See shipping costs in Appendix I.1.
Operating	-	-	Costs differences not considered (see operating costs*).
Discard	-	-	Scrap value present in fabrication price, see Appendix I.3.
Storage	No costs	13.0 $USD \cdot m^{-3} \cdot yr^{-1}$	Only for CAPEX parts, see Appendix C.
Maintenance	No costs	1.0% of CAPEX	
Insurance	No costs	0.5% of CAPEX	

QUALITATIVE COMPARISON OF OPERATING COSTS*

The project-specific character of the operating costs make it difficult, if not impossible, to quantify. Therefore, these operating costs are only considered qualitatively in this comparison.

The load-out, voyage and float-over operations are exactly equal with the use of both the single-use DSF or the RDSF. The corresponding costs are therefore similar.
The jacking, assembling and installation operations differ with use of the RDSF. The difference between these operations is described earlier on in Table 7.3. It is seen that for the jacking operation, the single-use DSF requires additional SPMT's for installation. Contradictory, the RDSF requires additional assembling at the yard. To make a fair comparison, it is assumed that both costs of these operations cancel each other out.

With this assumption, the differences in costs of operating the single-use DSF or RDSF do not have to be quantified for this economic feasibility.

8.2. COST OF THE RDSF SYSTEM

The total costs of the RDSF consists of the capital (CAPEX) and the operational expenditure (OPEX). Both CAPEX and OPEX of the RDSF system are mainly driven by the amount of the RDSF units and the height above deck. The costs are subdivided into RDSF systems with 4, 6 and 8 units. The variable costs due to the transportation height of the topsides are given with the terms: 'Low (8)', 'Mid (12)' and 'High (20)'.

8.2.1. CAPEX OF THE RDSF SYSTEM

The capital expenses (CAPEX) of the RDSF system consist primarily of the fabrication of the system. The total fabrication costs of the RDSF system are estimated by using a steel price of 6,000 US Dollar (USD) per tonnes which is close to the steel price of an offshore jacket [24]. This steel price includes all edits like welding, coating and other treatments next to the corresponding engineering costs. The steel price for unedited steel used in the single-use DSF is set on 4,500 USD per tonnes, this price includes the returning scrap value of steel. All steel prices are determined according to a number of interviews with experts within Boskalis and Mammoet. The development of the steel price indications can be found in section I.3.

The total weight of all CAPEX components is approximately 250 mT per unit. This weight is calculated with the help of a 3D model including a 10% uncertainty factor. The part list of this model can be found in Appendix C. The total CAPEX investment of the RDSF system for both 4, 6 and 8 nodes is given in Table 8.2.

Table 8.2: CAPEX of the RDSF system

	4 RDSF units	6 RDSF units	8 RDSF units	
Total CAPEX weight	1000	1500	2000	[mT]
Total CAPEX investment	6,000,000	9,000,000	12,000,000	[USD]

8.2.2. OPEX OF THE RDSF SYSTEM

The operational expenses (OPEX) of the RDSF system are the summation of the costs related to operating the RDSF system (variable OPEX) and the annual costs of managing the system (fixed OPEX). The summation of all OPEX costs can be found in Table 8.3. The OPEX costs are build-up as follows.

Project execution costs (variable OPEX)
The project execution costs consist of all the following costs which are made to successfully perform a project.

1. Project-specific equipment costs
   Modifications to the system mainly drive the project-specific equipment costs. The main legs, connection pipes and cross braces are unique for every configuration. The project-specific costs are strongly dependent on the transportation height above deck. To handle the differences in transportation heights, three scenarios are presented; Low ($8m$), Mid ($12m$) and High ($20m$), which are comparable to the projects Bongkot, Bokor and Angel respectively. The number between the brackets indicate the topsides' height above deck (H_{ad}) during voyage.
   Just like the standard single-use DSF, the steel price of the project-specific equipment is set up 4,500 USD. Eventually, the specific costs will reduce over time due to the growth of the RDSF inventory. This cost decreasing effect is not taken into account for the business case because of the high uncertainty.

2. Mobilization costs
   The dimensions, weight and mobilization distance of the cargo mainly determine the total mobilization costs. Only the CAPEX parts of the RDSF are to be transported, the project-specific (OPEX) parts are made at yard. The mobilization costs are validated by an official shipping party, see section I.1 for the correspondence.

Annual costs (fixed OPEX)
The annual costs are always in play whether there is an ongoing project or not. The annual costs consist of the following parts.

1. Storage costs
   The storage costs of the RDSF system are calculated based on the volume of the folded configuration and the price per year per cubic meter. However, the storage location is not known in advance, expected is that the RDSF is stored as close as possible to the platform installation site. Therefore, a conservative price of *13 USD per cubic meter per year* for outdoor storage in Flushing (the Netherlands) is taken into account as reference. This cubic meter price is based on the temporary storage of the buoyancy boxes for the Boskalis Hebron project. The RDSF outer dimensions of a box of 20x4x6.5 meters per unit in compact mode (de-assembled) are taken as input for the storage costs. The storage costs can be found in Appendix I.2.

2. Maintenance costs
   The RDSF system consists mostly of simple steel and does not include drive and control components. Therefore, there is expected that the maintenance costs are minor with *1.0% of CAPEX* on a yearly basis. This maintenance percentage is based on comparable projects of Mammoet, for example a crane which is expected to have more maintenance than the RDSF.

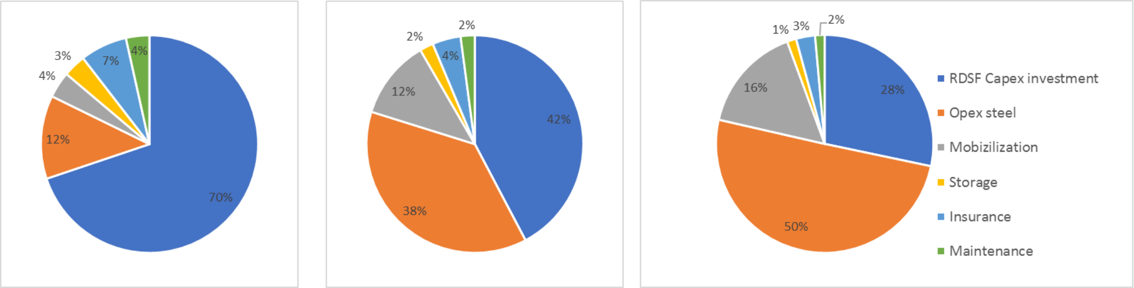
3. Insurance costs
   The insurance costs for equipment generally amount *0.5% of CAPEX* on a yearly basis. The insurance costs are based on comparable projects of Mammoet.

Table 8.3: OPEX of the RDSF system

Variable OPEX		4 RDSF units	6 RDSF units	8 RDSF units	
Project-specific equipment	Low (8m)	450,000	675,000	900,000	[USD/x]
	Mid (12m)	810,000	1,215,000	1,620,000	[USD/x]
	High (20m)	1,890,000	2,835,000	3,780,000	[USD/x]
Mobilization	Short	225,000	-	285,000	[USD/x]
	Medium	255,000	295,000	335,000	[USD/x]
	Long	375,000	-	475,000	[USD/x]
Fixed OPEX					
Storage (13.00 USD/m^3)		22,000	33,000	44,000	[USD/yr]
Maintenance (1.0%)		60,000	90,000	120,000	[USD/yr]
Insurance (0.5%)		30,000	45,000	60,000	[USD/yr]

8.2.3. DISTRIBUTION OF TOTAL COSTS OF THE RDSF SYSTEM

The distribution of the total costs is illustrated in Figure 8.1. In these figures can be seen that the investment costs most prominently present. After many installations the Opex-steel costs has the largest share. In reality, it is expected that this amount is less, as the Opex-steel components can be reused on some projects.



(a) 1 project (b) 5 projects (c) 10 projects

Figure 8.1: Cost distribution of the RDSF system for 1, 5 and 10 projects over 10 years

8.3. COST OF THE STANDARD SINGLE-USE DSF

The total costs of the DSF consist only of an one-time investment. The DSF is a by-product of the topsides which is made by the topsides fabrication yard. Since this information is not shared with third parties, the costs of single-use DSF are hard to figure out. The DSF costs are estimated on the price of construction steel (4,500 USD/mT), as described in Appendix I. A list of old float-over installation projects including the DSF weight and the corresponding cost estimation is given in Table 8.4. Behind every project name, the topsides' height above deck during voyage is (H_{ad}) is indicated. This list is used as reference for the business plan which is presented later on.

Table 8.4: Estimated cost of DSF for past projects

Project	Nodes	DSF Weight [mT]	Cost [USD]
Heera (12m)	4	1,085	4,900,000
Baku Chirag (12m)	4	1,520	6,800,000
Bokor (11m)	4	1,000	4,500,000
Angel (20m)	4	850	3,800,000
Shwe (13m)	6	1,248	5,600,000
North Rankin (20m)	6	5,000	22,500,000
White Rose (16m)	8	3,300	14,900,000
EAP East (7m)	8	1,653	7,400,000
CMMP (6m)	8	574	2,600,000
Tapis (7m)	8	1,622	7,300,000
Platong (10m)	8	802	3,600,000
Arthit (10m)	8	974	4,400,000
Bongkot (7m)	8	1,500	6,800,000
Ofon (6m)	8	1,739	7,800,000
CPOC (8m)	8	830	3,700,000
Average	4	1,114	5,000,000
Average	8	1,424	6,410,000

8.4. BUSINESS CASE OF THE RDSF SYSTEM

The business case presented in this section is based on the costs of the RDSF system. The project rate of the RDSF is calculated in Equation 8.1. This project rate gives the total costs for the RDSF to perform a project. The project rate is calculated according to the base settings in Table 8.5.

