Improving jack-up capabilities

MSc Thesis

A. Dimitriou dipl. civil engineer

Delft University of Technology

Improving Jack-up capabilities

By

Aristarchos Dimitriou

-Confidential-

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Supervisor:	Prof. dr. A. Metrikine,	TU Delft
Thesis committee:	Ir. P.G.F. Sliggers,	TU Delft
	Ir. J.S. Hoving,	TU Delft
	E. van Hattem MSc.,	Heerema Marine Contractors

This thesis is confidential and cannot be made public until September 1, 2014.

Abstract

So far jack-ups have successfully operated in depths of 80 to 100 m and some are capable of operating in water depths of up to 150 m. In order to circumvent the depth limitation, it was suggested by Heerema Marine Contractors (HMC) that a base could be designed with the ability to support a jack-up rig, thereby increasing its operational depth capability. Such a support structure for jack-ups (named SSfJ) that can possibly be mobilized and demobilized by an HMC vessel would allow HMC to offer its services to another part of the Oil and Gas industry, the Drilling and Workover sector. A first investigation into the feasibility of this idea is carried out in this thesis.

The focus of the thesis is placed on determining whether a 3-legged North Sea drilling jack-up can potentially survive on a SSfJ and on the calculation of the structural characteristics of the SSfJ that are required for enabling a jack-up to do so.

The first step in this research was to verify if there is a commercial driver for the SSfJ. Therefore a market research took place which focused on the North Sea offshore drilling industry and showed that there is a need for high spec and deep water jack-ups and a great need for reduction in drilling costs. The driver was therefore clear, namely that there is a need to design a SSfJ that will enable jack-ups to operate in deeper water without much increase in costs. Then, based on market information it was decided to consider a SSfJ that would add 30m of water depth capability to the GustoMSC CJ 70 jack-up type.

The main (technical) part of the thesis focused on identifying how the jack-up integrity will be influenced when it is placed on the SSfJ and what structural characteristics the SSfJ should have in order to enable a jack-up to survive on it through the harshest North Sea environmental conditions. The influence of the use of the SSfJ was assessed via reasonable assumptions that were then verified with analysis in the software SACS. The required structural characteristics of the SSfJ were identified as the SSfJ stiffness and rotational fixity at the SSfJ – jack-up interface. Recommended values for these characteristics were identified via an iterative procedure that includes a simplified dynamic analysis method that uses a Dynamic Amplification Factor. The results were then verified with a more accurate method that employs the time domain simulations in SACS.

The outcome of the research is that the jack-up integrity is not influenced negatively by the use of SSfJ and that if the SSfJ has the recommended structural characteristics then the jack-up can survive the harshest environmental conditions in the North Sea.

Acknowledgments

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Special thanks to Mr. Frank Koopman for introducing me to the idea of the Support Structure for Jack-ups and to Mr. Jan van der Graaf for inspiring me at the commercial aspect of the project.

I would like to express my appreciation to the members of the Graduation Committee for their guidance and support throughout this year.

Aristarchos Dimitriou
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Abbreviations

BS	Base Shear
DAF	Dynamic Amplification Factor
E&P	Exploration and Production
HMC	Heerema Marine Contractors
ISO	International Organization for Standardization
JONSWAP	Joint North Sea Wave Project
MODU	Mobile Offshore Drilling Unit
MPE	Ministry of Petroleum and Energy of Norway
NCS	Norwegian Continental Shelf
NOK	Norwegian Krone
NPD	Norwegian Petroleum Directorate
OTM	Overturning Moment
SDOF	Single Degree of Freedom
SSfJ	Support Structure for Jack-ups
SWL	Still Water Level
TU	Technical University
UC	Unity Check
UKCS	United Kingdom Continental Shelf
USD	United States of America Dollars
WD	Water Depth

1 Contents

1 Introduction

1.1 General Introduction

To provide a good start for every reader, experienced or not, this chapter will deal with introducing the research subject, explaining the setup of the report and giving a small presentation of Heerema Marine Contractors and jack-ups.

1.2 Problem Definition – Research background

Since 1954 the offshore industry has made use of hybrid self-elevating mobile structures called "jack-ups". So far jack-ups have successfully operated in depths of 80 to 100 m and some are capable of operating in water depths of up to 150 m. Initially concerning the water depth limitation, an idea is born within Heerema. This idea suggests that a base with the ability to support a jack-up rig could be devised, adding value to the jack-up as an offshore structure by increasing its operational depth capability. As discovered later on during the research apart from the water depth, soil and weather conditions often introduce challenges to the use of jack-ups. At that point it seemed that a support structure could possibly be the answer to various imperfections of jack-ups related for example to stability, integrity, reliability and water depth limitation. Such a support structure for jack-ups (also called SSfJ) that is possibly mobilized and demobilized by a crane vessel would let HMC offer its services to another part of the Oil and Gas industry, the Drilling and Workover sector.

1.3 Thesis Objective

The objective of this thesis is to determine whether a 3-legged North Sea drilling jack-up can survive on a SSfJ and to calculate the required structural characteristics of the SSfJ for enabling a jack-up to survive on it.

1.4 Research Structure and Report Setup

To achieve the thesis' objective a series of actions took place which is outlined in Figure 1:

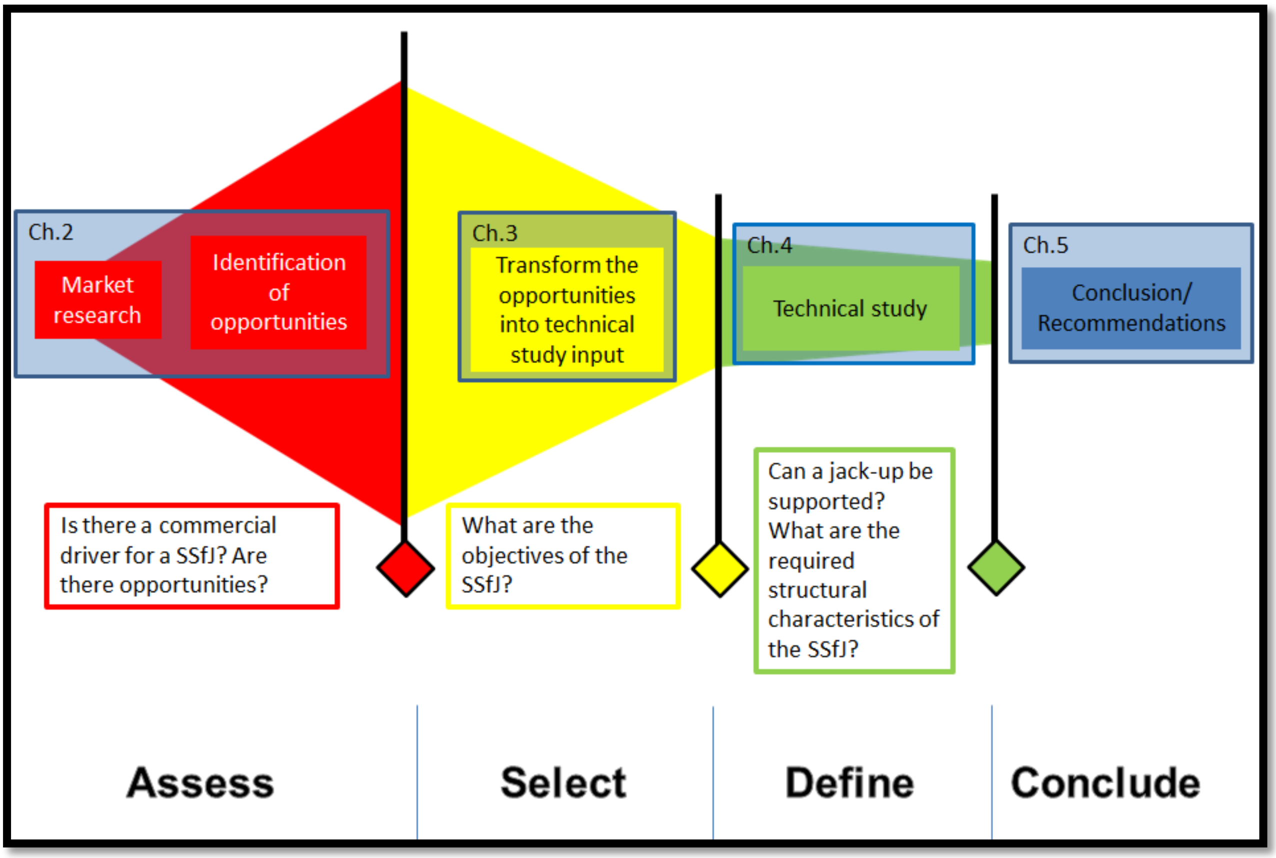

Figure 1 Research Procedure

The following procedure was devised. It was inspired by (University of Wisconsin Center for Cooperatives, 1998), (Hofstrand & Holz-Clause, 2009) and presentations held during the course of Survey of Offshore Engineering Projects of TU Delft in 2013. All the above sources refer to feasibility studies but it is considered that their principles can be applied in this research with some modifications.

A feasibility study, according to the aforementioned sources, should start with a market research in order to assess if there is need for a new product or service in the market. Then a technical study should be performed that will determine whether or not the product or service is technically feasible. The last part of a feasibility is usually the financial study which will determine if and when the suggested idea is likely to produce profit.

An adaptation of the above procedure led to the procedure that is followed in this thesis. This thesis focuses in the technical aspects of a SSfJ but first it investigates the market for the commercial driver for a SSfJ. The financial study that usually concludes a feasibility study is not included in the scope of this thesis.

The procedure followed in this thesis is adapted to the suggested research (Kite) model that was presented during the course of Survey of Offshore Engineering Projects of TU Delft in 2013.

According to this model at first the researcher has to “Assess” the opportunities of an idea (looking as wide as possible), then “Select” the most promising research direction (narrowing the scope), then “Define” the details and finally conclude and answer to the objective.

1.4.1 Chapter preview

A small description of the contents of each chapter follows:

1.4.1.1 Chapter 2 Market Research

This chapter aims to:

- Introduce the offshore drilling market and focus particularly in the North Sea jack-up drilling market, its characteristics and the main players active in it
- Provide information about the historical growth, the current status and the future trends in the North Sea jack-up drilling market in order to show if it is worth of investing in this market
- Process the trends and sense the needs of the market in order to address the commercial driver for the SSfJ concept

1.4.1.2 Chapter 3 Design Case Formulation

This chapter aims to:

- Define precisely the technical objective and requirements of the Support Structure for Jack-ups based on the conclusion of the market research
- Derive the technical research approach and scope (i.e. which part of the design/ calculations will be performed in this thesis), since a complete and detailed study is beyond the scope of a thesis project due to the limited amount of time and resources
- Form the input for the analysis, based on: a) the information collected through the market research, b) additional data that will be collected at this stage and c) some assumptions that will also be clarified in this chapter

1.4.1.3 Chapter 4 Technical Study

This chapter aims to focus on the most critical technical aspects of the concept and:

- Assess how the integrity of a jack-up will be affected when it is placed on an “ideal” support structure
- Locate the most critical technical aspect of the idea
- Provide specific technical recommendations regarding the structural characteristics that are required in order to overcome the most critical aspects
- Conclude on whether the most critical aspects can be treated and thus if a jack-up can survive on a SSfJ

1.4.1.4 Chapter 5 Conclusions and Recommendations

In this chapter the conclusion of the thesis is presented and an answer is provided with respect to the thesis objective. Also the necessary recommendations for further research are provided.

1.5 Introduction to HMC and jack-ups

1.5.1 Heerema Marine Contractors

Before an introduction to HMC is given, it is useful to provide the definition of the word contractor (from the Oxford Dictionary (Oxford, 2014)):

Contractor : "A person or firm that undertakes a contract to provide materials or labour to perform a service or do a job"

According to the official site of HMC (hmc.heerema.com, 2014):
"Heerema Marine Contractors (HMC) is a world leading marine contractor in the international offshore oil and gas industry. HMC excels at transporting, installing and removing offshore facilities. These include fixed and floating structures, subsea pipelines and infrastructures in shallow waters, deep and ultra-deep waters.

HMC manages the entire supply chain of offshore construction, from design through to completion. Headquartered in Leiden, our services encompass engineering, planning, logistics, project management and execution of projects all over the world."

1.5.2 The Jack-up Structure

For a good introduction to the jack-up structure one should refer to (DNV, 1995):

"*The term 'Jack-up' covers a large variety of offshore structures from small liftboat structures,[] to large deepwater designs[]. The purpose of the jack-up design is to provide a mobile, self-installing, stable working platform at an offshore (or off-land) location. The jack-up platform itself may be designed to serve any function such as, for example; tender assist, accommodation, drilling of production."*

In this thesis only three legged drilling jack-ups (Figure 2) are taken into consideration and according to (Bennet & Associates L.L.C., 2005):

"A Jack-up is an offshore structure composed of a hull, legs and a lifting system that allows it to be towed to a site, lower its legs into the seabed and elevate its hull to provide a stable work deck capable of withstanding the environmental loads. A typical modern drilling Jack Up is capable of working in harsh environments (Wave Heights up to 25m, Wind Speeds in excess of 185km/h) in water depths up to 150m. Because Jack-ups are supported by the seabed, they are preloaded when they first arrive at a site to simulate the maximum expected leg loads and ensure that, after they are Jacked to full airgap and experience operating and environmental loads, the supporting soil will provide a reliable foundation."

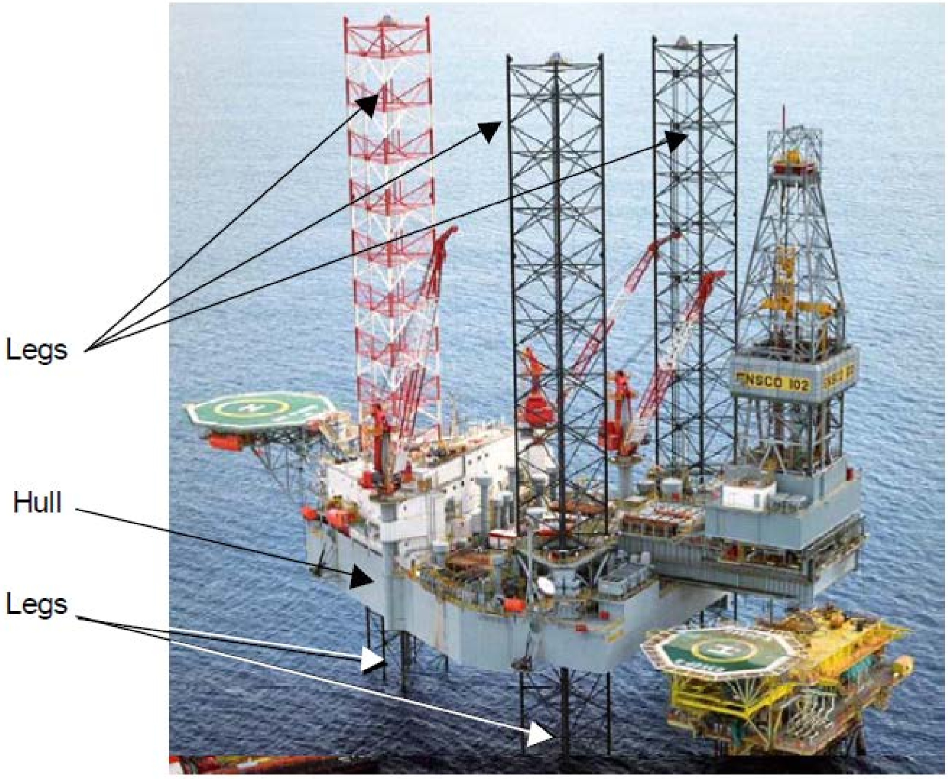

Figure 2 Jack-up's main parts

2 Market Research

2.1 Introduction

The market research is the first and fundamental step in the procedure of this thesis as shown in Figure 3:

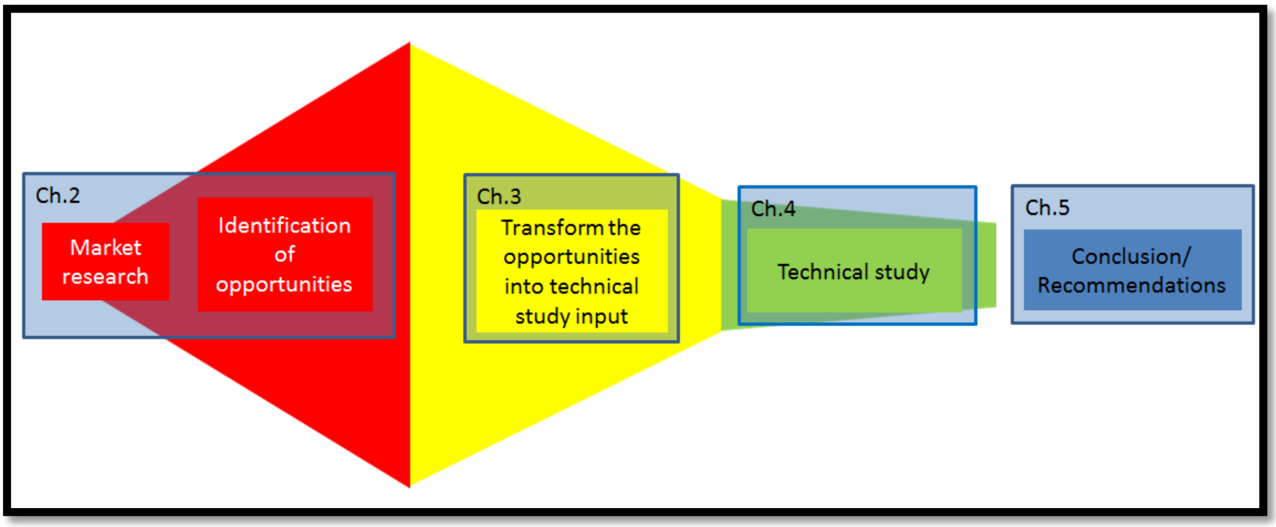

Figure 3 Thesis procedure

It is very important to get a clear view on the market in order to be able to substantiate whether there are opportunities for a Support Structure for Jack-ups (a.k.a. SSfJ).

This chapter aims to:

- Introduce the offshore drilling market and focus particularly in the North Sea jack-up drilling market, its characteristics and the main players
- Provide information about the historical growth, the current status and the future trends in the North Sea jack-up drilling market in order to show if it is worth of investing in this market
- Process the trends and sense the needs of the market in order to address the commercial driver for the SSfJ concept

1.5.3 Definition of the term “market”

Before explaining what the Offshore Drilling market is, it is useful to explain what in general the term market means. This term has many interpretations but the one that is interesting for this research is the following:

“A market is an area or arena in which commercial dealings are conducted” (Oxford University, 2014)

The market can be a fictitious place. The commercial dealings take place between companies that buy or rent and companies that offer services or goods. It is not necessary that the companies that offer are also those that produce, as in many cases goods or services are put in the market by intermediaries.

The companies that acquire services or goods are motivated by their specific related needs and usually they aim to negotiate for higher value with less cost. The companies that offer services or goods are usually motivated by the need of making profit. Therefore the two different forces that shape each market are: the demand and the supply. The balance of these forces is determining the price that the buyer has to pay to the supplier.

Since products and services are offered in many parts of the world, there are several markets where a kind of goods or services is traded. Those markets can function very differently and can have different balance of supply and demand forces. Moreover even in a single market the conditions can change with the course of time for reasons related to suppliers’ and customers’ characteristics, strategy, number, technology but also due to factors irrelevant to the members of the market such as political instabilities, natural disasters etc.

1.5.4 Introduction to the offshore drilling market

As explained in the previous paragraph every market is characterized by the forces of supply and demand. This is the case for the offshore drilling market too. To explain what the offshore drilling market is, one should therefore initially explain which companies take up the roles of suppliers and customers and what are the products or services offered. Since the offshore drilling market is related to the upstream petroleum industry, it is helpful to give a small introduction to this industry.

Upstream Industry as part of the Oil & Gas Industry
This is one of the three major sectors of the oil and gas industry. The other sectors are midstream and downstream. Hydrocarbons are explored and produced in the upstream sector, transported as crude or refined petroleum products in the midstream sector and finally reach consumers in the form of fuel and other petrochemical products via the downstream sector. The upstream sector is also known as the Exploration and Production sector (Trend Capital Limited, 2013). This sector includes the searching for oil and gas fields and the drilling of wells to produce the raw forms of oil and gas, crude oil and natural gas respectively.

2.1.1.1 Services traded

The offshore drilling market is closely related to the upstream industry as the main commodity traded in this market is the contracts for drilling, completion or workover of offshore wells.

Usually exploration or appraisal wells are drilled by ocean-going vessels known as Mobile Offshore Drilling Units (MODUs). There are two classes of MODUs, the bottom supported and the floating rigs.

The bottom supported class includes barges, submersibles and jack-ups while the floating class includes semisubmersibles and drillships. The majority of the modern offshore fleet comprises of Jack-ups, drillships and semisubmersibles (Kaiser, et al., 2013).

Contracts Dayrate vs. Turnkey

Drilling contracts may be on either a “dayrate” or “turnkey” basis. Under dayrate contracts, the contractor receives a fixed amount per day for drilling the well with higher rates while the unit is operating and lower rates or a lump sum payment for periods of mobilization or when operations are interrupted or restricted by equipment breakdowns, adverse weather conditions or other factors. The E&P company (see 2.1.2.2 for definition of E&P) bears all of the ancillary costs of constructing the well and supporting drilling operations and carries the risk for the overall success of the operation.

In a turnkey drilled well, the E&P company defines the well specifications (e.g. total depth and target, minimum hole size at total depth, formation evaluation requirements) and retains a turnkey company to plan and supervise the well on a lump-sum basis.

The turnkey company subsequently retains a contractor under a dayrate contract. The turnkey company, not the drilling contractor, holds all of the risk of cost overruns. Turnkey contracts are relatively rare and are used primarily for exploration drilling by jackups when the E&P company is a small firm with limited financial and technical expertise.

Source: (Kaiser, et al., 2013)

2.1.1.2 Main Parties

The rigs mentioned in the previous paragraph are owned by companies called drilling contractors. These companies play the role of supplier in the Offshore Drilling Market.

The services of the drilling contractors are covering the drilling, completion and workover related needs of the Exploration and Production firms. The E&P firms deal with the planning, management and control of all the activities (usually performed by contractors) that are needed to locate and extract the hydrocarbons from their initial position. Part of their activities is also getting in touch with governments to obtain rights on territories that may contain resource deposits. In many occasions the E&P firms are (parts of) the big oil companies. It is obvious that the E&P firms are the buyers in the Offshore Drilling Market.

2.1.1.3 Other parties

So far the main players of the Offshore Drilling Market are addressed. Apart from those players other types of companies are also present in this market. For instance companies that supply project management or technical expertise and aim in assisting E&P Firms or drilling contractors to extract hydrocarbons more effectively. There are also companies that build or maintain rigs or equipment. Another type of companies involved in the offshore drilling market supplies seismic imaging services used to locate the hydrocarbons' formations. Last but not least the offshore drilling industry makes use of the services such as transportation of rigs and equipment, design and fabrication of equipment and supplies etc. offered by various other companies.

Apart from companies, governments play an important role in this market. First of all they are representing the states that possess the national resources that E&P look for. It is the governments that define which parts of their national waters will be available for survey and development and this is always in accordance with the states’ strategy and planning. Governments are also involved in the forming of the regulations that should be followed by any party operating within their states' territory.

A sketch of the main and other players in the drilling market is presented in Figure 4

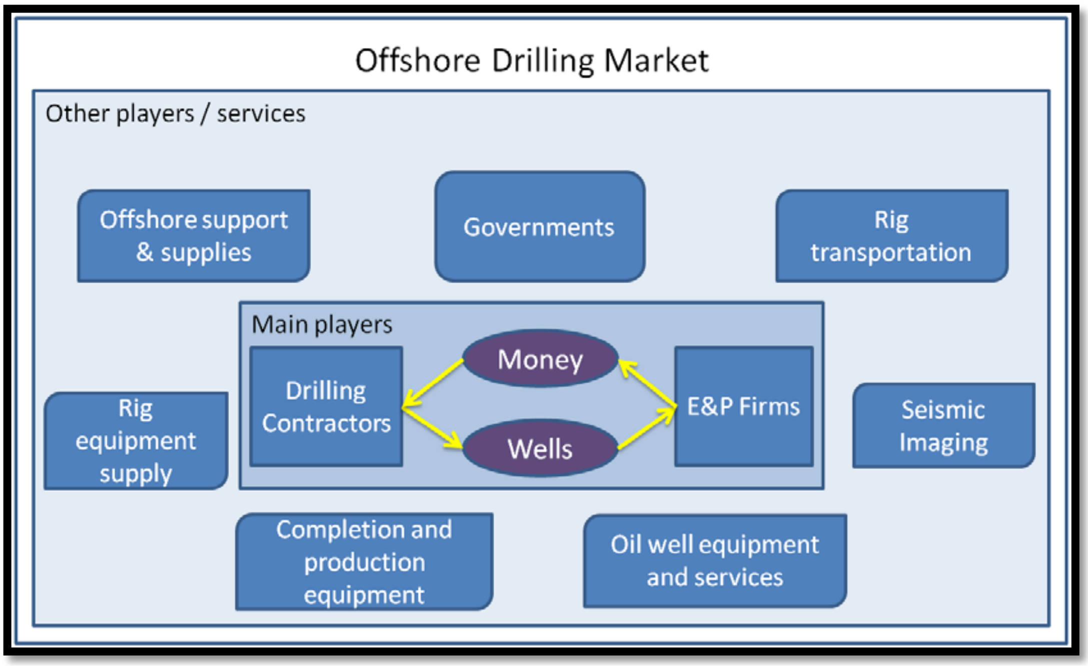

Figure 4 Offshore Drilling Market Sketch

2.2 North Sea jack-up drilling Market

1.5.5 Region characteristics

North Sea is one of the markets that host deep water and high spec jack-ups (Kaiser, et al., 2013). The reason for this is not only the water depth but also the weather conditions which in many cases include harsh storms.

The North Sea jack-up market is categorized by two distinct areas, the Southern and the Northern according to (International Association of Drilling Contractors, 2004)[1]. The southern area has shallower water (generally around 60 m) and generally does not require large heavy duty harsh environment jack-ups. The central area has water depth of up to 90 m. In some specific cases though, heavy duty jack-ups are contracted in the southern area, for instance when soil conditions or platform rig configurations make it hard for regular Southern North Sea jack-ups to drill. It must be noted that this paragraph refers only to the parts of the North Sea where jack-up activities take place and therefore the parts of North Sea that have water depths of up to 700m are excluded here, since they are irrelevant with this research project.

2.2.1.1 Dependence on oil prices

A big risk in offshore drilling industry, that influences also the jack-up drilling market, is derived by the fact that the suppliers depend a lot on the customers' budgets and the highly sensitive commodity prices. When lower energy prices are expected, the E&P firms reduce their drilling budgets, thus drill less wells. This is presented very well in Figure 5 for the Norwegian continental

[1] Other sources divide the North Sea in three parts, namely Northern, Central and Southern.

shelf, where the drop in oil price is followed by a decrease in exploration wells and in the number of players on the shelf. The decrease in the number of exploration wells leads to a drop in the demand for rigs and therefore in a drop in dayrates and utilization rates. When in 2011 the oil price increased rapidly the utilization also increased the following year (2012). In other words, when the oil price drops, some fields are no longer profitable since the overall field development cost will be bigger than the value of the resources. On the other hand when the oil prices are high, even small fields can have enough value so that there are worth of being developed.

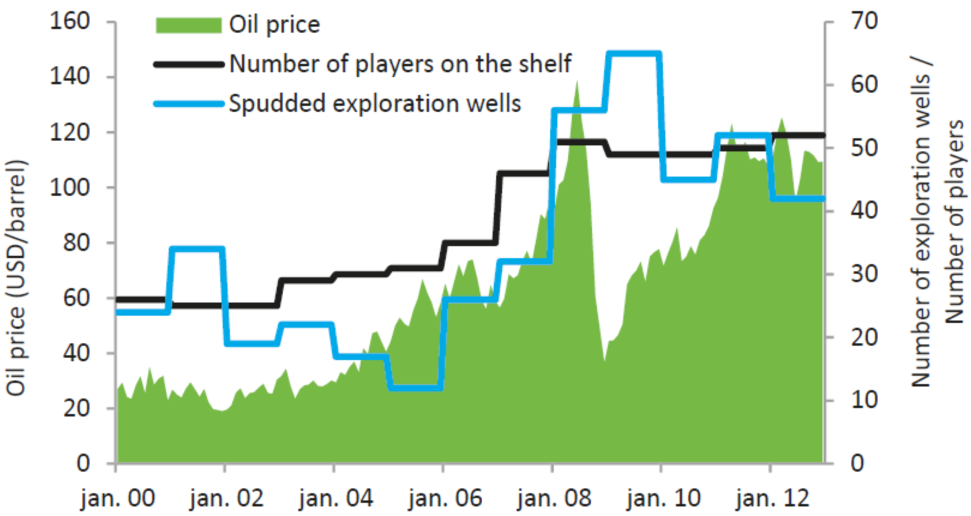

Figure 5 Oil price - Number of players and exploration wells relationship in the NCS (Norwegian Petroleum Directorate, 2013)

1.5.6 Players

2.2.1.2 Suppliers

The main drilling contractors operated 39 jack-ups in the north sea by 11-03-2014 according to Rigzone.com. Those contractors were: ENSCO, Maersk, Noble, Rowan and Transocean. All these contractors had at least 4 drilling jack-ups active in this region at that time. There were also 5 other companies that operated 8 rigs in total.

2.2.1.3 Customers

The main E&P companies that use the services of jack-ups in the North Sea are (Offshore Media Group AS, 2014):

- Total, Conoco, Centrica, Statoil for UK and Norway and
- Maersk Oil, Wintershall in the rest of North Sea

2.2.1.4 Other parties

2.2.1.4.1 UK and Norwegian Governments

These parties are involved in the market by taking the role of regulator and in general by representing the two states.

Part of the UK government is the Department of Energy and Climate Change which is among others responsible for “secure, clean and affordable energy supply” in the country (Government Digital Service, 2014). This department is monitoring the offshore oil and gas industry within the country’s borders, expresses the government policy related to energy in general and arranges the government and industry strategy for the upstream oil and gas sector.

Similarly in Norway there are two main government bodies related to offshore oil and gas industry. The first is the Ministry of Petroleum and Energy and the second is the Petroleum Directorate. The Ministry of Petroleum and Energy is responsible “to achieve a coordinated and integrated energy policy.” (Norwegian Ministry of Petroleum and Energy, 2014). The Norwegian petroleum directorate reports to the ministry of petroleum and energy and has as objective to “contribute to creating the greatest possible values for society from the oil and gas activities by means of prudent resource management based on safety, emergency preparedness and safeguarding of the external environment” (Norwegian Petroleum Directorate, 2011). In practice The NPD advises the MPE and sets frameworks, stipulates regulations and makes decisions related to the petroleum industry in Norway.

2.2.1.4.2 Jack-up Designers and manufacturers

There are several companies active in the sector of designing jack-ups. The principal are: Friede and Goldman, LeTourneau, Gusto MSC, Baker Marine and Keppel (Kaiser, et al., 2013).

The main jack-up manufacturers are : Keppel (Singapore), Sembcorp (Singapore), Cosco/Dalian (China), Lamprell (UAE), AmFELS (USA) and LeTourneau (USA). An interesting fact is that more than 50% of jack-up construction in 2012 took place in Singapore and another 25% took place in China (Kaiser, et al., 2013).

1.5.7 Current status and forecast

According to (Kaiser, et al., 2013) the North Sea jack-up market value (number of rigs * average dayrate) was in 2010 equal to $1.865 billion while the Investment of E&P firms in contract drilling services in the same year were equal to $8.3 billion.

The number of rigs (jack-ups and floating MODUs) has declined over the past decade and until 2011 as shown in Figure 6.