In the chapter 3, it is concluded that the H_{ad} of most new projects are expected to vary between 5 and 15 meters. Therefore, for the base case only projects with H_{ad} of $12m$ are considered, which is comparable with Bokor project. The majority of all past topsides installations are performed in Asia, the mobilization costs for the base case are therefore determined for medium long voyages like Busan (South-Korea) to Singapore which is 3,000 nautical mile (NM).

$$projectrate = \frac{CAPEX}{projects} + \frac{OPEX_{fixed}}{lifespan} + OPEX_{var} \tag{8.1}$$

Table 8.5: RDSF system base case settings

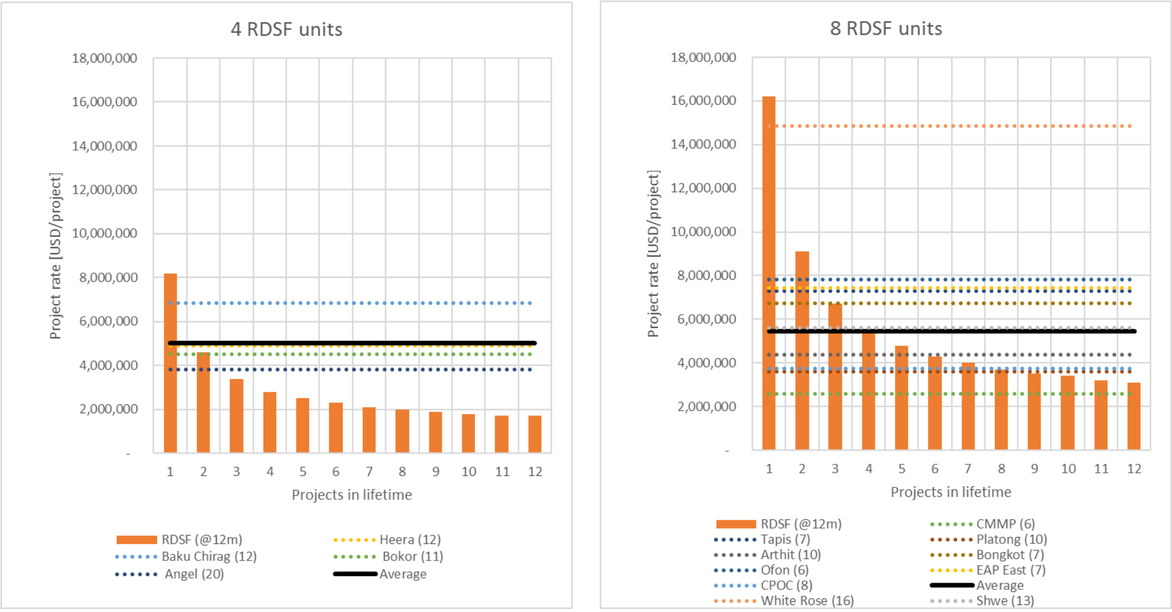
Voyage	Medium long (Busan - Singapore)
Height above deck (H_{ad})	12 m
Equipment depreciation lifetime	10 years
Projects in lifetime	5 x
Residual value	0 %

The resulting project rates for the base case are shown in Table 8.6 for 4, 6 and 8 RDSF units.

Table 8.6: Project rates for base case of the RDSF system

	RDSF 4 units Base	RDSF 6 units Base	RDSF 8 units Base	
CAPEX	6,000,000	9,000,000	12,000,000	[USD]
Var OPEX	1,070,000	1,510,000	1,960,000	[USD/x]
Fixed OPEX	110,000	170,000	220,000	[USD/yr]
Project rate base case (at 5x/10yr)	2,500,000	3,600,000	4,800,000	[USD/x]

The project rates are compared with the costs of the single-use DSF projects drawn in the previous section. This comparison is shown in Figure 8.2. The comparison is shown for 4 and 8 RDSF units only, because there is not sufficient data available of 6 node DSFs to make a fair comparison. The bar charts in the figure indicate the costs of the RDSF system for the a certain amount of projects. The horizontal dashed lines indicate the single-use DSF fabrication costs and the horizontal thick line indicates the average of these projects, as given in Table 8.4. The costs of the DSF of Shwe and White Rose topsides seen in Figure 8.2b are not included in the average DSF costs. These topsides are not covered by the RDSF system as can be seen in Figure 7.27. The intersection of the bar chart and the horizontal lines point out the break-even period. It is seen that for the 4 and 8 nodes topsides projects the break-even period is on average 2 and 4 projects respectively.



(a) Business case 4 RDSF units

(b) Business case 8 RDSF units

Figure 8.2: Business cases

8.4.1. SCENARIOS TO PROCEED BUSINESS CASE

The presented business plan is focused on historic data. A mismatch could result if such data does not properly represent the future tender projects that could be achieved. Two scenarios with corresponding actions are given below.

1. *The future topsides specifications are similar to the specification of historic topsides as expected.*
    - Have a full detailed engineering and the approval of classification society ready even without any incoming projects.

- Start fabricating the RDSF system when tender on float-over project is won.
  When awarded with a future float-over installation project the fabrication of the RDSF system should start. The amount of RDSF units that should be build has to be equal to the amount of nodes. So when it the first project has 4 nodes, invest in 4 RDSF units.
- Only invest in new RDSF units when topsides with more DSF nodes are awarded.

2. *The future topsides are heavier than expected.*
   This causes the Black Marlin to be inapplicable to perform most installations. Therefore, the applicability to other vessels has to be investigated. This is not expected to become an issue, as the design is scalable.

8.5. CONCLUSIONS OF ECONOMIC FEASIBILITY OF THE RDSF

In this chapter, the business case of the RDSF is presented. This business case considers only the difference in costs for both the use of the new RDSF and the standard single-use DSF. The cost analysis ignores the costs for operating the RDSF system, because it is seen that the differences herein cancel each other out. The operational (dis)advantages of the RDSF are elaborated in chapter 7.

Interviews within Boskalis and Mammoet show that a wide variation of steel prices apply for the fabrication of both the RDSF and the single-use DSF. The steel price of the RDSF equipment is estimated on 6,000 USD per tonnes. The price of single-use steel as adopted in both the OPEX-parts of the RDSF and in the single-use DSFs is estimated on 4,500 USD per tonnes. Considering these costs, it is seen that the break-even point for the base case of the RDSF system varies between 2 and 4 projects. With the expectation of minimal 5 projects in the life time of the system, it can be concluded that the RDSF system is economically feasible in terms of cost reduction.

9

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The discussion, conclusions and recommendations of the study are presented in this chapter.

9.1. DISCUSSION

This section reflects on the assumptions, decisions, and results of this thesis.

RESEARCH METHOD

The answering of the research question is approached by developing a conceptual design to the reusable deck support frame in according with the "methodical design approach" [8]. As consequence of this design approach the result of this thesis has led to new design. With this approach, future opportunities to buy, modify and reuse single-use DSFs are excluded in this study, although they might well result in more cost-effective solutions.

SCOPE OF THE RDSF DESIGN

The initial scope or the functional requirements of the RDSF system mainly relate to the choice of the heavy transport vessel, the "Boskalis Black Marlin". This choice of vessel is in line with the capabilities of Boskalis. However, developing the RDSF system for this vessel has the following consequences for the results.

- The Black Marlin has a limited carrying capacity due to the load introduction and stability requirements. This consequently limits the scope of the system to a certain weight of the topsides. However, this does not have great effect on the scope as the majority of the topsides are within this weight category.
- The transverse load-out direction is chosen because it is preferred for heavy transport vessels. This contrasts with barges, where the longitudinal load-out direction is preferred. The different load-out direction conflicts with the basic principle of a stable RDSF system in the roll plane thus making the RDSF system inapplicable. If the system needs to handle future longitudinal load-out operations, modifications to the system must be made. This implies that minor adjustments need to be made to the skid shoe-leg connections and to the grillage concept.
- The grillage is assumed to be a boundary layer with an uniform compression capacity of 300 tonnes per meter per skid track, which is supported by two web frames. This grillage capacity is based on a basic structural calculation for the Black Marlin, see Appendix H. A decrease in the actual grillage capacity reduces the capacity of the RDSF system.

9.2. CONCLUSIONS

The deck support frame (DSF) is one of the most prominent cost assets of the float-over installation method. The reusing of the deck support frame is seen as an attractive business opportunity for installation contractors, including Mammoet and Boskalis. This urged the need for a feasibility study of a reusable deck support frame (RDSF) for float-over installations. The objective of this research was *"to design a reusable deck support frame in order to optimize the float-over installation method and reduce the costs of the entire operation"*.