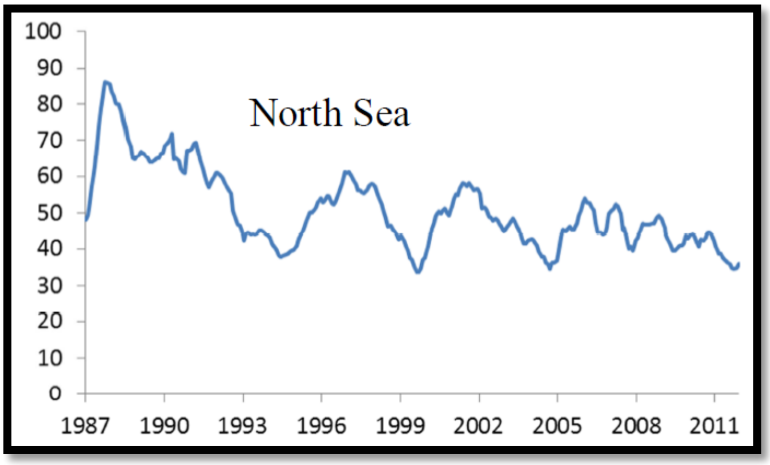

Figure 6 Number of active rigs in years in North Sea (Kaiser, et al., 2013)

However lately the dayrates and the utilization of high spec jack-ups are rising as seen in Figure 7. This increase in operating cost (that must be paid by the E&P firms), caused by the limited number of available rigs, is one reason for the **decrease in exploration drilling activity** during 2013 according to (OGJ Editors, 2014). The same source foresees a longer-term decline in exploration and appraisal drilling in the UKCS based on announcements of key player companies of the UK sector that they no longer focus on investing in North Sea (see also UK Continental Shelf Status and forecast)

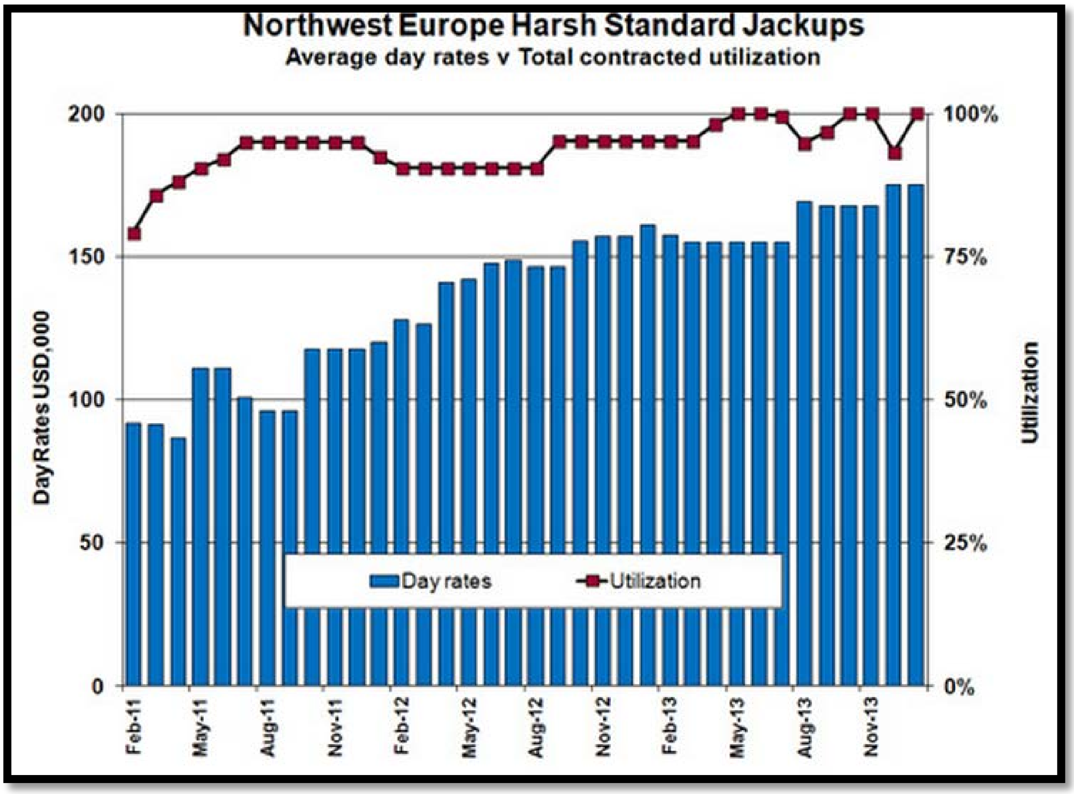

Figure 7 Latest NS Harsh Standard Jack-ups Dayrates (IHS, 2014)

2.2.1.5 Dayrate Difference between UKCS and NCS

It is interesting at this point to note that dayrates in the UKCS are generally lower than dayrates in the NCS. This is presented in Figure 8 where actual dayrates of jack-ups currently working in the

North Sea are plotted with respect to water depth specification. There are several explanations for the great differences in dayrates.

One reason for this could be the harsher conditions that jack-ups need to withstand in the NCS, thus newer and more capable rigs are suited for there, compared to other parts of North Sea. These newer and more developed rigs have bigger construction costs (see next paragraph) and thus drilling contractors ask for higher dayrates in order to have a reasonable payback period. Older rigs in other regions cost one third compared to the most modern rigs which operate in Norway. Related to this, the quality of the equipment and its work capacity and efficiency also play a role and oil companies prefer newer rigs that offer increased efficiency and also safety (Cramon, et al., 2014).

Also according to (Offshore Media Group AS, 2011) there is a surplus of jack-ups in other regions, whilst the Norwegian market is tight. As a remark, only 9 of the 200 recent built jack-ups can work in the NCS (Stoichevski, 2012).

Moreover the approval costs are higher in Norway and this has impacts on the dayrate. Sometimes existing rigs need to be modified in order to get the permission to work in Norwegian waters and this procedure can cost millions to the contractors, thus leading to increase in dayrates (Stoichevski, 2012).

Operational costs also play a role and it is known that wages and in general labor costs are higher in Norway than in the rest of the countries around North Sea. The reason for this is most likely the fact that offshore employees in Norway work 2 weeks offshore and then get 4 weeks of leave while in the UK the distribution of work and leave is 2 weeks on-2 weeks off (Parkes, 2012). This means that for one post 2 men are needed in the UKCS and 3 men are needed in the NCS throughout the projects. Thus the labor cost is at least 50% higher in NCS than in UKCS. Other operational costs are related to travel, catering repair and maintenance and freight. According to (Ralls, 2012) the operational costs are around $70-80 thousand/day in UKCS and $130-140 thousand/day in NCS.

These could be the reasons why in one case the same rig (Rowan Stavanger) moves from a site in the UKCS to a place in the NCS and its dayrate changes from $245000 to $413000 (Rowan Companies Plc, 2013).

At an early stage of the idea of the SSfJ, it was considered worth of looking for an opportunity to create a SSfJ that could enable a small jack-up with a small dayrate to operate in the NCS and make profit from the difference in dayrates. Based on the outcome of the dayrates research presented in this chapter this idea is considered poor opportunity.

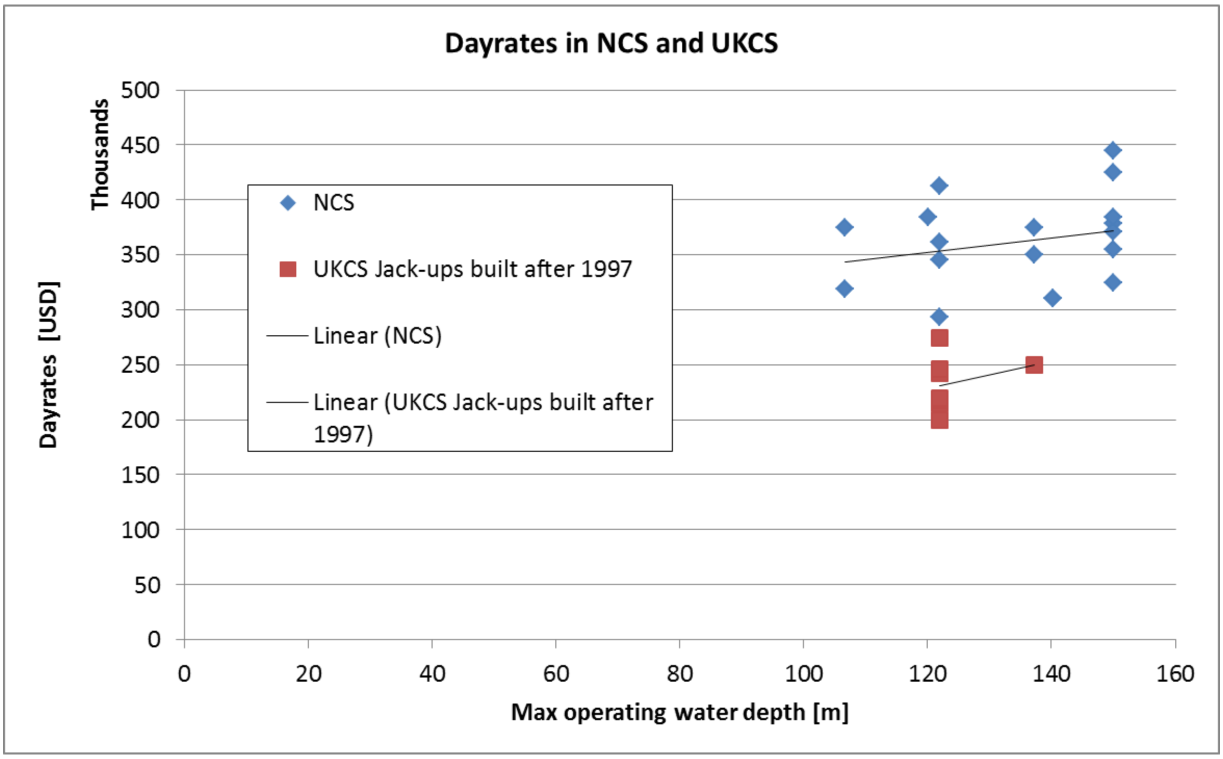

Figure 8 Dayrates per water depth comparison between UKCS and NCS (processed data from: (Offshore Media Group AS, 2014) and (A.P. MOLLER - MAERSK GROUP, 2014))

2.2.1.6 North Sea Jack-up rig construction costs

At this point it is interesting to note the difference in the construction costs for various jack-up types. Of course the construction cost depends on the balance of the demand and supply forces in the jack-up construction market. According to (Kaiser, et al., 2013) the demand for new jack-ups depends on various factors such as: Oil prices, utilization and dayrates, technology development, new hydrocarbon discoveries, fleet age and construction cost. These factors will not be explained further here, instead, a comparison in construction cost for various jack-ups delivered after 1992 for the North Sea is illustrated in Table 1.

Table 1 Jack-up Construction cost for North Sea jack-ups delivered after 1990

Model	Cost [million USD]	Water depth rating [m]	Year of Order	Source #
KFELS MOD V-A*	179	122	2000	(Maritime Activity Reports, Inc., 2000)
MSC CJ46	180	114	2013	(Cavendish Group, 2013)
MSC CJ 50	218	122	2013	(Offshore Energy Today, 2013)
MSC CJ62*	237	130	1992	(Oilpro, 2014)
Friede & Goldman JU2000E	250	122	2013	(Offshore Energy Today, 2013)
MLT Super Gorilla 219-C*	289	122	1996	(International Association of Drilling Contractors, 2002)
KFELS Class N	392	122	2007	(Keppel Corporation Communications, 2007)
MSC CJ70	650	150	2012	(International Associaction of Drilling Contractors, 2012)
MSC CJ80	730	175	2014	(Rigzone.com, Inc., 2014)

*The construction costs for jack-up ordered up to 2000 is adapted in order to include inflation up to 2014

What must be noted, is the significant increase in construction costs for the “tallest” jack-ups of Table 1. To illustrate this in a clearer way a plot of water depth rating versus construction cost for the rigs of Table 1 is presented in Figure 9

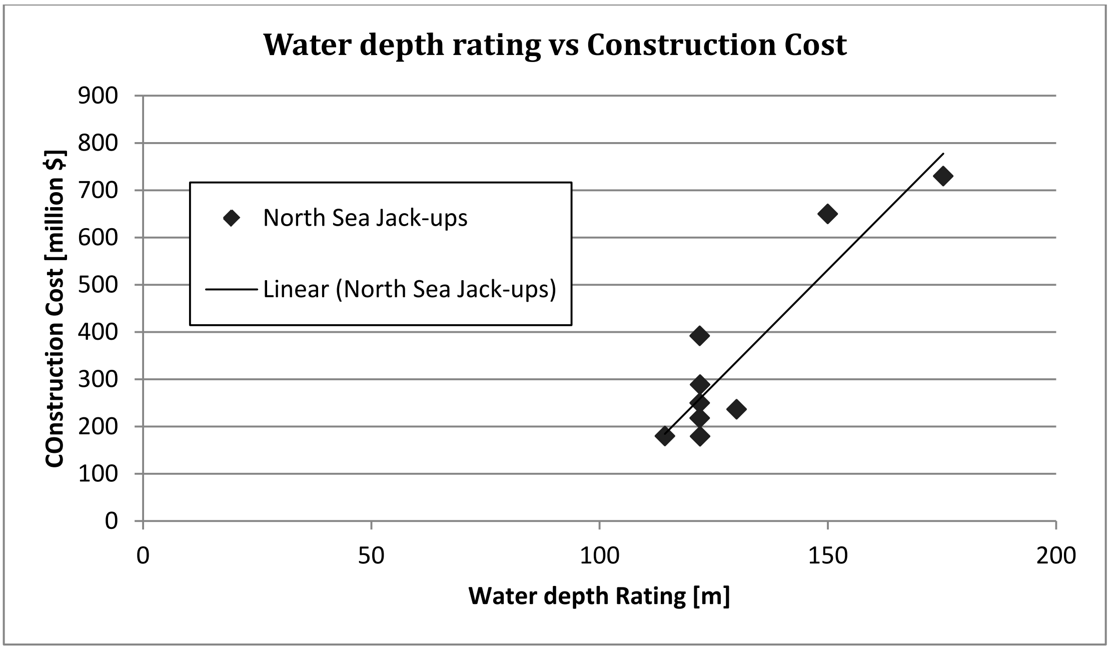

Figure 9 Water Depth Rating vs Construction cost for jack-ups in the North Sea

This significant difference in construction costs with a small increase in water depth rating can be an **opportunity** for the SSfJ concept, provided that the increase in construction cost is only related to the increase in water depth related parts of the jack-ups rather than on any other capabilities' increase (such as drilling capacity, installed power, material storage capacity etc.). In fact, at a later stage during this thesis a meeting took place with representatives of jack-up designers and they expressed the opinion that the increase in construction cost with the increase in water depth is mostly caused by the increased use of steel for the legs and the hull for the construction of jack-ups for deep water. Further technical and economical study shall be done in order to verify if a support structure for jack-ups can "bridge the gap" in water depth without requiring such a big investment. However this financial study is beyond the scope of this thesis and therefore it is a recommendation for further research at a later stage in case the concept of the SSfJ proceeds to the next phase.

2.2.1.7 UK Continental Shelf Status and forecast

In the UK, during 2013 the capital investment in the offshore oil and gas industry was almost $23 billion (£ 14.4 billion) but **it is expected to halve** by 2016-17, according to (Maslin, 2014). According to (Oil & Gas UK, 2014) exploration in UKCS is facing its biggest challenge in 50 years and the last three years saw the lowest rate of exploration activity history (Figure 10). The expenditure on E&A activity was $2.8 billion (£1.6 billion). This downward trend continues since 2009 (caused by the financial crisis) and in 2011 it was related to the increase in the Supplementary Charge rate. However the Development wells are stable in number for the last 4 years.

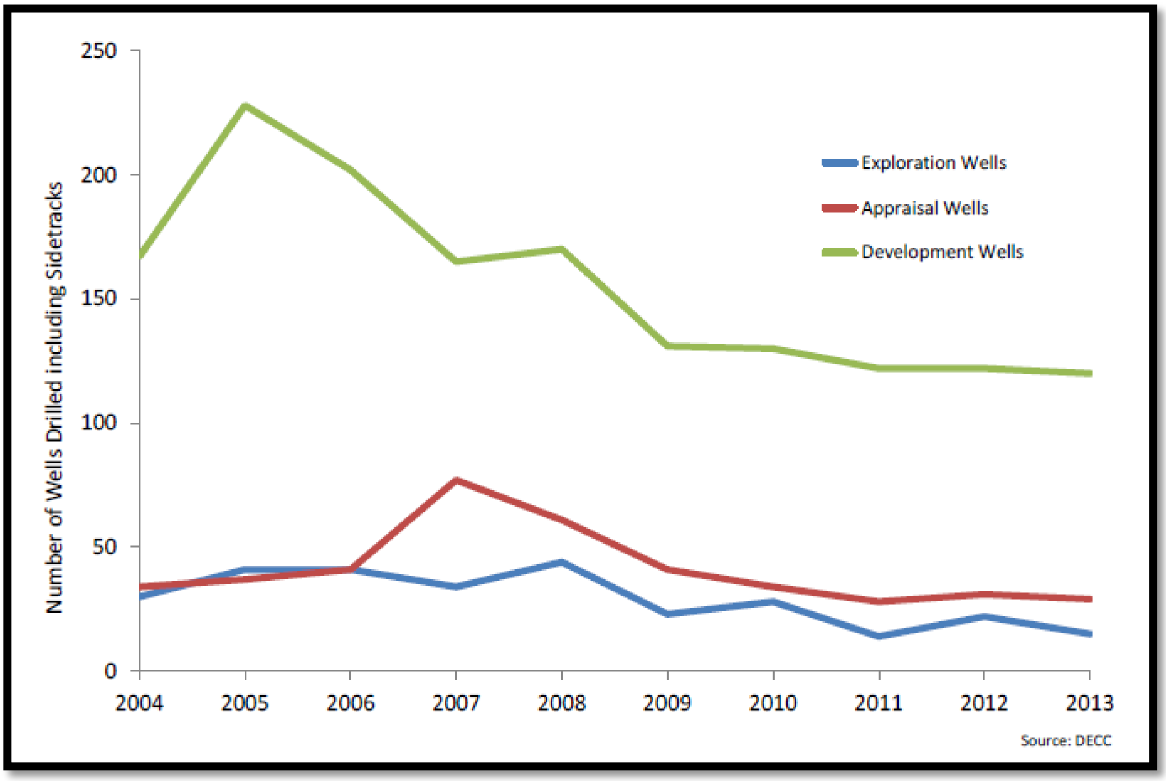

Figure 10 Drilling activity on the UKCS (Oil & Gas UK, 2014)

It is interesting to mention the constraints on exploration and appraisal drilling according to Oil &Gas UK (Figure 11). Drilling rig availability is the most important reason for postponing the drilling of the wells with lack of access to funding following, according to the same source.

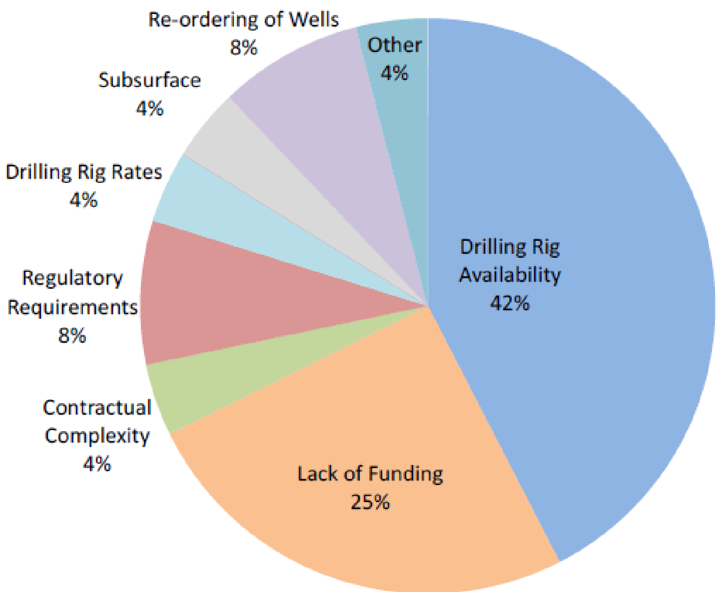

Figure 11 Constraints on Exploration and Appraisal Drilling in 2013 (Oil & Gas UK, 2014)

When it comes to forecast the future of the UKCS, Oil &Gas UK sees that the likelihood of drilling the planned wells of the next years depends on the abilities of the E&P firms to overcome the constraints that appeared in recent years. In Figure 12 the expected number of wells to be drilled in the near future in the UKCS is presented, and seems to be less than the recent past years.

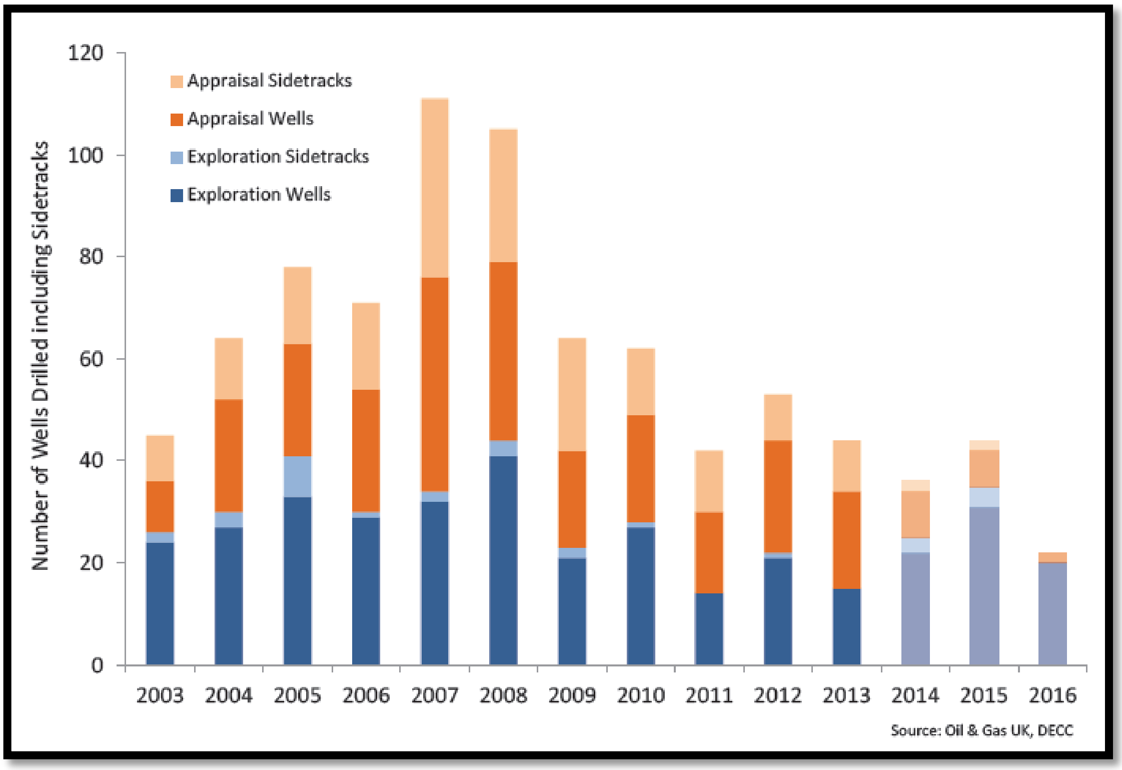

Figure 12 Exploration and Appraisal Forecast in the UKCS (Oil & Gas UK, 2014)

2.2.1.7.1 Jack-ups in the UKCS

As for the rig distribution it is interesting to mention that the number of MODUs in the UKCS during 2013 was at its highest since 2008 with 20 jack-ups and 19 semisubmersibles active in the region (Figure 13).

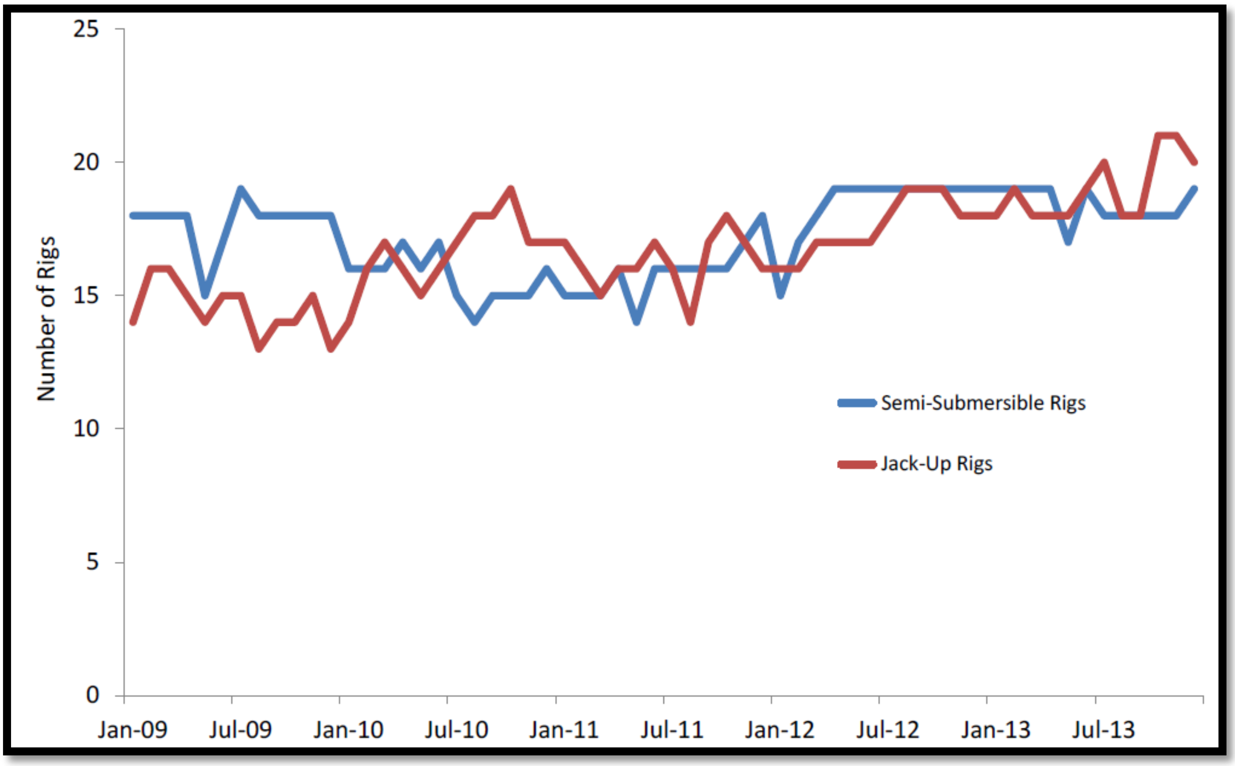

Figure 13 Number of active Rigs in the UKCS (Oil & Gas UK, 2014)

The increased rig demand combined with the stable number of rigs lead to increased dayrates. This is depicted in Figure 14. The increase in dayrates leads to the increase in E&A costs and is adding up to the effect of decrease in E&P activity. To make matters worse according to (Oil & Gas UK, 2014) the average time to drill a typical well on the UKCS has increased by 17 days over the last five years thus explaining the shortage of rigs while the E&P activity is decreasing. To make it simpler, this means that jack-ups need to stay longer in a site in order to finish the job and therefore there is a shortage in jack-ups for new sites, given that the jack-up population remains stable or increases slowly.

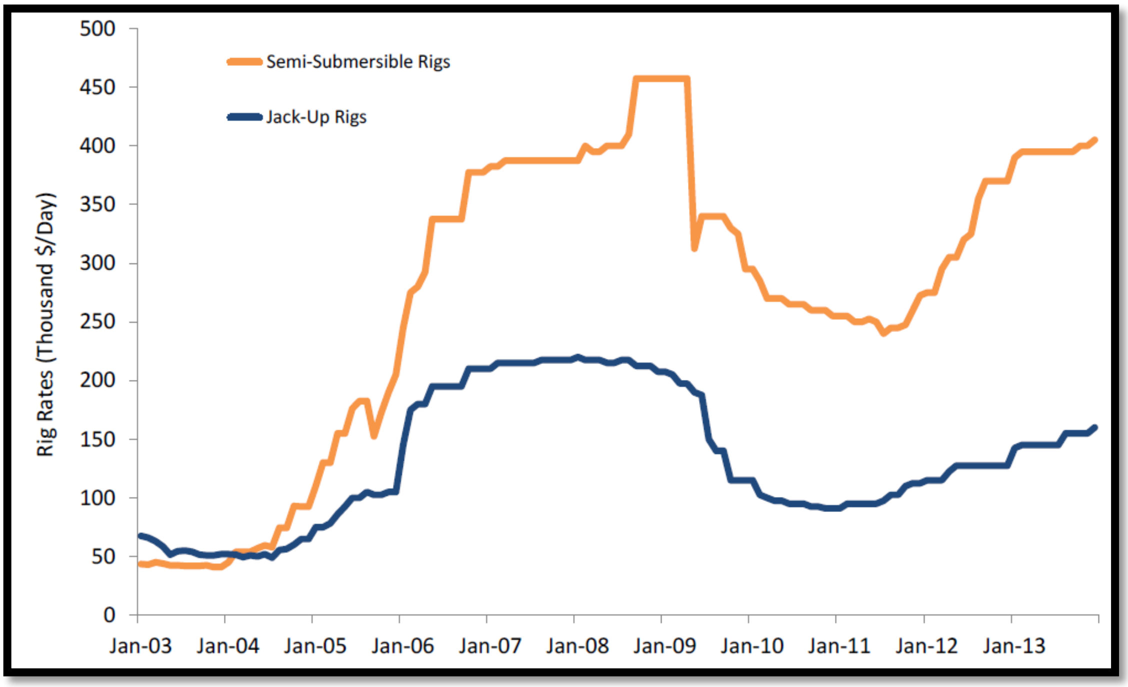

Figure 14 Jack-up and Semisubmersible dayrates in the UKCS (Oil & Gas UK, 2014)

The jack-ups that are currently operating in the UKCS are presented in Table 2. It can be seen in Table 2 that the older rigs are also those with low water depth rating and dayrates. Another interesting fact is the variety of designs, as there are no more than 3 rigs per design. Moreover, it must be mentioned that there is one rig under construction for the UKCS (Statoil Cat J 1) (Offshore Media Group AS, 2014).

Table 2 Jack-ups operating in UKCS (Offshore Media Group AS, 2014)

Name	Vessel design	Max Water Depth [m]	Construction year	Dayrate [USD]
Ensco 80	MLT Class-116-CE	69	1978	130000
Ensco 70	Hitachi K1032N	76	1981	140000
Noble J. Robertson	Baker Marine Europe Class MOD	88	1981	150000
Ensco 100	MLT 150-88-C "Gorilla" Class	100	1987	Private
Maersk Resilient	MSC CJ50-X100 MC	106	2008	Private
GSF Monarch	Friede & Goldman L780 Mod V	110	1986	160000
GSF Galaxy I	Friede & Goldman L780 Mod VI	120	1991	Private
Ensco 102	KFELS MOD V-A	122	2002	200000
Ensco 101	KFELS MOD V-A	122	2000	215000
GSF Galaxy II	Friede & Goldman L780 Mod VI	122	1998	218000
GSF Galaxy III	KFELS Mod. VI Universe Class	122	1999	220000
Noble Hans Deul	Friede & Goldman JU2000E	122	2009	242500
Rowan Viking	KFELS Class N	122	2010	246000
Rowan Gorilla V	MLT Super Gorilla 219-C	122	1998	274000
Rowan Gorilla VII	MLT Super Gorilla 219-C	137	2001	250000

2.2.1.8 Norwegian Continental Shelf Status

The investment in exploration on the Norwegian Continental Shelf during the latest years as well as a forecast for the next five years according to (Norwegian Petroleum Directorate, 2014) is presented in Figure 15. A stable trend is depicted in this figure for the last five years with an exceptional investment during 2013. This trend is expected to continue in the same way in the upcoming years. So far around 33 billion NOK ($5.5 billion) are invested only in exploration activities every year.