The research question was defined as: *"Is it feasible to perform float-over installations with a reusable deck support frame?"*. This question was answered by conducting a design study resulting in a conceptual design of the 'RDSF system' that works in cooperation with the Black Marlin. The resulting RDSF system includes a general arrangement drawing, an RDSF system configuration tool, and a cost estimation. From this study, it can be concluded that the reusable deck support frame is found to be technically, operationally and economically feasible.

The following conclusions can be drawn with respect to the reusable deck support frame:

- Market analysis of the float-over method shows that over 95 platforms are installed using the float-over installation method. Topsides weighing between 5,000 and 20,000 tonnes are most frequently installed using this method. Topsides within this weight range are seen as the ones that are the interesting for the scope of the design of a reusable deck support frame. It was noted that the corresponding topsides transportation height during voyage (H_{ad}) for this weight range varies between 5 and 15 meters.
- The stakeholder assessment concludes that the most important design criterion for the field operator and installation contractor is to increase the level of reliability and safety of the entire installation. In order to ensure this, the preferred design is one that has a limited amount of temporary connections. Additionally, the wide applicability of the reusable deck support frame is of great importance to the installation contractor.
- The onboard jacking operation provides flexibility by rearranging the float-over operations. This flexibility does not outweigh the disadvantages of the designing of a new and stronger onboard jacking system. Even though onboard jacking has high potential for extremely heavy topsides that do not comply with the stability criteria for normal voyages.
- The integrated jacking operation decreases the total required time, space and equipment to perform a float-over installation by eliminating one operation. The degree of improvement to the installation process does, however, vary greatly between different projects. For that reason, an independently working existing jack-system is integrated to the RDSF system. This compromise results in a more flexible and applicable system, but with the need of mobilizing two systems.
- The conceptual design of the RDSF system is the most suitable design for repetitive float-over installations in conjunction with the constraints laid down in chapter 4. The RDSF system uses single modules per topsides DSF nodes, and can easily be applied to all types of topsides with different nodal spacing and heights. This design is operationally and technically feasible for installing four types of topsides that together form a good representation of the scope.
- The maximum capacity of the RDSF system is mainly limited by the amount of topsides DSF nodes. Historic data shows a correlation between the weight and the number of nodes of the topsides. The higher the weight, the more nodes the topsides will have. This works in favour for the RDSF system that has a maximum capacity of 17,500 mT and 25,000 mt for topsides with 4 and 8 nodes respectively.
- Finally, it is concluded that the RDSF system is an attractive business opportunity in terms of cost reduction. It is seen that the cost break-even point is already reached after two to four projects for respectively 4 and 8 RDSF units. It can be concluded that the RDSF system is economically feasible, because the expected use of the RDSF system is minimally five times. The economic feasibility is described in chapter 8.

9.3. RECOMMENDATIONS

In order to continue with the further development of the reusable deck support frame the following recommendations are presented.

1. *Validate future expectations of topsides installations.*
   All the design choices that are made are based on historic data. A mismatch could result if such data does not properly represent the future tender projects that could be achieved. It is therefore recommended that these expectations be validated by involving the field operator and fabrication yard. The possible scenarios and the corresponding action plan is presented in chapter 8.

2. *Model technical assumptions and add to configuration tool.*
   The configuration tool is set up to assess the overall technical feasibility of multiple float-over installations. The assumptions made during the development of the tool create uncertainties surrounding the result. The following additions to the configuration tool are recommended:

   - Model detailed grillage capacity.
   - Model horizontal centre of gravity offsets (LCG and TCG) and unequal load distributions of the topsides.
   - Model deflections of vessel and topsides during the load-out and voyage operation.
   - Model impact loads during the float-over operation.
   - Model the self-weight of the RDSF system.

3. *Perform a structural analysis and optimize RDSF system.*
   After gaining a clear view on the actual loads, it is recommended that an extensive structural analysis be performed, preferably with dedicated software. The resulting stresses can be used to optimize the system for detailed design.

4. *Perform a fatigue analysis on the RDSF system.*
   It is recommended to perform a fatigue analysis, as the reusing is the key feature of the success of the RDSF system.

5. *Research on the integration of existing equipment.*
   The existing high capacity Novarka skid shoes could replace the skid shoes used with the RDSF system. This is expected to result in lower fabrication costs, a smaller installation dimension and a desired actively compensated load-out operation. It is expected that this improvement to the system can lead to a 15% cost reduction. The setup of this improvement is described in Appendix J. To incorporate the existing skid shoes in order to achieve this cost reduction, the following recommendations are proposed:

   - Research on Novarka skid shoes for offshore use.
   - Design of different sea fastening concepts.

6. *Research on using the RDSF system for other disciplines.*
   The use of the RDSF system or individual components of the system can increase the uptime of and thereby decrease the project rate. One example of the using the entire RDSF system and one of using only one component of the RDSF system are proposed, next to these many other ideas are worthwhile.

   - *Bridge installation and removal*
     "The collapse of a bridge in Genoa, Italy, on 14 August 2018 that killed 43 people has set off warnings on the current status of bridges in many Western countries. Expected incoming news about neglected maintenance to other bridges will launch a series of bridge removals and installations" [25]. Although, the RDSF system is probably overqualified as the acceleration of bridge section during voyages are not comparable with worldwide topsides transportations. Though, the applicability of the RDSF system on the installation and removal of bridges is a way to enlarge the uptime of the RDSF and therefore increasing the returns on the investment.

   - *Spreader beam*
     The main legs of the RDSF system may function as future spreader beams in high capacity cranes. Both the main legs and the spreader beams are subjected to compression loads and have comparable geometries.

A

OVERVIEW OF TOPSIDES INSTALLATION BY THE FLOAT-OVER METHOD

*Confidential

B

GENERAL ARRANGEMENT OF THE RDSF SYSTEM

*Confidential

C

THE RDSF SYSTEM COMPONENTS

*Confidential

D

THE RDSF SYSTEM CONFIGURATION TOOL

*Confidential

E

DEVELOPMENT OF DESIGN

In this appendix all additional tools that are used during the development of the design are presented.

E.1. 5W2H METHOD

The goal of 5W2H method is to generate and validate an effective action plan [8].

WHAT?

Problem:	Single-use DSF costs money every time again.
Effect:	Expensive tender ->smaller win chances of tender.
Wishes/Goals:	Less expensive cost to make more cost effective tender.
Idea:	Reusable DSF (cost reduction on multiple (x) projects).

WHO?

Stakeholders	
Field operator	Client Pays for entire topsides installation operation Only interested in safety and total costs
Boskalis :	User of design Wants to enlarge tender win chances Pays for design (business decision)
Mammoet :	User of design Wants to enlarge scope of work and entry float-over market Pays for design (business decision)
Yard:	Not really active role Has to be installable without many modifications/time/space
Classification society:	Inactive role. Design should comply with rules.
Frame manufacturer:	Inactive role. Design has to be manufacturable

WHERE?

Physical Context	Worldwide		
	At Yard	At Sea	At installation location
Conditions	Static	Heavy sea states	Moderate sea states

WHEN?
Problem since start of using float-over installations. **WHY?**

Plausible causes?	- Topsides are too different from each other? - Installation companies DSF fabricator do not collaborate. - Few installations each year? - Mobilization of DSF expensive?
Why problem?	- Business case hard to make profitable - Safety of reusable frame at issue

HOW?

Inventory current solutions:	- Single DSF -> Made for every specific solution - McDermott load-out beams -> Fixed for specific designed. - Few installations each year?
Used technologies:	- Constructed frame - Constructed beams - Jacking system (ALE/MAMMOET)

HOW MUCH?
Occurrence of the problem? -> Every topsides installation project.
Who deals with the problem? -> Installation contractor, if they don't get the job.

E.2. DESIGN LAYOUTS

Figure E.1 shows the layout of the design cases used in multiple brainstorm sessions.

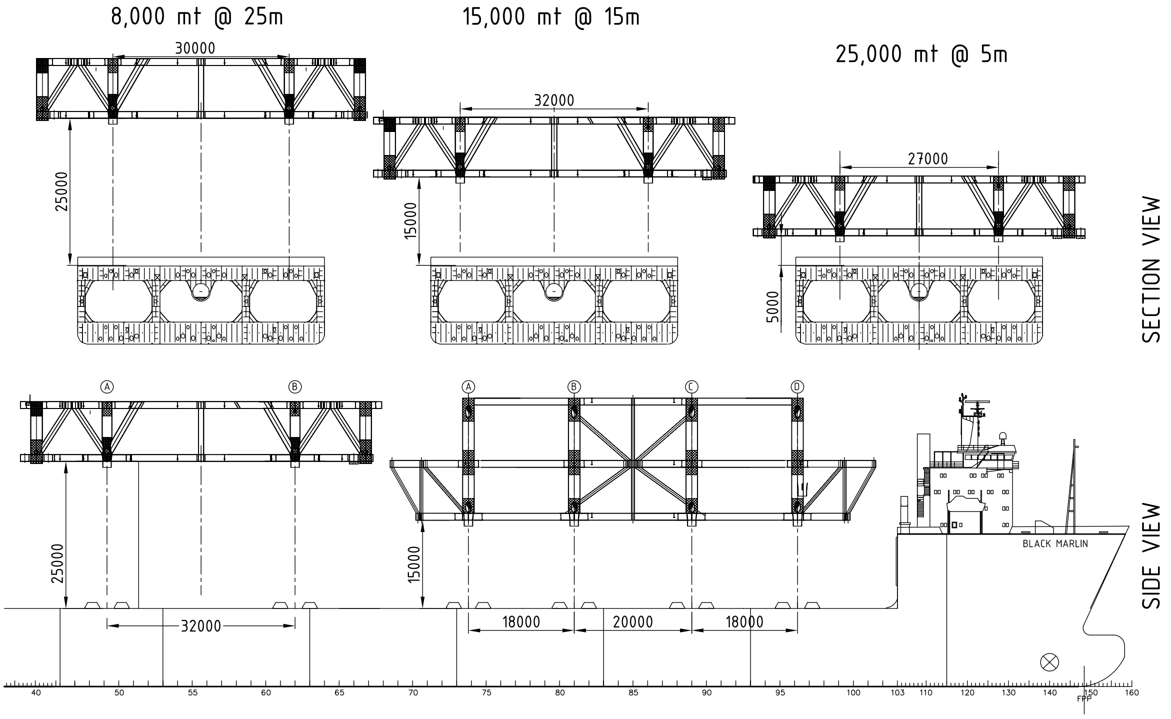


Figure E.1: Layout of design cases

E.3. DESIGN CRITERIA TREE

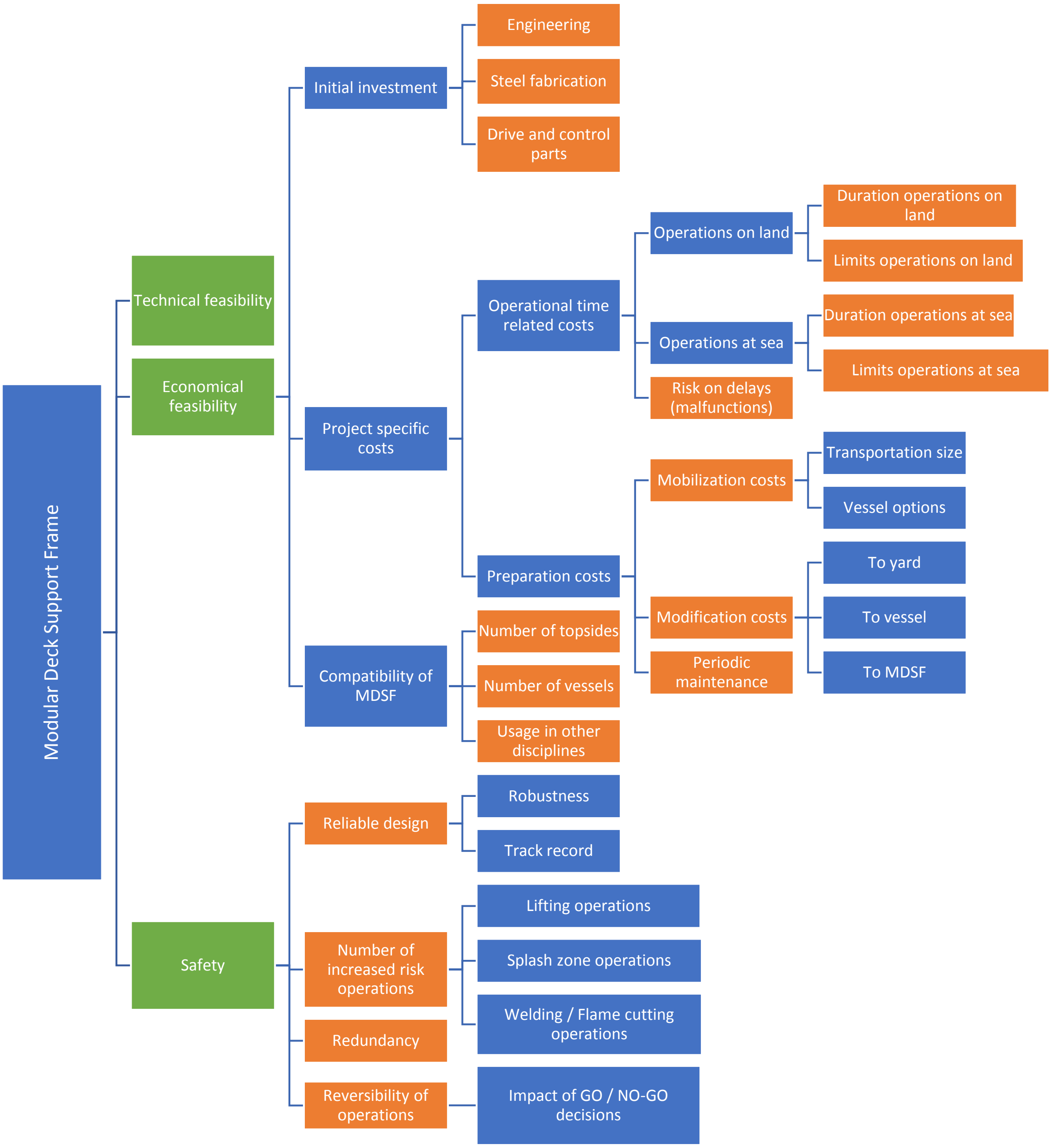


Figure E.2: Criteria tree

F

HTV

F.1. HTVS FOR FLOAT-OVER INSTALLATIONS

Table F.1: Boskalis HTVs

Vessel name	# Used	Deadweight [Te]	Length [m]	Breadth [m]	Depth [m]	Caisson
Vanguard	0	117,000	275	70	15.5	Movable
White Marlin	0	72,146	217.8	63	13.3	Movable
Mighty Servant 1	0	45,407	190.03	50	12	Movable
Fjord	1	24,500	159.24	45.5	9	Movable
Forte	0	48,000	216.75	43	13	Movable
Black Marlin	6	57,021	217.8	42	13.3	Movable
Blue Marlin	2	56,000	224.8	42	13.3	Movable
HYSY 278	2	52,789	222	42		Movable
Transshelf	2	34,030	173.50	40	12	Movable
Mighty Servant 3	1	27,720	181.23	40	12	Movable
Fjell	2	19,300	147.24	36	9	Movable
Finesse	1	50,000	216.75	43	13	Movable
Teal	1	32,101	180.96	32.26	13.3	Not movable
Swift	1	32,187	180.96	32.26	13.3	Not movable
Swan	0	30,060	180.96	32.26	13.3	Not movable
Triumph	0	54,000	216.79	44.5	14	Not movable
Trustee	0	54,000	216.79	44.5	14	Not movable
Talisman	0	54,000	216.79	44.5	14	Not movable
Treasure	0	54,000	216.79	44.5	14	Not movable
Transporter	0	54,000	216.79	44.5	14	Not movable
Target	0	54,000	216.79	44.5	14	Not movable

Webframe spacing of Forte, Black Marlin, White Marlin and Blue Marlin is 2400 / 2500 mm.

Table F.2: Competitor HTVs

Vessel name	# Used	Deadweight [MT]	Length [m]	Breadth [m]	Depth [m]	Caisson
Pioneering Spirit	1	43,000[1]	382	124[2]		-
HMC H-851	4	110,720	260	42	15	-
Intermac 650	4	26,400	198.1	42	12.2	-
S600	0	60,760	183	47.24	11.58	-
XRK	4	48,232	216.7	43	13	-
XYK	1	48,232	216.7	43	13	-
TAK	5	20,131	156	36	10	-
Boa Barge 29	1	17,480	124	31.5		-
S600	0					-
HYSY 229	2	80,000	215	42	14.25	-
HYSY 221	3					-
B42	1		180	42	11	-
Yuri Kuvykina	3		140	30	9.3	-
Saipem S45	2	20,000	180	42	11.5	-

[1] Allseas Pioneering Spirit has a installation capacity of 43,000 tons.

[2] Allseas Pioneering Spirit is a catamaran vessel with a slot width of 59m.

F.2. Boskalis Black Marlin float-over installations

Table F.3: Black Marlin float-over installations

Topsides	Year	Country	Yard	Weight	L	W	H	VCG	Had	GM
East Area Project NGL	2007	Nigeria	HHI	6,000						
Angel A	2008	Australia	MMHE	7,568				43.52	20	
CPOC Muda MDPP	2009	Thailand	MMHE	16,734				37.66	7.85	
Bongkot	2011	Thailand	TlST	19,500	76.6	59.8	53.3	36.47	6.6	5.89
Tapis R	2014	Malaysia	MMHE	18,984	120	70	60	33.32	6.93	
Vyborg Semisub	2010	Russia	MMHE	19,000	85	73	92	27.87	3.05	

G

MOTION ANALYSIS

G.1. VESSEL CHARACTERISTICS FOR MOTION ANALYSIS

Table G.1: Topsides and vessel characteristics for roll motion analysis

Topsides:	Bongkot	Vessel:	Black Marlin
Weight:	19,500 mT	Lightweight:	18,845 mT
Length:	56.0 m	Length:	172.4 m
Height:	30.5 m	Breadth:	42 m
Width:	56.0 m	Depth:	13.3 m
Height cog	12.65 m	draught:	8.55 m

G.2. LOAD ON VESSEL DUE TO WAVE EXCITATION

VESSEL MOTIONS, STABILITY AND NATURAL PERIOD

Both vertical and transverse loads are affected by the accelerations and motions of the vessel.They are described by the following equation of motion with 6 degrees of freedom ([26] equation: 6-27).

$$(M_n + A_n)\ddot{x}_n + B_n\dot{x}_n + C_n x_n = F_n \tag{G.1}$$

Where Mass (M), Added mass(A), Damping (B), Restoring coefficient (C) and External loads (F) all depend on the system properties. The external loads (F) depend on the environment as well, and in this case in particular analysis, only the loads excited by waves.