In Figure 16 the number of exploration (wildcat) and appraisal wells per year in the NCS is presented. Even though a negative trend is visible from 1997 until 2004, since 2005 the situation was overturned and it reached a peak in 2009. During the past 4 years a negative trend appeared again but 2013 was a very productive year in terms of exploration and appraisal wells. The forecast for 2014 is showing slightly less wells compared to 2013 but still more than the previous 4 years.

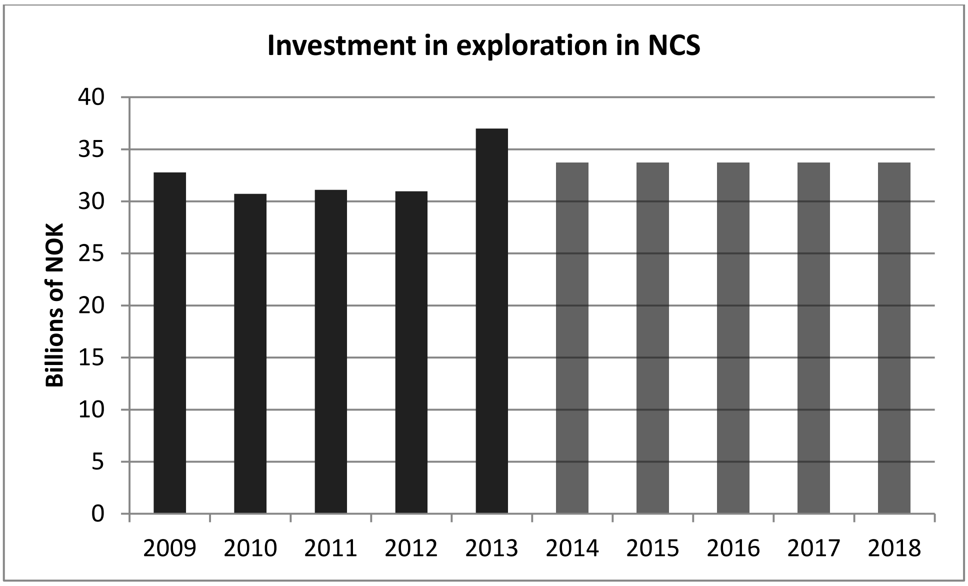

Figure 15 Investment in Exploration in the NCS (Norwegian Petroleum Directorate, 2014)

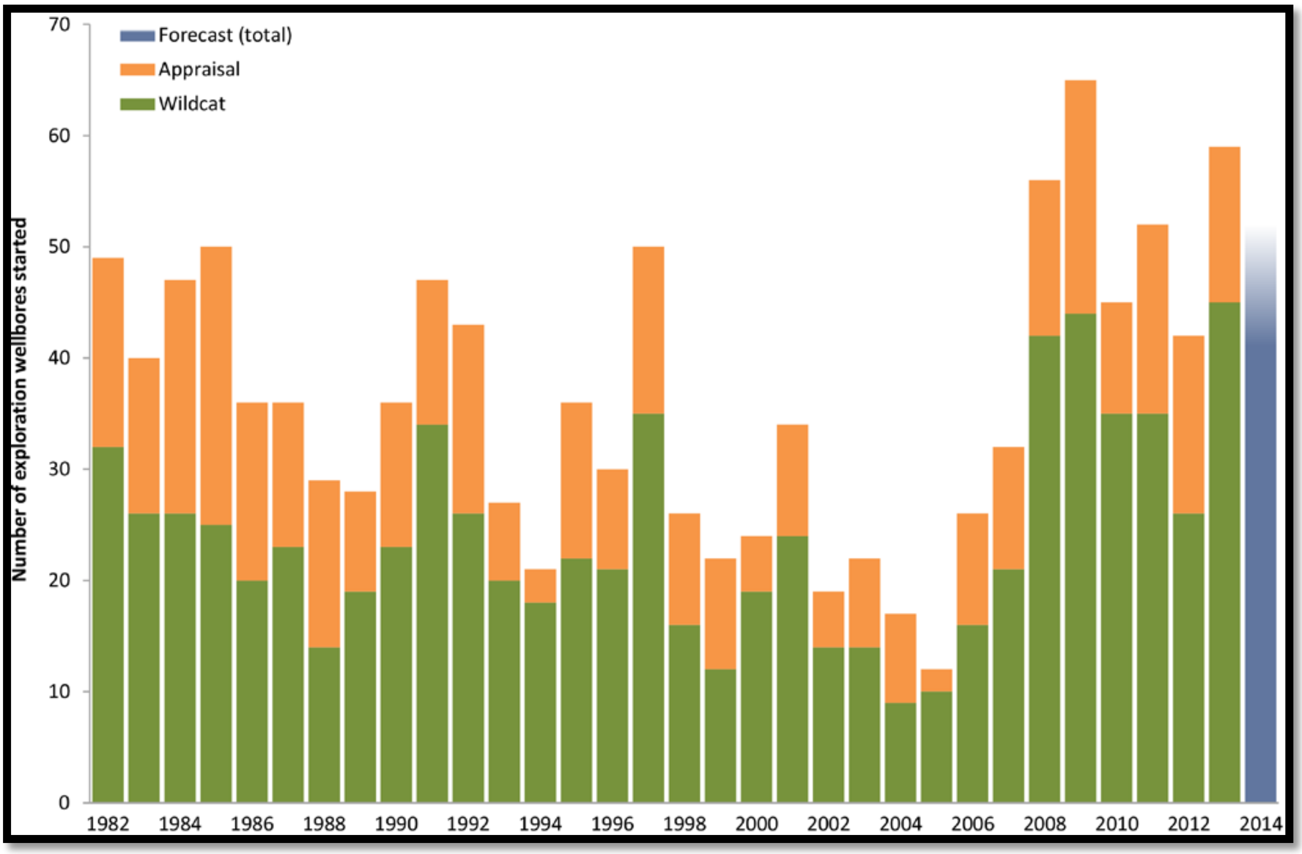

Figure 16 Exploration wells started per year (Norwegian Petroleum Directorate, 2014)

When it comes to development wells, a negative trend is observed during the last five years for the wells that are drilled from permanently placed facilities but what seems more interesting for this research project is that the number of wells drilled from MODUs is showing a positive trend (Figure 17). This is important because it could possibly lead to increase in the number of development wells drilled by jack-ups, which means more demand for this kind of rigs.

Trying to explain this fact, one could say that as the big, already developed oil fields turn to be mature and to produce less, other smaller fields need to be developed. The smaller fields are developed using subsea facilities that have wells usually drilled from MODUs. Those subsea facilities are connected (tied) to the big permanent offshore facilities of the already mature and big fields. Those permanent facilities have spare capacity due to decrease in production as a result of depletion of the reserves in the course of time. Moreover the depletion of mature and big oil fields could be the cause of decrease in the number of development wells drilled from permanent placed drilling facilities (those mounted on the permanent offshore structures).

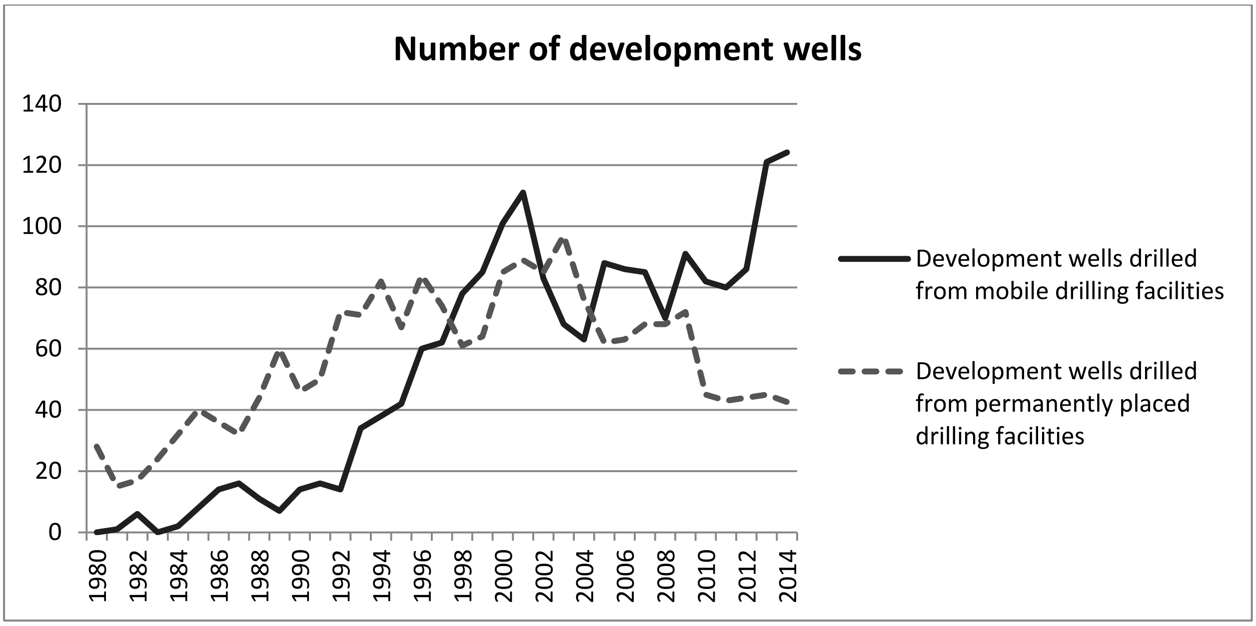

Figure 17 Development wells in NCS (Norwegian Petroleum Directorate, 2014)

2.2.1.8.1 Jack-ups in the NCS

Right now there are 8 jack-ups active in the NCS. All these rigs are rated >100m and some of them are capable of working in water depths of 150m (Offshore Media Group AS, 2014). It is interesting to note that these rigs belong to 2 drilling contractors: Maersk Drilling and Seadrill. The need for jack-ups in the NCS during the past 14 years is presented in Figure 18. During this period the utilization was constantly equal to 100%. This verifies the above statement that the Norwegian jack-up market is tight (see 2.2.3.1).

The condition of the NCS jack-up market can be described by the (ultra-harsh) jack-ups dayrates as seen in Figure 19. An increasingly positive trend is depicted in this graph from 2000 to 2012.

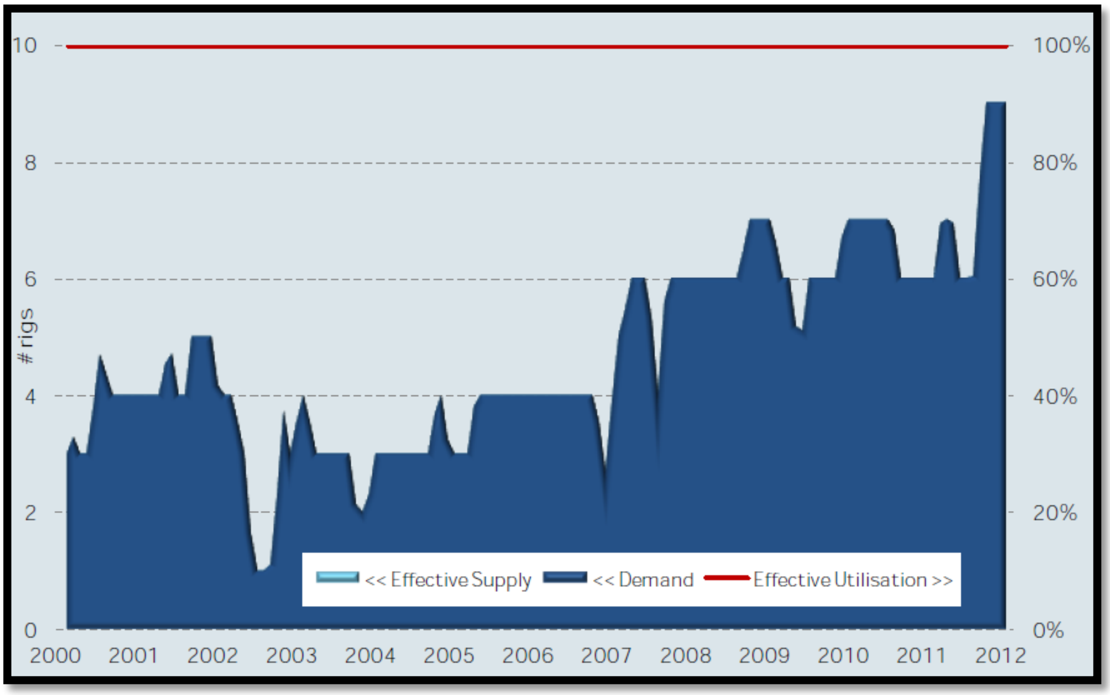

Figure 18 Norway Jack-up Demand and Supply (Jorgensen, 2012)

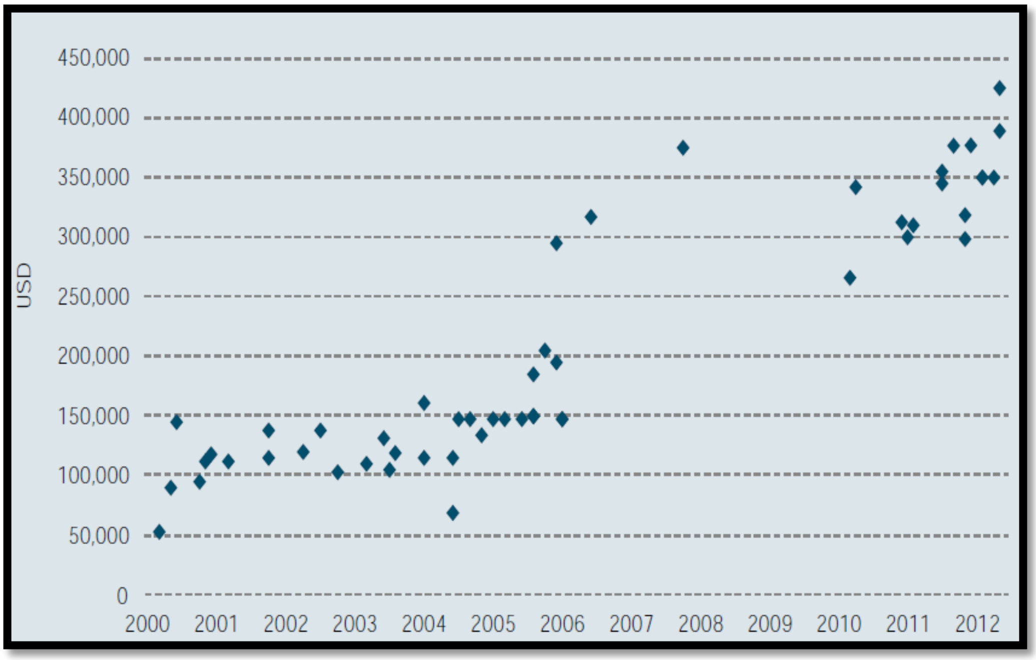

Figure 19 Ultra Harsh Jack-ups' Dayrates in Norway (Jorgensen, 2012)

The jack-ups that are currently operating in the NCS are presented in Table 3. In the case of the NCS it must be noted that only 3 drilling contractors share the market. Moreover it is also notable that most of the rigs are built after 1990 and are rated at water depths greater than 122m.

Table 3 Jack-ups operating in the NCS (Offshore Media Group AS, 2014)

Name	Vessel design	Max Water Depth [m]	Construction year	Dayrate [USD]
Maersk Giant	Hitachi Zosen Giant Class	107	1986	375000
Maersk Guardian	Hitachi Zosen Giant Class	107	1986	Private
Maersk Innovator	MSC CJ 70-150MC	150	2003	Private
Maersk Inspirer	MSC CJ 70-150MC	150	2004	Private
Maersk Reacher	MSC CJ 50-X100 MC	107	2009	Private
Rowan Gorilla VI	MLT Super Gorilla 219-C	137	2000	350000
Rowan Norway	KFELS Class N	122	2011	361000
Rowan Stavanger	KFELS Class N	122	2011	413000
West Elara	MSC CJ 70-X150 A	150	2011	371000
West Epsilon	MSC CJ62S 120	122	1993	293000

It would be interesting also to show a table with the rigs that are under construction and will be operating in the NCS in the next years. This is presented in Table 4. It is remarkable that all these jack-ups are of the same type and approximately the same water depth rating (150 m). Another remarkable fact is the dayrate difference between the CAT J rigs and the rest. This is a result of a unique license ownership model launched by Statoil (Statoil, 2014) (Unofficial Networks, 2013).

Table 4 Jack-ups under construction for the NCS (Offshore Media Group AS, 2014)

Name	Vessel design	Max Water Depth [m]	Construction year	Dayrate [USD]
Maersk Intrepid	MSC CJ 70-X150MD	150	2014	[378000]*
Statoil CAT J 2	MSC CJ 70-X150 A	140	2016	[310000]*
Statoil CAT J 3	MSC CJ 70-X150 A	140	2016	[310000]*
West Linus	MSC CJ 70-X150 A	137	2013	375000
XL Enhanced II	MSC CJ 70-X150MD	150	2014	[384000]*
XL Enhanced III	MSC CJ 70-X150MD	150	2015	[425000]*
XL Enhanced IIII	MSC CJ 70-X150MD	150	2016	[445000]*

* Estimated dayrate using the contract value and duration (A.P. MOLLER - MAERSK GROUP, 2014) and (Unofficial Networks, 2013).

2.3 Summary - Conclusion

1.5.8 Summary

After the introduction to the offshore drilling industry the market research focused in the North Sea market for drilling jack-ups. The most important findings of the market research are presented below.

In 2013 in UKCS and Norwegian CS the total exploration and appraisal expenditure was $8,8 billion. **The costs are rising in both countries** and this is related to high dayrates, delays in contracts and limited amount of available and capable rigs. The dayrates vary from $200000 for premium jack-ups in the UKCS to $425000 for the latest ultra-harsh environment jack-ups in Norway. Moreover the difference in dayrates between shallow and deep water depth rated jack-ups in each region should be noted.

Low drilling rig availability is an issue in the UK even though the amount of rigs has increased over the last 6 years. It led to high dayrates and therefore increased cost for exploration which then influenced negatively the exploration activity. **In Norway exploration is expected to continue in the same trend** during the next years and it is sure that **more ultra-harsh jack-ups will be needed**. For ultra-harsh jack-ups the utilization lately reaches 100%. Moreover for rigs that are being built for North Sea a great difference in the construction costs is shown with respect to water depth, and this might be an opportunity for the SSfJ concept.

It is discovered that in general the oil companies try to increase exploration, appraisal and production, motivated by high and stable oil prices, while decreasing costs. At the same time a significant demand for jack-ups exists, especially for deep water and harsh environment. A **support structure for jack-ups could find a place in the market** if it focuses on dealing with the needs of the E&P firms. This would be possible if there is a technically feasible design that reduces the cost of exploration by enabling more, and preferably cheaper, rigs to offer the services that only a few modern rigs can currently offer.

1.5.9 Conclusion

The conclusion of the market research is that the main driver for the SSfJ concept is to enable jack-ups to operate in deeper water without significant increase in costs. This is and will remain the most intense need in the market.

3 Analysis Case Formulation

3.1 Introduction

In this chapter the scope of the research will become narrower as shown in Figure 20. After having researched the characteristics and identified the needs of the market, it is aimed to determine what the Support Structure for Jack-ups will be designed to do. In addition, the focus of the technical part of this thesis will be presented along with the related input.

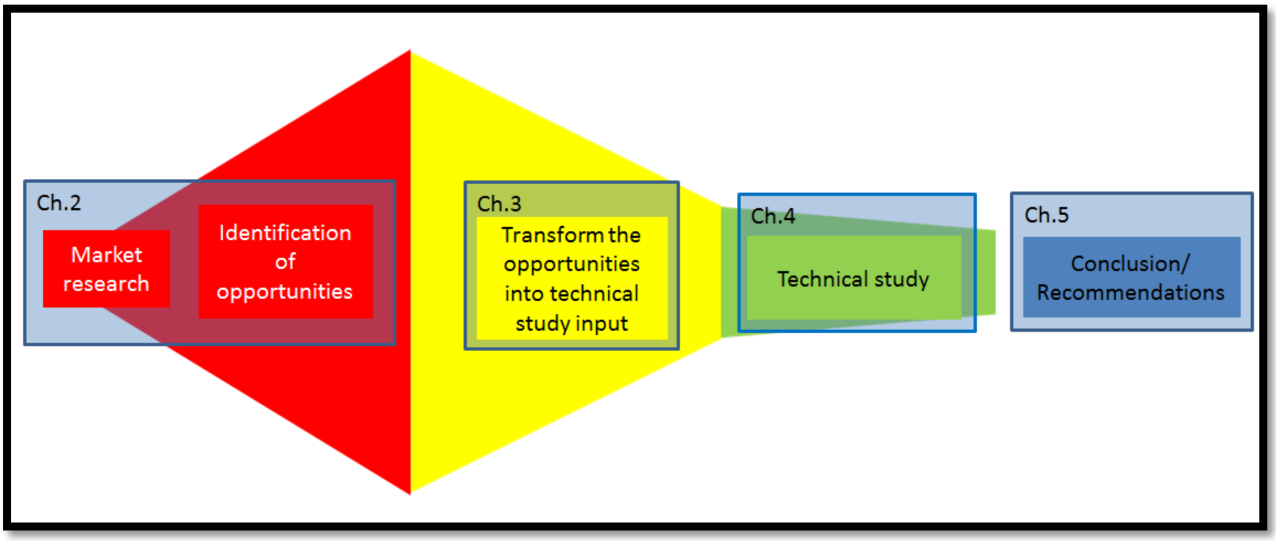

Figure 20 Thesis procedure

In some more detail, this chapter aims to:

- **Define** precisely **the technical objective and requirements** of the Support Structure for Jack-ups based on the conclusion of the market research
- **Derive the technical research approach and scope** (i.e. which part of the design/ calculations will be performed in this thesis), since a complete and detailed study is beyond the scope of a thesis project due to the limited amount of time and resources
- **Form the input for the design**, based on the information collected through the market research, additional data that will be collected at this stage and some assumptions that will also be clarified in this chapter

3.2 SSfJ technical objective

The technical objective of the SSfJ is based on the conclusion of the market research. The conclusion of the market research is to:

Focus on how to enable rigs to operate in deeper water without significant increase in costs

Therefore:

The technical objective of the SSfJ is to enable certain jack-ups to operate in deeper water.

Regarding the objective the following need to be specified in this chapter:

- Which jack-up types will be compatible with the SSfJ
- What increase of operational water depth will the SSfJ offer to the supported jack-up

1.5.10 Compatible jack-up type

To decide which jack-up types will be compatible with the SSfJ a set of criteria is established and a second look at the market is taken. Then a list with some characteristics of the jack-ups that are currently operating in the North Sea was made. Finally a jack-up type from the list is selected based on the criteria.

3.2.1.1 Selection Criteria

3.2.1.1.1 Number of available units per type

It is important that there are several jack-ups available in the market to be used with the SSfJ because this increases the potential market share of the SSfJ.

3.2.1.1.2 Jack-up age

To ensure that the SSfJ can be used for many years it is obvious that it should be designed to accommodate jack-ups that will be in service for many years. Moreover the fact that newer jack-ups are more developed and efficient (Kaiser, et al., 2013) makes the selection of a newer jack-up more sound as it is expected to fulfill the technical requirements of the E&P firms for many years.

3.2.1.2 Available jack-up types

A list with all the jack-ups that are operating and are expected to operate in the North Sea was made. This list also contains information about the age and the technical characteristics of jack-ups.

3.2.1.3 Selection

After consideration and discussion within HMC and based on the criteria presented in 3.2.1.1, it is decided to design a SSfJ that will support the GustoMSC CJ 70. The criteria are fulfilled because:

- There are already 5 units of this type active in the North Sea and other 6 are under construction. With such a population the CJ 70 will be the most popular jack-up type in the North Sea.
- Three of the CJ 70 jack-ups in North Sea are active for less than 3 years and the rest (two) units are active for around 10 years. This indicates CJ 70 jack-ups will be in service for at least 30 years from now, considering that the service life of a jack-up is approximately 35 to 40 years (Pareto Securities, 2012).

1.5.11 Increase of the operational water depth of jack-ups

Again a set of criteria was established in order to select what the increase of the operational water depth of a jack-up will be when it will be placed on the SSfJ. Those criteria are:

- The jack-up height that is expected to be needed in the market in the following years
- The existence of price indications for a deeper water jack-up with water depth capacity equivalent to the combined CJ 70 – SSfJ capacity. This will make the cost comparison (after this thesis) easier and well grounded.

Based on the above criteria, it is decided to consider a SSfJ that adds 30 m to the maximum operational water depth specification of the CJ 70 (which is currently limited to 150 m water depth). Both criteria are fulfilled since recently an order was placed for a CJ 80 jack-up, which can operate in 175 m water depth in the North Sea, and since the latest construction prices of both CJ70 and CJ80 are known, an insight can be provided for the cost margin of the SSfJ.

Note 1: in the end it may be even more valuable to add more than 30 m to the maximum water depth specification, but the selection of 30 m in this case is just a convenient starting point for the technical research.

Note 2: Technically it may be feasible to add even more to the operational water depth, but this can be determined at a later stage (e.g. by calculating the limit until which a jack-up can withstand the environmental loads while on the SSfJ).

3.3 SSfJ technical requirements

The SSfJ technical objective can be complimented by some technical requirements in order to describe better the concept of the SSfJ. These suggested requirements are derived after several discussions within HMC and between HMC and TU Delft. It was agreed that the SSfJ should be: installable, removable, reusable and adopted to the jack-up in order to require minimum modifications from its side.

3.4 Technical study approach and scope derivation

This paragraph aims to show the derivation of the approach and the scope of the technical part of this thesis. Due to the limited amount of time and resources available during a thesis project, not all of the technical aspects could be investigated in detail. Therefore **the scope of the technical study was to focus only on the most challenging technical aspects of the concept**. Other aspects were treated through reasonable assumptions which were checked for validity by the end of the research.

The technical study procedure was devised based on the scope presented above and can be summarized as follows. The first stage of the technical study aims to identify the most critical aspects of the concept and assess through assumptions how they will be affected when the jack-up is placed on an “ideal” SSfJ. The second stage aims to produce exact technical recommendations for the design of the SSfJ in order to solve the most challenging aspects of the concept. The third stage will focus on checking the assumptions, conclude on whether there are solutions to the critical aspects for the survival of the jack-up on the SSfJ and give suggestions for further technical research. A more detailed description of the technical study procedure follows in the next paragraph.

1.5.12 Technical Research Approach

3.4.1.1 Stage 1 - Identification

The first stage is to identify whether a jack-up can be placed on an "ideal SSfJ". This implies that **in this stage the research will focus only on the jack-up and not on the SSfJ**. The SSfJ will be considered as a "black box", stable and strong enough to bare any loads introduced by the supported jack-up. The following steps are suggested:

1. Identify through literature study for a jack-up placed on the seabed:
    a. the main failure modes and related checks
    b. the main critical aspects in the design (e.g. leg-hull interface, overturning moment, dynamics etc.).
2. Collect and explain briefly the main parameters (e.g. water depth, environmental conditions, soil conditions etc.) that influence the failure modes and the critical aspects.
3. Evaluate the effect of placing a jack-up on an "ideal SSfJ" (also called "black box SSfJ") on the parameters that influence both the main failure modes and the critical aspects in the design. This procedure will highlight which aspects seem less challenging (and which failure modes will become unlikely when the jack-up stands on the SSfJ) but also which checks are important.
4. Perform simplified versions of the important checks for the jack-up on the SSfJ in order to validate the most important assumptions.

3.4.1.2 Stage 2 – Technical recommendations for the design of the SSfJ

In this stage a closer look at the most important checks identified in Stage 1 takes place. The objective is to produce specific technical requirements that will be very useful during the design of the SSfJ. The technical requirements will guarantee that the critical aspects addressed in Stage 1 will be covered.

3.4.1.3 Stage 3

This stage acts as a verifying and concluding stage for the technical study. At this stage all the assumptions taken in the previous stages are summarized and checked for validity. Moreover, an answer is given on whether there are solutions to the critical aspects for the survival of the jack-up on the SSfJ. Finally, some recommendations for further technical research are given so that the technical feasibility of the concept can be fully addressed in case the project is continued after this thesis.

3.5 Input for the Technical Study

This paragraph summarizes the input that is produced for the technical study by chapters 2 and 3. It must be noted that after consultation of experts at the TU and HMC it was decided to make use of specific standards and software as explained below. The input can be summarized in the following:

- Compatible jack-up type:
  - GustoMSC CJ70 with technical specifications defined in (GustoMSC, 2009)
- Increase in water depth capacity through the usage of the SSfJ:
  - 30 m
- Design code to be consulted:
  - (ISO 19905-1, 2012) with references to (SNAME, 1994)
- Computer analysis software:
  - Bentley SACS version 5.6
- Environmental conditions:
  - Same as the design conditions for the CJ 80 jack-up type as shown in Figure 21:

Survival conditions	CJ80	CJ70
	North Sea, all year	North Sea, all year
leg length	232.0 m	206.7 m
max water depth	175.0 m	150.0 m
air gap	23.0 m	24.0 m
wave height/ period	29.0 m/ 16.0 s	29.0 m/ 16.0 s
surface current	1.0 m/s	1.0 m/s
wind velocity (1 min sustained)	49.0 m/s	49.0 m/s

Figure 21 Design survival conditions for CJ 70 and CJ 80 (GustoMSC, 2009)

3.6 Conclusions

In this chapter the objective and the technical requirements of the SSfJ are formed and a technical research approach is derived. Based on the market research and additional information presented in this chapter, it is decided to investigate the feasibility of a SSfJ that will add 30 m to the maximum operational water depth specification of the CJ 70 jack-up type.

Based on discussions with various experts, the technical requirements for the SSfJ are formed and shall be used in the design of the SSfJ after this thesis. It is aimed to design a SSfJ that is installable, removable, reusable and adapted to the supported jack-up.

The technical study approach consists of three stages:

In the first stage the research focuses only on the jack-up for which the SSfJ is to be designed. The aim is to identify the most critical aspects in the design of a jack-up and which parameters they are related to. Then the effect of the usage of an "ideal" SSfJ on those parameters will be investigated. This is done in order to quickly identify which are the most critical aspects for the technical feasibility of the SSfJ and to decide where the technical study should focus during the next step.

The second stage will produce specific technical requirements that shall be used during the design of the SSfJ after this thesis. The technical requirements will guarantee that the critical aspects addressed in Stage 1 will be covered.

In the third stage all the assumptions taken in the previous steps will be checked for validity and a conclusion will be drawn on whether there are solutions to the critical aspects for the survival of the jack-up on the SSfJ.