The largest changes in accelerations and motions are expected to be in roll direction, because in this direction the system (vessel and topsides) has the least resistance. For less time consuming calculations, the analyses of the systems motions and accelerations are limited to 2D YZ plane. With this assumption, the motions of the vessel are limited to sway, heave and roll and therefore effects of surge, pitch and yaw are not taken into account. The equation of motion of roll is described as: ([26] equation 6.28)

$$(I_\phi + A_\phi) * \ddot{\phi} + B * \dot{\phi} + C * \phi = M_\phi \tag{G.2}$$

The roll motion of the system depends specifically on the transverse stability of the system. The hydrostatic term for stability is given by [26] equation 2-36.

$$GM_T = KB + BM_T - KG \tag{G.3}$$

Where:

GM_T = Transverse metacentric height, a stable system has a GM higher than 0.
KB = Keel to buoyancy point.
BM_T = Transverse metacentric radius for parallel sided vessels.($BM_T = (l * b^3)/\nabla$)
KG = Keel to System Vertical Centre of Gravity (VCG).

As for the onboard jacking operation, the overall stability (GM) can be tuned by varying the H_{AD}. Varying the topsides H_{AD} changes the overall system's vertical centre of gravity (KG). The terms KB and BM do not change by a varying H_{AD}, because the draught, total mass and ballast conditions are fixed. A decreasing topsides H_{AD} causes an increase in GM and therefore the system becomes more stable. A more stable system is consequently more forced to return to its original position, because of the increased stiffness. The stiffness of a parallel sided barge increases proportional with GM, according the Equation G.4 for a barge ([26] equation 6.3.2.3). The natural roll period for an un-dampened system ($B = 0$) is described in Equation G.5. ([26] equation 6-38)

$$C_\phi = \rho g \nabla GM_\phi \tag{G.4}$$

$$T_{n.\phi} = 2\pi * \sqrt{\frac{I_\phi + A_\phi}{C_\phi}} \tag{G.5}$$

So an increasing stability (GM), increases the stiffness of the system and therefore decreases the natural roll period of the system.

NORMAL LOADS ON THE VESSEL

Normal loads on the vessel are induced by the vertical accelerations of the system in the vessel's reference frame (Equation G.6). Where

$$F_N = TS_{mass} * \ddot{x}_3 \tag{G.6}$$

The normal motions and accelerations of a vessel can be described by the modified general equation of motion for 6 degrees of freedom Equation G.1, with n=3 for heave. Where the matrices M, A, B, C and F for heave are not influenced by the variation of H_{AD}. Therefore the normal loads are not taken into account for the analysis on the effects of variation of H_{AD}.
The default motion criteria of DNVGL are taken for the value of the normal acceleration, which is 0.2g (for vessels with L >141m & B >30m).

TRANSVERSE LOADS

transverse loads on the topsides are induced by the transverse accelerations of the system (Equation G.7).

$$\begin{aligned} F_T &= TS_{mass} * a_T \\ a_T &= \ddot{\phi} * R + g\sin(\phi) + \ddot{y} \end{aligned} \tag{G.7}$$

TS_{mass} = Weight of the topsides.
R = The arm from centre of rotation to the point of acceleration.
g = Gravitational acceleration ($9.81 m/s^2$).

The transverse accelerations are caused mainly by the roll of the vessel. The roll motion of the vessel is described by by the modified general equation of motion for 6 degrees of freedom (Equation G.1), with n=4 for roll. The sway acceleration ($\ddot{y}$) is not considered in this analysis, because the topsides H_{AD} does not influence the sway accelerations. The H_{AD} does influence the transverse motions and accelerations due to roll, by the matrices M (Mass) and C (Restoring Coefficient). A lower H_{AD} causes a smaller Steiner term of the topsides, which reduces the total value of the inertia in the M matrix (see Equation G.8). A lower H_{AD} of the topsides will increase the upright stability GM and therefore the system stiffness (see Equation G.9).

$$M_{44} = I_{vessel} + I_{topsides} = I_{vessel} + (K_{TS}^2 + H_{ad}^2) * TS_{mass} \tag{G.8}$$

$$C_{44} = \rho g \nabla GM_\phi \tag{G.9}$$

The H_{AD} influences both the inertia as the stability (GM) and therefore different responses for a changing H_{AD} are expected.

MOMENT LOADS

The moment loads are a result of the transverse loads in combination with the H_{AD} (Equation G.10). The moment is transferred into the deck as a combination of a positive and negative normal load in the connection points or skid-tracks of the DSF.

$$M = F_T * (H_{ad} + H_{TS}) \tag{G.10}$$

Where H_{TS} is the vertical distance between the topsides centre of gravity and the connection between topsides and DSF, H_{TS} has a fixed distance (see Figure 5.6). Both horizontal loads and H_{AD} changes with a changing vertical distance of the H_{AD}. Therefore different results in moment loads are expected.

G.3. MOTION ANALYSES PROCESS

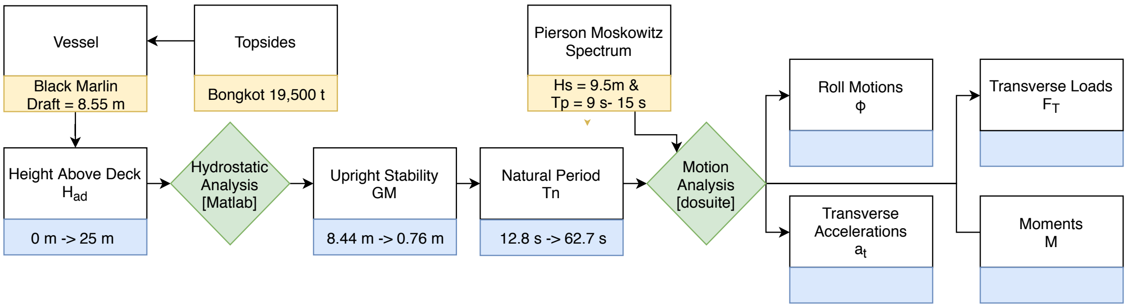


Figure G.1: Motion analysis 1 flow chart

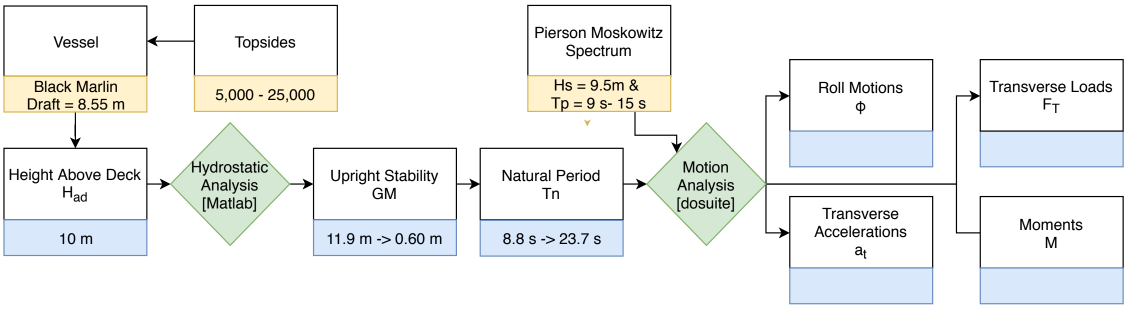


Figure G.2: Motion analysis 2 flow chart

Hydrostatic analysis For simplicity, the vessel is considered as a cubic barge in the hydrostatic analysis. Consequence of this simplification is a higher GM than in reality. In the hydrostatic analysis, the upright stability (GM), the system vertical centre of gravity (sys.vcg), the radius of gyration (Kxx) and the water displacement (∇) are determined by a calculation.

Input hydrostatic analysis:
Vessel characteristics: Lightweight, Ballast, Transport draught, Inertia, Centre of gravity.
Topsides characteristics: Weight, Inertia, Centre of gravity.
Hydrostatic analysis
Output hydrostatic analysis
System characteristics: Radii of gyration, Vertical centre of gravity, Upright Stability (GM) and Natural periods.

Motion analysis A motion analysis using in-house Boskalis software DOSUITE is performed to identify the responses of the earlier mentioned system configurations. DOSUITE is an interface program which uses SHIPMO as basis for the hydrodynamic calculations. SHIPMO is a potential theory based motion response analysis tool which includes added mass, viscous damping [27]. After the motion analysis, the data is processed to obtain the acceleration and loads at the desired positions.

Input motion analysis: Output hydrostatic analysis and sea states.
Motion analysis: Analysis based on potential and strip theory.
Output motion analysis: Response Amplitude Operators (RAO) for motions and accelerations.
After processing motion analysis:
1. Translate RAO to position of interest, topsides CoG.
2. Calculate most probable maxima (MPM) for accelerations at topsides.
3. Calculate most probable maxima of transverse loads and moments.