4 Technical Study

4.1 Introduction

The previous chapters aimed at providing the input for this chapter (see Figure 22):

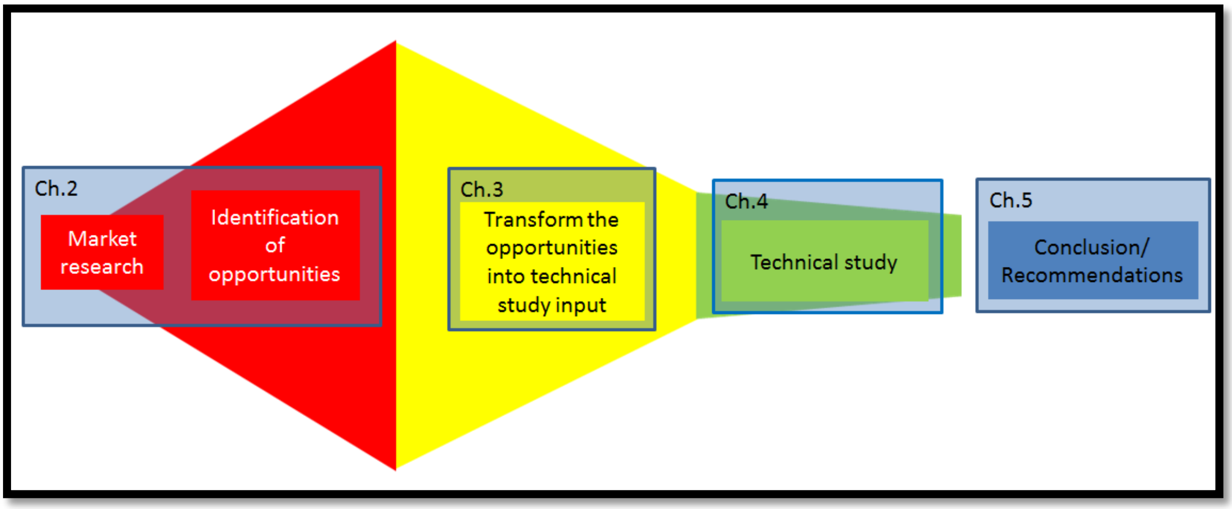

Figure 22 Thesis procedure

This chapter aims to focus on the most critical technical aspects of the concept. A technical study is performed in 3 stages, as developed in Ch.3, and is summarized below:

- Stage 1

Identification of structural challenges ("bottle necks") of jack-ups on the seabed. Evaluation of the effect of the use of an "ideal" SSfJ on these challenges

- Stage 2

Recommendations for the design of the SSfJ in order to solve the most challenging "bottle neck"

- Stage 3

Validation of assumptions and conclusion on whether there are solutions to the critical aspects for the survival of the jack-up on the SSfJ

4.2 Stage 1

The question to be answered in this stage is: "How will the jack-up integrity be affected if it is placed on an "ideal" SSfJ?". It is noted that at this early stage the installation of the jack-up on the SSfJ is not treated and only the in-place condition is taken into account.

1.5.13 Summary of the steps in Stage 1

A flow chart of the procedure followed on Stage 1 is presented in Figure 23.

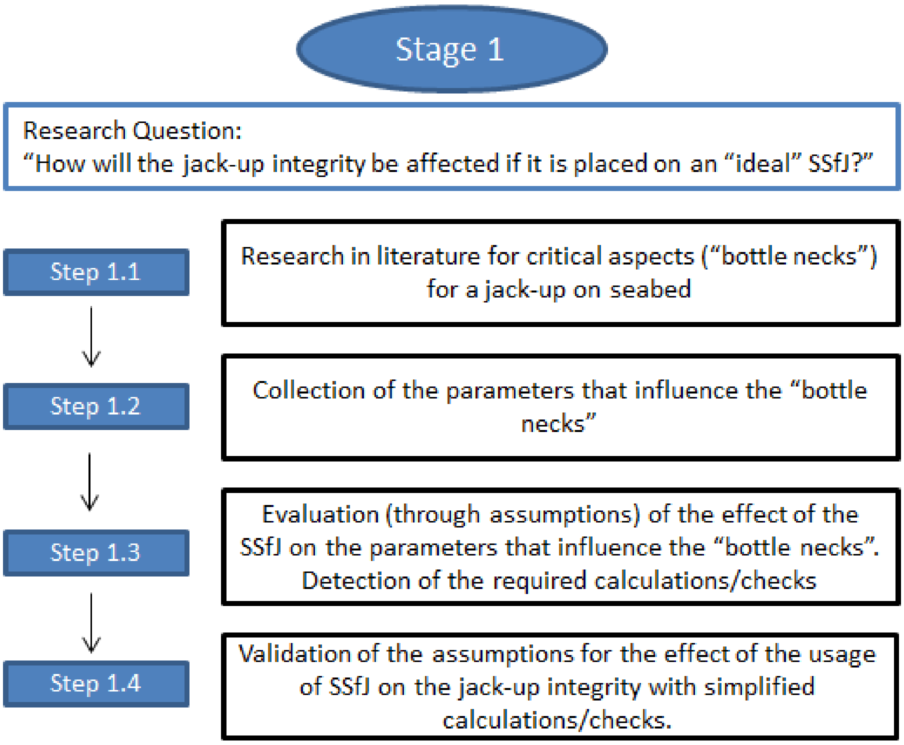

Figure 23 Stage 1 Flowchart

A more detailed explanation of each step of Stage 1 of the technical study follows:

1.1 Identify through literature study the "bottle necks" for a jack-up placed on the seabed, looking at:
   a. the main failure modes and related checks
   b. the main critical aspects in the design (e.g. leg-hull interface, overturning moment, dynamics etc.).

1.2 Collect and explain briefly the main parameters (e.g. water depth, environmental conditions, soil conditions etc.) that are included in the checks related to the critical aspects identified in the precious step.

1.3 Evaluate the effect of the use of an "ideal SSfJ" on the parameters that influence both the main failure modes and the critical aspects in the design. In this way, some design aspects proved to be less important and some failure modes became unlikely when the jack-up stands on the SSfJ. In that case some checks could be omitted. At the same moment, the important checks emerged.

1.4 Validate the assumptions of 1.3 with simplified static checks. This is a first view on whether or not the critical aspects are within the capacity limit for a jack-up on the SSfJ. (For a more detailed view the reader should refer to Stage 2 of the Technical Study).

1.5.14 Step 1.1

In this step the research focuses only on the jack-up that is aimed to be supported by the SSfJ and its operation on the seabed. In this case the objective is to identify:

a. the main failure modes for the jack-up on the seabed and the related checks
b. the main critical aspects in the design (e.g. leg-hull interface, overturning moment, dynamics etc.).

The research makes use of literature in order to obtain information about the above mentioned.

Following the suggestion of an expert, the first source to be looked at is the (ISO 19905-1, 2012). According to this standard, in order for a jack-up to be accepted to operate on a specific site the following issues must be assessed:

- structural strength of legs, spudcan and holding system
- hull elevation
- leg length reserve
- overturning stability
- foundation integrity including preload, foundation capacity, sliding displacement, settlement resulting from exceedance of the capacity envelope
- interaction with adjacent infrastructure
- temperature

The most important of these checks are grouped and explained briefly by (Hoyle, et al., 2006) as follows:

- Geometry: Are the legs long enough to cope with the water depth, predicted penetration, air gap, leg length reserve, etc.?
- Overturning Stability: Is there an adequate vertical reaction under all legs under the influences of the assessment storm?
- Structure: Are the legs and leg holding system strong enough?
- Foundation: Is the soil sufficiently strong to resist additional penetration and spudcan sliding?

The above checks deal with all the failure modes. However they are not equally critical for all the sites that a jack-up is called to operate.
According to (Hoyle, et al., 2012) and (Hoyle, et al., 2006) the most common critical part in the site-specific assessment is the foundation integrity check for reasons explained below:
The foundation must have sufficient strength so that the spudcans at the base of the legs do not penetrate too far into the seabed when preload is applied.
The foundation can also provide moment fixity to the bottom of the legs. Site specific assessments are usually carried out under conservative assumptions as far as foundation fixity is concerned. When relatively small fixity is considered, the critical section of leg is normally near the lower leg

guide, close to the hull keel. At that point the leg bending moment is high, and in some designs there is a large lateral force applied to the leg by the lower guide which induces high bending moments in the chords of the leg. However, the CJ 70 jack-up used in this technical study uses a fixation system, assumed to be just above the hull, and this is where the maximum moment is located according to (ISO 19905-1, 2012). Figure 24 gives two leg bending moment diagrams: one with some spudcan fixity, and one without. It can be seen that any moment reacted at the base of the leg directly reduces the leg bending moment at the keel.

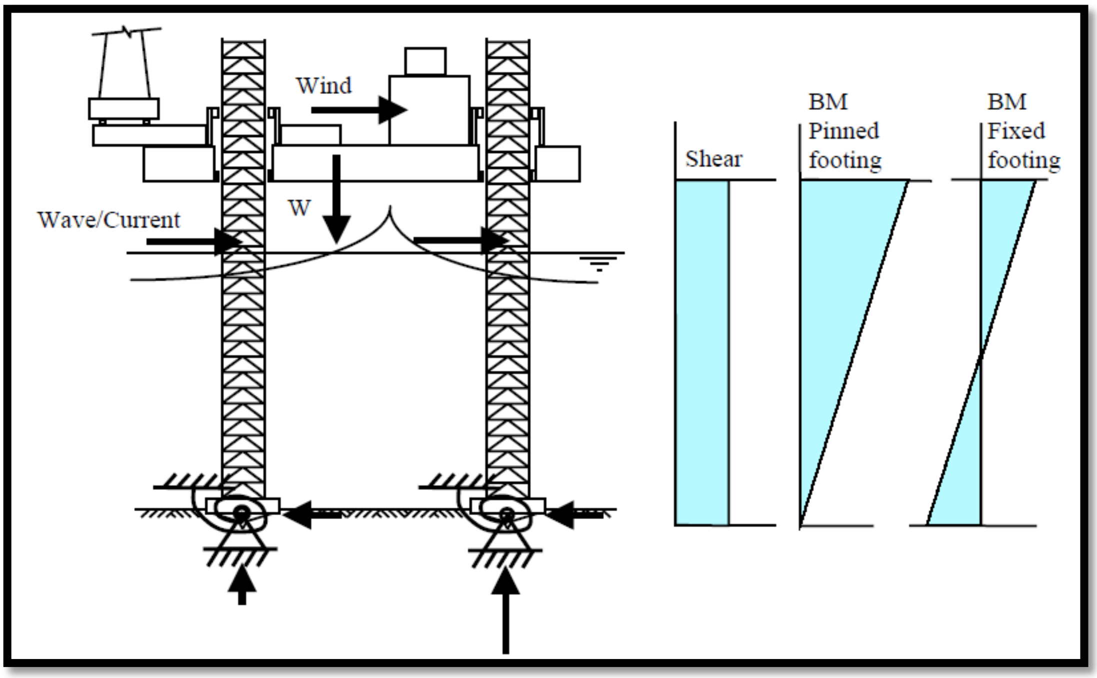

Figure 24 The effect of spudcan fixity on the leg moments (Hoyle, et al., 2006)

This reduction can significantly alter that acceptability of a rig at a specific location.
Foundation fixity not only beneficially reduces the leg bending moment in the region of the leg-to-hull connection but also increases the sway stiffness of the jack-up. One should consider that the natural period of a typical deep water jack-up is in the range of 6 to 10 seconds and this depends very much on the sway stiffness. Increased surge and sway stiffness reduce the natural period and the dynamic displacements of the jack-up. The reduction of natural period has as an effect the reduction of the large-displacement loading and the inertial loading of the jack-up.

Therefore it is can be concluded in this step that the most important aspects (the “bottle necks”) in the design and operation of jack-ups for the normal on bottom operation are:

1. Foundation, which also influences
2. Leg-to-hull level moment and
3. Dynamics

1.5.15 Step 1.2

In this step the objective is to identify the main parameters that influence the critical aspects mentioned in Step 1. To achieve this, the parameters involved in the checks related to the critical aspects are collected. To find those parameters, a closer look on the standard was taken. Below the relevant parameters for each check are mentioned briefly.

4.2.1.1 Geometry

4.2.1.1.1 Hull elevation

The related parameters are:

- extreme wave height
- tide and storm surge
- settlement due to storm

4.2.1.1.2 Leg length reserve

This accounts for the uncertainty in the prediction of leg penetration and is influenced by parameters related to various types of settlements (long term foundation settlement, reservoir settlement or settlement due to scour)

4.2.1.1.3 Interaction with adjacent infrastructure

This check is related to the displacements of the jack-up. Therefore the parameters involved in this check are:

- The arrangement of the adjacent structures and their distance from the jack-up
- The movement of the jack-up due to external loading

4.2.1.2 Overturning stability

The main parameters for this check are the overturning moment and the stabilizing moment. The overturning moment depends on the external loading and the height of the jack-up. The stabilizing moment depends on the variable load, the weight of the jack-up, the position of the center of gravity of the jack-up, the distance between the jack-up's legs and potential foundation fixity.

4.2.1.3 Structure

The parameters used in the structural checks are mostly related to the geometry of the jack-up structure (member dimensions and wall thicknesses, structural configuration etc.), the external loads (wind, wave and current) and the foundation characteristics. In order for these checks to be performed detailed computer models of the jack-up need to be prepared so as to check each structural member separately but also the structure as a whole.

4.2.1.4 Foundation integrity

The main parameters in the foundation integrity check are:

- External loading (due to wind, waves and current)
- Foundation fixity
- Soil properties
- Foundation stress history
- Structural stiffness of the jack-up
- Spudcan geometry
- Spudcan displacements
- Other (Geohazards, hard sloping strata, footprints etc.)

1.5.16 Step 1.3

In this step the jack-up is considered to be standing on an "ideal SSfJ". The objective of this step is first to assess with reasonable assumptions how the parameters mentioned in Step 1.2 are influenced by the usage of the SSfJ and then to understand which aspects and checks (identified in Step 1.1) are the most critical for the concept researched in this thesis, so, when a jack-up is placed on the SSfJ.

4.2.1.5 Jack-up on the SSfJ

Before identifying which aspects change when a jack-up is placed on an "ideal SSfJ", it is important to describe the configuration of a jack-up on the ideal SSfJ. This is derived from the design input that was presented in Chapter 3 of this thesis.

The SSfJ is placed on the sea bottom. It is assumed at this stage to be stably and perfectly fixed on the seabed and strong enough to support the jack-up at any circumstances. Moreover it is also assumed that the SSfJ does not influence the flow of water particles, i.e. it is assumed to be "hydro-dynamically transparent". According to the input, the SSfJ will add 30 m to the water depth specification of a GustoMSC CJ 70 type jack-up and the jack-up will not receive any modifications in order to be placed on the SSfJ. In order to show the different configurations Figure 25 is drawn where: a) jack-up stands on the seabed, b) jack-up stands on the "ideal" SSfJ

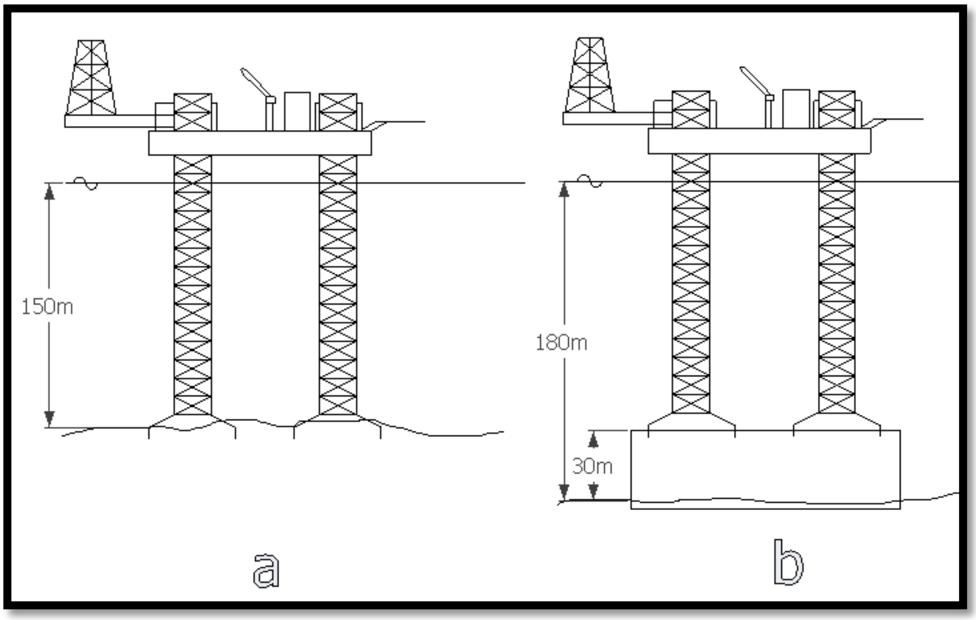

Figure 25 Jack-up on an "ideal" SSfJ

4.2.1.6 Effect of using the SSfJ on the parameters of each check

~Beginning of Note~

Design environmental conditions for the jack-up on the SSfJ

Before addressing the changes it is important to present the design environmental conditions. According to the design input (Chapter 3), the jack-up on the SSfJ must be able to withstand the same environmental conditions as those used for the design of the CJ 80 jack-up (Figure 26).