The responses on irregular waves spectra are determined with probability theory, where the amplitude of the waves obey to a Rayleigh distribution []. Most probable maxmima motions and accelerations can therefore calculated according the following formula:

$$MPM_{a_T}(\omega) = \sqrt{0.5 * \log(\frac{T_{span}}{T_{zr}})} * S_{a_T}(\omega) \tag{G.11}$$

Where T_{zr} is the response spectrum zero-crossing period ($T_{zr} = 2\pi\sqrt{\frac{m_0}{m_2}}$ ([26] eq 6-48)).

G.4. Response Accelerations

Response for analysis 1 - H_{ad}-analysis

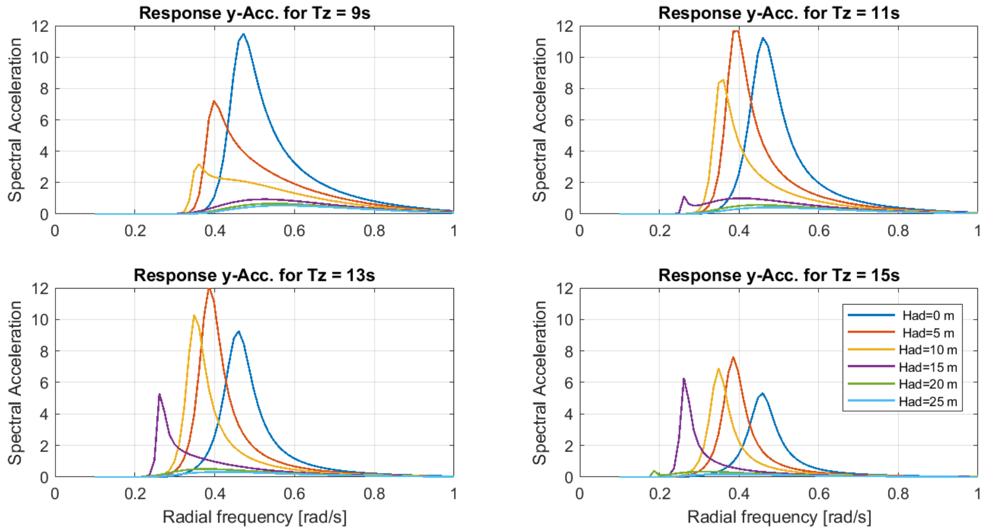


Figure G.3: Acceleration response spectra H_{ad}-analysis (Analysis 1)

RESPONSE FOR ANALYSIS 2 - WEIGHT-ANALYSIS

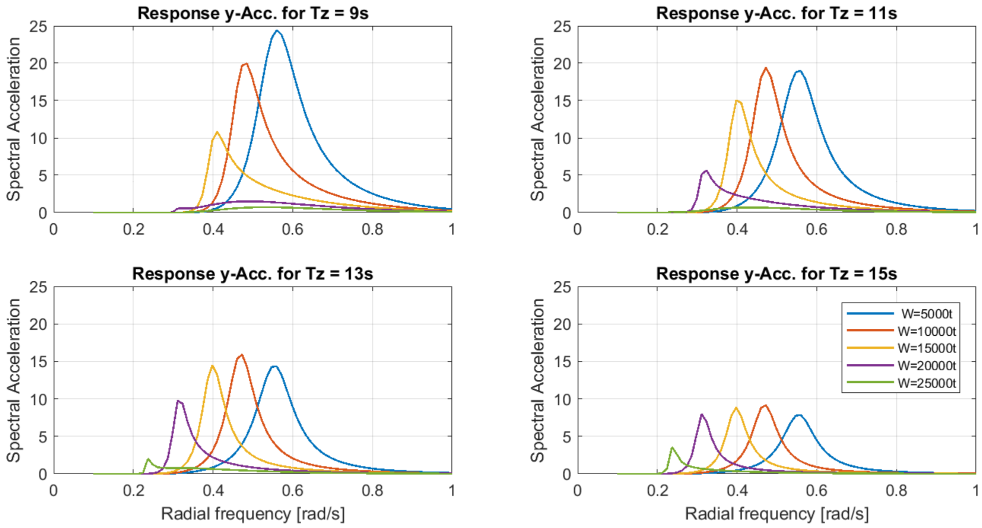


Figure G.4: Acceleration response spectra weight-analysis (Analysis 2)

H

DECK AND GRILLAGE CAPACITY

Generally, the limiting deck capacities of HTVs dominates the RDSF geometry. The deck capacity can be enlarged by an additional grillage welded on top of the deck. In this document the gain in capacity by enlarging the grillage structure is reviewed. Figure H.1 shows the layout of the wing part of the deck including the grillage on top. The wing part are the parts positioned longitudinally in the middle and transversally on the sides of the vessel. The wing part, is the location of the support points of the RDSF. The grillage is welded in line with the web frames on top of the deck, so that the grillage and web frames plates function as one plate.

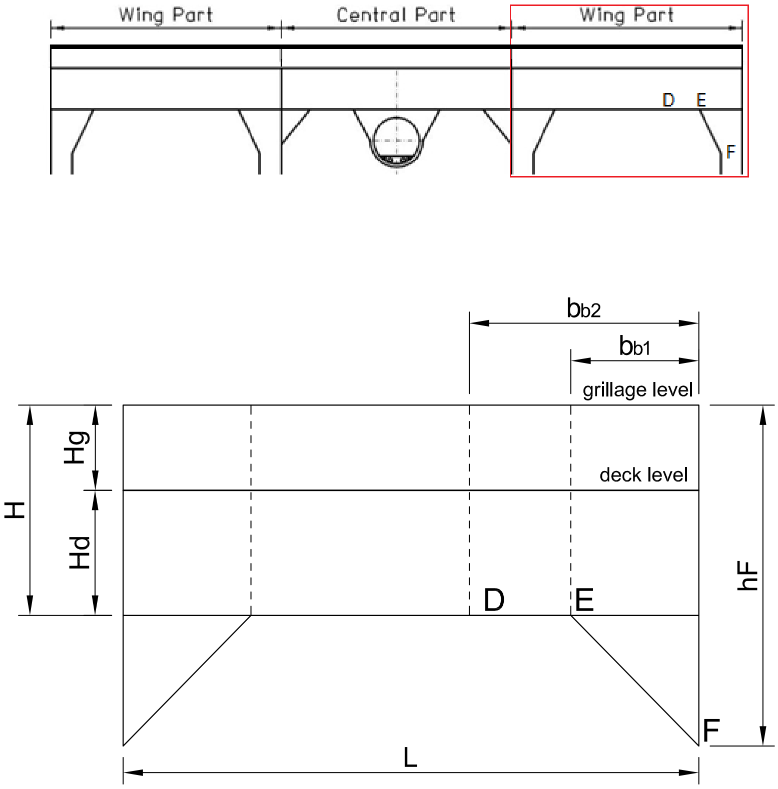


Figure H.1: Deck Layout wing part

The grillage analysis is executed for 2 Boskalis vessels: the Black Marlin and the Forte. The characteristics of both decks can be seen in H.1. The maximum allowable stresses to be used are according to API-RP-2A, "Recommended practice for Planning< Design and Construction Fixed Offshore Platforms-WSD".

Table H.1: Maximum distributed load on deck and grillage

		Black Marlin			Forte			
Max. yield stress		$\sigma_{y.235} = 235$			$\sigma_{y.345} = 345$			MPa
Max. bending stress		$\sigma_{max} = 0.6 * \sigma_{y.235} = 141$			$\sigma_{max} = 0.6 * \sigma_{y.345} = 207$			MPa
Max. shear stress		$\tau_{max} = 0.4 * \sigma_{y.235} = 94$			$\tau_{max} = 0.4 * \sigma_{y.345} = 138$			MPa
Max. combined stress		$\tau_{max} = 0.7 * \sigma_{y.235} = 164$			$\tau_{max} = 0.7 * \sigma_{y.345} = 241$			MPa
Point		D	E	F	D	E	F	
Height all	H	4000	4000	7630	4000	4700	6000	mm
Height deck	Hd	2500	2500	5130	1500	220	4500	mm
Thickness deck	td	15	18	16	16	16	17	mm
Height grillage	Hg	1500	1500	1500	1500	1500	1500	mm
Thickness grillage	tg	20	20	20	20	20	20	mm
Length all	L	14000			10125			mm
Connection length	Bb	2625			1750	2250		mm
Section area	A	67500	75000	112080	54000	65200	106500	mm^2
Section modulus	Syy	4.29E7	4.93E7	1.24E8	2.53E7	3.86E7	1.06E8	mm^3

H.0.1. LOAD CASE: UNIFORM LOAD

Only the limiting uniform distributed loads are considered. Point loads cause local stresses which cannot be captured without a finite elements model. A finite element model is to be used in further detailed design. The shear and bending capacity for the deck and deck+grillage are determined below.

SHEAR CAPACITY

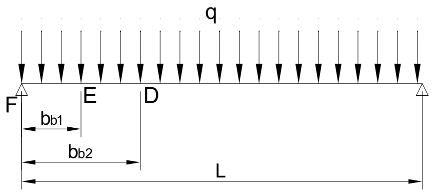


Figure H.2: Shear capacity

The maximum allowable shear force is calculated according to the following formula and is different for section D, E and F.

$$F_{shear} = \begin{bmatrix} D \\ E \\ F \end{bmatrix} = \begin{bmatrix} q * /(L - 2 * b_{b2}) \\ q * (L - 2 * b_{b1}) \\ q * L/2 \end{bmatrix}$$

$$q_s = \begin{bmatrix} D \\ E \\ F \end{bmatrix} = \begin{bmatrix} 2 * A_D * \tau_{max}/(L - 2 * b_{b2}) \\ 2 * A_E * \tau_{max}/(L - 2 * b_{b1}) \\ 2 * A_E * \tau_{max}/L \end{bmatrix}$$

BENDING CAPACITY

The bending moment has the largest value when a distributed load is applied on the small section with length $(L - 2 * b_{b1})$.

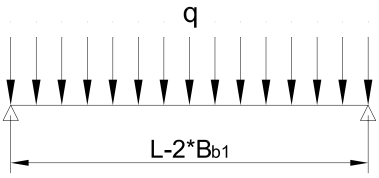


Figure H.3: Bending capacity

$$
\begin{aligned}
M_{max} &= \frac{q * L^2}{8} \\
q_b &= \frac{8 * \sigma_{max} * S_{yy}}{(L - 2 * b_b)^2}
\end{aligned}
\tag{H.1}
$$

H.1. TOTAL COMPRESSION DECK CAPACITY

Table H.2: Deck and grillage capacity

			Black Marlin			Forte			
			D	E	F	D	E	F	
Excl. grillage (Hg=0)	Shear	q_s	103	99	112	117	149	212	mT/m
Excl. grillage (Hg=0)	Bending	q_b		157			99		mT/m
Incl. grillage (Hg=1500)	Shear	q_s	185	164	153	264	277	296	mT/m
Incl. grillage (Hg=1500)	Bending	q_b		265			174		mT/m

A grillage of H=1500 mm and t=20 mm on top of the Black Marlin has a capacity of approximately $q_{max} = 150\frac{Te}{m}$. This capacity value is used in further design of the RDSF system.

There is a limit to reinforcing deck and grillage, as the stress needs to be introduced to neighbouring plating and framing which is not being reinforced. As this analysis is a first estimation, a finite element model is recommended to give a more complete view on deck capacity.

H.2. UPLIFT DECK CAPACITY

Tension, or uplift, is a positive vertical force on the HTV deck. In general, the uplift capacity is depended on the local phenomena. In the Table H.3 the uplift capacity of the web frame is calculated by considering the fillet weld between the main deck and the web frame. This weld is seen as the weakest link, in terms of uplift. Generally, the width of a fillet weld is half the plate thickness. The weld is visualized in Figure H.4.

As seen in the uplift calculation, the maximum allowable uplift could reach up until 125 mT/m for the Black Marlin and 196 mT/m for the Forte.

Geometry input		Black Marlin	Forte	
Plate thickness	td	15	16	mm
Leg single weld	leg	7.5	8	mm
Weld section area	Aweld	10607	11314	mm2/m

Table H.3: Uplift deck capacity

Results maximum uplift (q_{max})	Black Marlin	Forte	
Tension capacity	215	337	mT/m
Shear capacity	143	225	mT/m
Combined capacity	125	196	mT/m

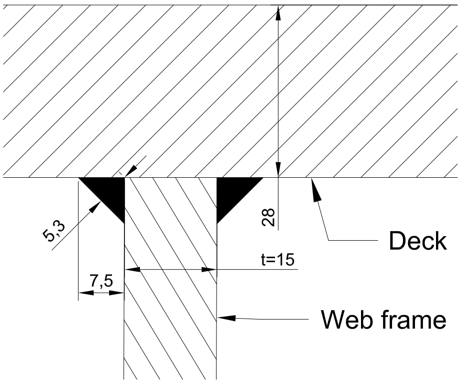


Figure H.4: Web frame weld of the Black Marlin

I

SHIPPING, STORAGE AND STEEL COSTS

I.1. SHIPPING

The shipping costs estimated for a primary design of the RDSF system. The geometry and weight of this design are slightly overestimated resulting higher shipping and storage prices.

1x assembly = 20m x 4m x 6.5m => 325 Tons

Cargo 1: 4x the assembly -> So 1500 ton in total.
Cargo 2: 8x de assembly -> So 3000 ton in total.

1. SHORT VOYAGE Indication Busan / Masan in O.O. – Tianjin, China
    (a) basis LTHH (4 units) Lumpsum USD 225,000.00
    (b) basis LTHH (8 units) Lumpsum USD 285,000.00
2. MEDIUM VOYAGE Indication Busan / Masan in O.O. - Jurong, Singapore
    (a) basis LTHH (4 units) Lumpsum USD. 255,000.00
    (b) basis LTHH (8 units) Lumpsum USD. 335,000.00
3. LONG VOYAGE Indication Busan / Masan in O.O. – Rotterdam, the Netherlands
    (a) basis LTHH (4 units) Lumpsum USD. 375,000.00
    (b) basis LTHH (8 units) Lumpsum USD. 475,000.00

- Subject to final packing list, cargo details and technical drawings
- Our quotation is based on today's rate of exchange, tariff rates and surcharges and is subject to change without notice

I.2. STORAGE

Storage of 750m3 @ 0.93 EUR/month over 3 years: 30K EUR (from Moerdijk)

I.3. STEEL PRICE ESTIMATION

One of the drivers for the economic feasibility of the RDSF system are the costs of the steel. The economic feasibility of the system depends mainly on the correct estimation of the steel price for both the standard DSF and for the new RDSF system. However, these steel prices vary strongly based on production location, amount of edits, handling easiness and many others. The estimation of the steel price is based on a number of interviews with the some experts from Mammoet and Boskalis over the steel price of many construction. The results of these interviews are listed in Table I.1.

Table I.1: Reference structures

	Specifications	Estimation steel price [USD/tons]	
		Asia	*Europe*
Grillage	- no pipe junctions - lots of onboard welding	2,900 - 5,800	4,230 - 6,000
Monopiles	- no welds - no pipe junctions		1,600 - 2,500
Tripods	- little welded junctions - outdoor construction -coating splash zone		4,200 - 5,900
Jackets	- many welded junctions - outdoor construction - coating splash zone		4,900 - 5,700
Cranes	- many welded junctions - drive and control parts - many machining operations - overall coating		8,000- 30,000

The steel price for the standard DSF and the new RDSF system are needed to make an good estimation for the economic feasibility. The following list describes the generation of the steel price. It is to be mentioned that these prices are a very rough indication and are only to be used for spot a trend. The list is summarized in Table I.2.

- Standard DSF
  The standard DSF is usually made of average quality construction steel. The construction of the DSF only contains of the steel production, the plate cutting and welding. A standard DSF does not contain machining and paint coating because it is not being reused. The DSF structure is in principle very good comparable with tripod or jacket structures.The steel price of the DSF structures is therefore estimated on 4,500 US Dollars per tonnes steel. This price includes the refunded scrap value of the steel.
- RDSF System
  The reusable components of the RDSF system do require machining and paint coating operations. However, due to the smaller geometry of all individual parts the fabrication of the RDSF system takes place indoor, causing scaffolding and outdoor protection to be unneeded. In addition, the RDSF system needs to be a more qualitative product because of the longer lifetime. The quality of European steel products is more in line with the companies objectives. The price for the RDSF system is estimated on 5,000 USD per tonnes, due to the high quality of the steel, the many machining and coating operations but the easy handling during fabrication.

Table I.2: Cost of reference steel structures

	Specifications	Estimation steel price [USD/tons]	
DSF structure	- No machining and coating - outdoor construction	Asia	4,500
RDSF system	- high quality - machining and coating - indoor construction	Europe	6,000

I.3.1. SUMMARY OF INTERVIEWS

In this section, a summary of the interviews about the steel price is given.

1. PETER VAN DE VELDE (MAMMOET)

DSF structures require more stiffness than grillage structures and the welded joints need to endure more stress. This leads to a higher steel price for DSF structures than for grillage structures. The fabrication of DSF structures is performed at an outdoor location, where scaffolding and outdoor protection is necessary. These outdoor conditions are disadvantageous for the steel price of DSF structures. The extreme high DSF constructions from 10-25 meters generally consist out of pipe members to increase overall stiffness. The smaller DSF construction untill 10 meters generally consist out of beam members. The construction of the high topsides causes generally in an higher price due to the more complex fabrication and welding costs. The following prices are a result of the discussion and are based on European region.

DSF PRICES
Labor (Europe) = 2.25 EUR / KG
Production = 1.75 EUR / KG
Total Steel price of DSF Steel = 4.25 EUR/KG (5.00 USD/KG) including small management and scaffolding fee.

RDSF PRICES
More complex system as machining and welding increases the price.
Total steel price of the RDSF Steel = 6.00 EUR/KG = 7.00 USD/KG

2. BOSKALIS

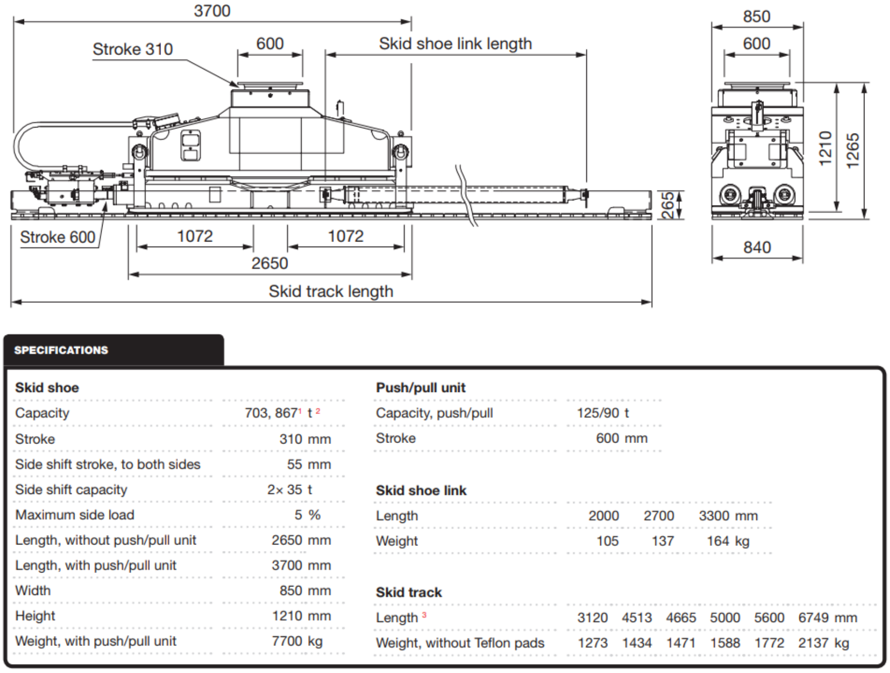
The results of the interview within Boskalis is given below.

Capex parts RDSF	€5.2	6.0 $	[per kg]	Many machining and welding costs

J

INTEGRATION OF MAMMOET NOVARKA SKID SHOE TO RDSF SYSTEM

The Mammoet Novarka skid shoe is a high capacity skid shoe. The parameters of this skid shoe are given in Figure J.1. Integration of the Novarka skid shoe to the RDSF system is expected to result in less fabrication costs, a smaller installation dimension and a desired active compensated load-out operation. An impression of integrating the Novarka skid shoe to the RDSF system is given in Figure J.4.



Skid shoe	
Capacity	703, 867[1] t [2]
Stroke	310 mm
Side shift stroke, to both sides	55 mm
Side shift capacity	2× 35 t
Maximum side load	5 %
Length, without push/pull unit	2650 mm
Length, with push/pull unit	3700 mm
Width	850 mm
Height	1210 mm
Weight, with push/pull unit	7700 kg

Push/pull unit	
Capacity, push/pull	125/90 t
Stroke	600 mm

Skid shoe link			
Length	2000	2700	3300 mm
Weight	105	137	164 kg

Skid track						
Length [3]	3120	4513	4665	5000	5600	6749 mm
Weight, without Teflon pads	1273	1434	1471	1588	1772	2137 kg

Figure J.1: Novarka skid shoe specifications

Technical

The capacity of the Novarka skid shoes maximal 876 mT and the length of the skid shoe is 2.65 meters. The resulting grillage load is calculated according the following formula.

$$q = \frac{876mT}{2.65m} = 331\frac{mT}{m}$$

$$331300\frac{mT}{m} = q_{max}$$

With the use of the Novarka skid shoes, the maximum grillage load limitation is exceeded. The skid shoe capacity is therefore decreased to the maximal load according to the following formula.

$$q = q_{max} * L_{shoe} = 300 * \cdot 2 \cdot 2.65m = 1590\frac{mT}{m}$$

The capacity envelope for the 4 and 8 RDSF units are given in Figure J.2 and Figure J.3. It is seen that the RDSF capacity reduces by using the Novarka skid shoes. For the RDSF system with 4 units this is harmful, as the installation of multiple projects will be infeasible. For the 8 RDSF unit system this is not the case. As all projects are still positioned within the RDSF8 system envelope.

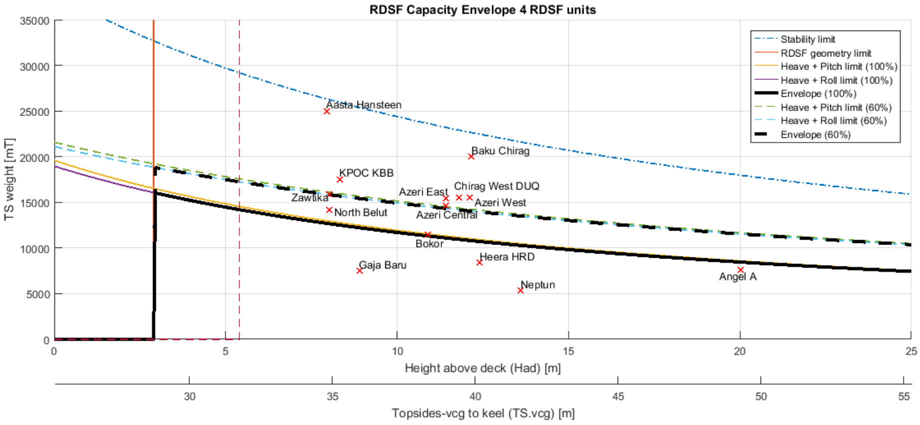


Figure J.2: RDSF 4 units envelope including Novarka skid shoe

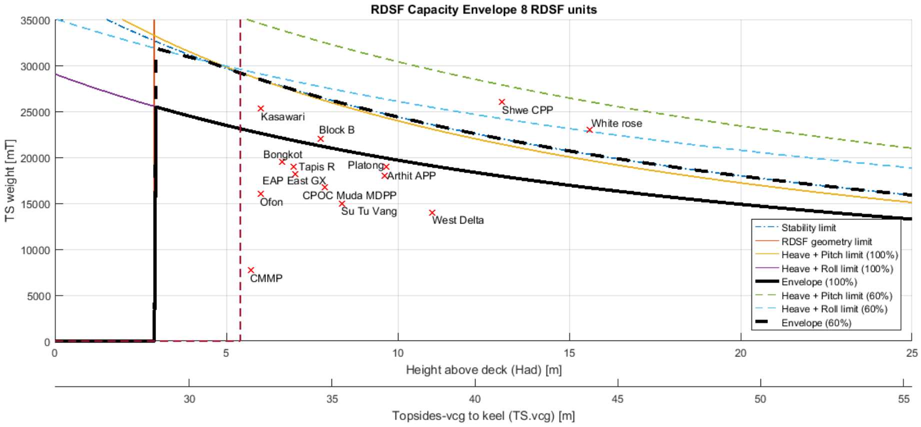


Figure J.3: RDSF 8 units envelope including Novarka skid shoe

Economic

The weight saving is estimated to be similar to the weight of a Novarka skid shoe, so 7.5 mT each. One RDSF system requires 8 Novarka skid shoes, so the weight saving amounts approximately 60 mT per RDSF unit. This results in a total weight saving of 24% of the Capex components. The new project rates are presented in Table J.1. The use of the Novarka skid shoes decreases the project rate with approximately 15%.

Table J.1: Project rates for base case of the RDSF system

	RDSF 4 units	RDSF 6 units	RDSF 8 units	
Original project rate (at 5x/10yr)	2,500,000	3,600,000	4,800,000	[USD/x]
Novarka skid shoe project rate (at 5x/10yr)	2,200,000	3,100,000	4,100,000	[USD/x]

Additional research required
The following problems arise when integrating the Novarka skid shoes, it is recommended to investigate the consequences of these problems.

- The Novarka skid shoes are not for offshore use. Research on the offshore use of the skid shoes has to be performed.
- The Novarka skid may not be subjected to side loads. It is required to design a different sea fastening concept.

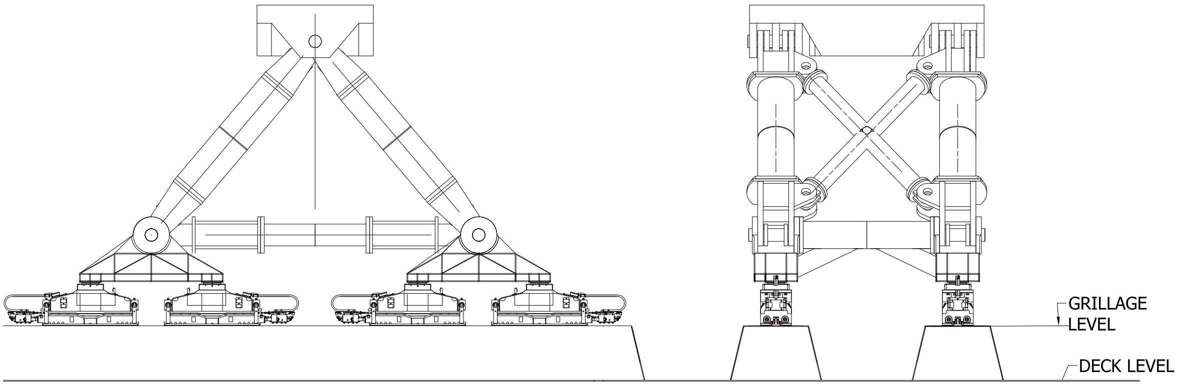


Figure J.4: Impression of the integration of the Novarka skid shoe

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