Survival conditions	CJ80	CJ70
	North Sea, all year	North Sea, all year
leg length	232.0 m	206.7 m
max water depth	175.0 m	150.0 m
air gap	23.0 m	24.0 m
wave height/ period	29.0 m/ 16.0 s	29.0 m/ 16.0 s
surface current	1.0 m/s	1.0 m/s
wind velocity (1 min sustained)	49.0 m/s	49.0 m/s

Figure 26 Design survival conditions for CJ 70 and CJ 80 (GustoMSC, 2009)

What can be inferred from the table is that the design environmental conditions for a CJ 80 type jack-up are actually the same as for the assessment of a CJ 70 on the SSfJ, with the water depth being the only difference.

~End of note~

The influence of the use of SSfJ on the parameters related to each check is presented below.

4.2.1.6.1 Geometrical checks

4.2.1.6.1.1 Hull elevation

The effect of the use of the SSfJ on the parameters that determine the hull elevation is for each parameter as follows:

- extreme wave height — No influence- this parameter is independent of the SSfJ
- tide and storm surge — No influence- this parameter is independent of the SSfJ
- settlement due to storm — Assumed positive influence. SSfJ must have bigger area in contact with the seabed compared to the spudcans so as to reduce the load on the soil

4.2.1.6.1.2 Leg length reserve

The use of the SSfJ is expected to have a positive influence on long term foundation settlement and settlement due to scour. This assumption is based on the fact that the SSfJ can be designed such as to distribute the vertical loads from the jack-up to a wide area. Moreover scour should not be as challenging for the SSfJ as it is for the spudcans and this can be achieved through proper design of the SSfJ. As for the reservoir settlement, this parameter is independent of the use of the SSfJ

4.2.1.6.1.3 Interaction with adjacent infrastructure

It is possible that the combined movement of the SSfJ and the jack-up due to environmental loading can be large enough for this check to be important. This idea produces a recommendation for the design but is not relevant with the objective of this thesis, which is to identify if a jack-up can survive on a SSfJ. The suggestion for the design is to aim on a SSfJ that is stiff enough so that the movements of the jack-up are within acceptable limits. At this point little can be said about the magnitude of the movements of the jack-up since the limits are dependent on the site characteristics and on the type of drilling performed (above a jacket or above a subsea well). However if the design of the SSfJ takes place after this thesis, the movements of the jack-up on the SSfJ should be taken into account.

Conclusion on the influence of the SSfJ on the parameters related to geometrical checks:

The use of the SSfJ will have neutral or positive effect => <u>This check is not critical for a jack-up on an ideal SSfJ</u>

4.2.1.6.2 Overturning stability check

As mentioned earlier, the main parameters for this check are the overturning moment and the stabilizing moment. The overturning moment depends on the external loading (wind, wave and current). The stabilizing moment depends on the variable load, the weight of the jack-up, the position of the center of gravity of the jack-up, the distance between the jack-up's legs and potential foundation fixity.

4.2.1.6.2.1 Overturning Moment

The overturning moment is calculated using the environmental loads and the jack-up's dimensions. As for the environmental loads, it is assumed at this point that they will be experienced by the jack-up in the same way whether it stands on the seabed or on the SSfJ. An explanation of this assumption with respect to each load is given below:

4.2.1.6.2.1.1 Current

The use of the SSfJ will change the water depth around the jack-up and a question rises regarding the current load that acts on the jack-up legs when the jack-up is on the SSfJ. It must be noted again that the SSfJ is considered "hydro-dynamically transparent". The ISO standard suggests that a uniform current speed must be used in the checks (Figure 27). In this case the current load that acts on the jack-up legs will not be influenced by the increase of water depth.

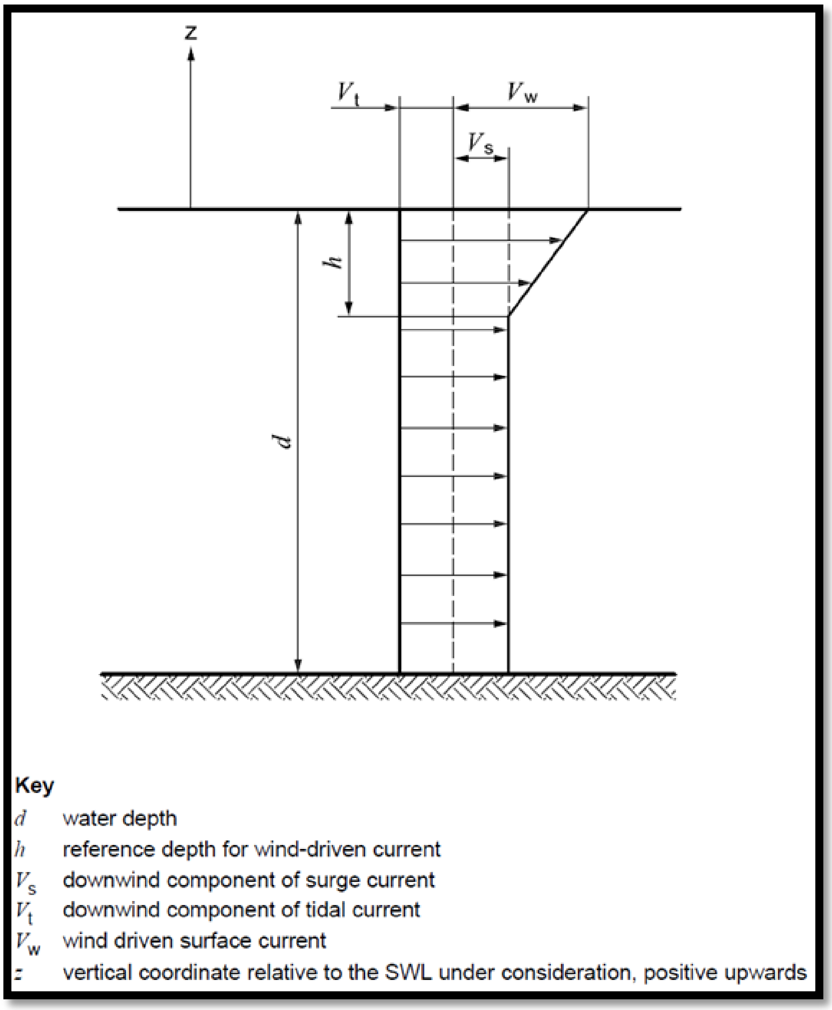

Figure 27 Current load in ISO 19905-1 (ISO 19905-1, 2012)

Moreover it should be taken into account that the current design velocity for the CJ 70 on the SSfJ is equal to that of the CJ 80 on sea floor (1m/s). Therefore it can be concluded that **there is no influence on the current velocity** due to use of a jack-up in deeper water along with a SSfJ. Of course this is an assumption that needs to be verified and this would not be the case if the current profile was not uniform. However, In other studies the current profile is not uniform from the sea surface to the sea bottom but it decreases with depth. Therefore considering a uniform velocity over depth that has the value of the maximum velocity at the sea surface is on the conservative side.

4.2.1.6.2.1.2 Wind and waves

A question that rises is whether the use of the SSfJ will influence the wind and wave loading applied on the jack-up. It is assumed that **both the wind and the wave loading will not be more severe** when the jack-up stands **on the SSfJ** in the North Sea. This assumption is based on:

- the fact that areas with water depths between 150 m and 180 m have similar environmental conditions for the case of a small sea like the North Sea. This is also verified by the fact that the design loads for the CJ 80 and the CJ70 are identical even though those types are designed for different water depths.

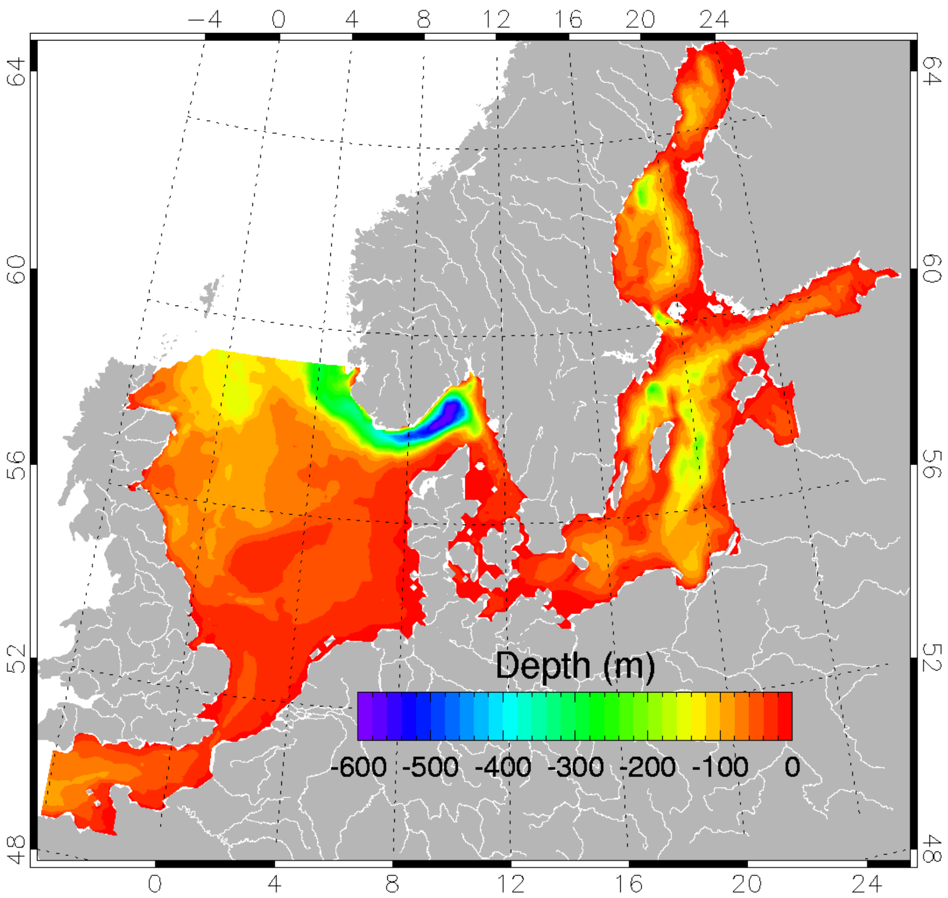

Figure 28 Water depths in North Sea

- the fact that the SSfJ will not interfere with waves, since it is close to the sea floor and it is assumed to be "hydro-dynamically transparent"

The conclusion is that the jack-up will not be challenged more by the environmental loads while placed on the SSfJ compared to when it stands on the sea floor. This assumption is verified in step 1.4.

4.2.1.6.2.2 Stabilizing moment

The stabilizing moment depends on the variable load, the weight of the jack-up, the position of the center of gravity of the jack-up, the distance between the jack-up's legs and potential foundation fixity. Out of all these parameters, the use of the SSfJ can influence only the foundation fixity. For this reason it is decided to take a closer look at the foundation fixity for the jack-up on the SSfJ at a later stage (together with the general foundation checks). What appears to be important is that a good fixation should be achieved for the jack-up on the SSfJ in order to ensure that overturning stability is not crucial.

Conclusion on the influence of the SSfJ on the parameters related to the overturning stability check:

The use of the SSfJ can and should have a positive effect on the overturning stability check. It is assumed that the overturning moment is not affected intensively and that the stabilizing moment can be increased through a good fixity of the spudcans on the SSfJ in combination with at good foundation of the SSfJ on the seafloor. Therefore the positive effect on the foundation fixity should be a requirement for the SSfJ – Jack-up interface design. If a significant amount of fixity can be achieved then the overturning check will easily be fulfilled. Therefore <u>this check is not considered crucial for a jack-up on the SSfJ</u> unless it is impossible to achieve a significant level of fixity of the jack-up on the SSfJ. A check of this assumption is performed in 4.2.5

4.2.1.6.3 Structural checks

As mentioned in step 1.2, the parameters used in the structural checks are mostly related to the geometry of the jack-up structure (member dimensions and wall thicknesses, structural configuration etc.), the external loads (wind, wave and current) and the foundation characteristics.

4.2.1.6.3.1 Jack-up geometry

This jack-up geometry itself is not influenced by the SSfJ according to the design input. However a new structural system applies for the dynamic analysis. The new system consists of both the jack-up and the SSfJ. The difference with the on-bottom situation is caused by the fact that the dynamic characteristics of the SSfJ can be very different from those of the soil on which the jack-up is designed to operate. A reliable answer cannot be given with a simple check where the SSfJ is assumed as a “black box”. This issue is quite complicated and is researched in depth at Stage 2.

4.2.1.6.3.2 External loads

As mentioned in 4.2.4.2.2.1 the environmental are not expected to change a lot when using the SSfJ.

4.2.1.6.3.3 Foundation – Fixity on the SSfJ

The foundation conditions will not be the same for a jack-up on the SSfJ and on the sea floor. This is addressed later (see 4.2.4.2.4). What must be noted here is that from structural point of view, the fixity of the spudcans on the SSfJ is a very crucial aspect as it affects the moment distribution on the jack-up legs and the sway stiffness that influences the dynamics of the jack-up.

4.2.1.6.3.3.1 Moment Distribution over the leg length

If the interface between the spudcans and the SSfJ acts as a pinned foundation, then the moments on the leg-to hull interface level (i.e. at the fixation system) will be high and might cause a problem at the legs’ chords at that level. On the contrary, if high spudcan fixity is achieved, then the moments are distributed in a way which is more favorable for leg chords close to the leg-to hull interface level (Figure 29).

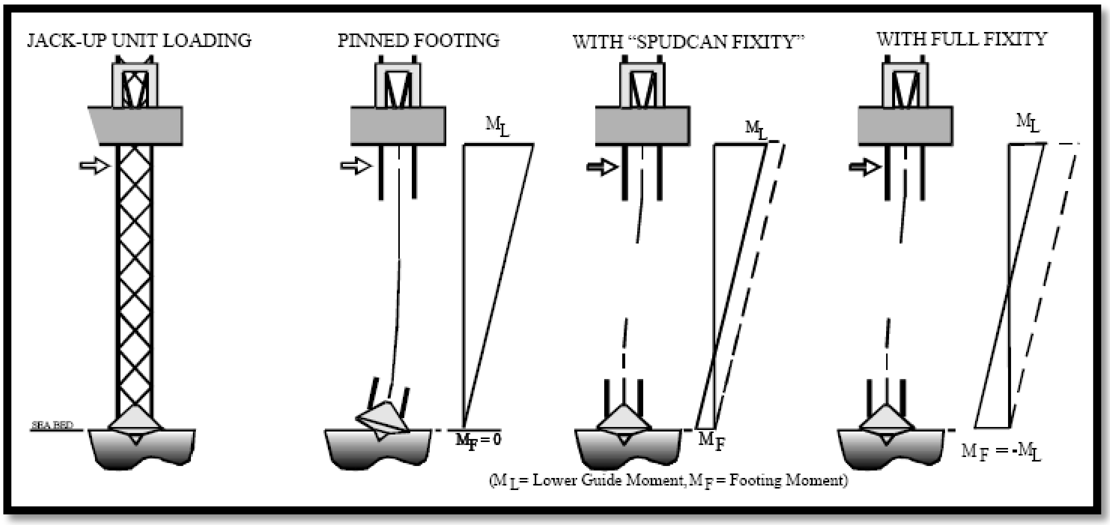

Figure 29 The effect of spudcan fixity on the moment diagram of a jack-up leg (Nelson, et al., 2000)

4.2.1.6.3.3.2 Spudcan fixity, SSfJ stiffness and dynamics

A pinned foundation introduces less stiffness compared to a fixed foundation. According to the basic knowledge on dynamics, less spudcan fixity on a stable base leads to bigger natural periods, wider oscillations and potentially (depending also on the characteristics of the external load) to more intense inertial loads as presented in Step 1.1. The lower and higher limits of spudcan fixity and their effect on the natural period of the jack-up are presented in Figure 30.

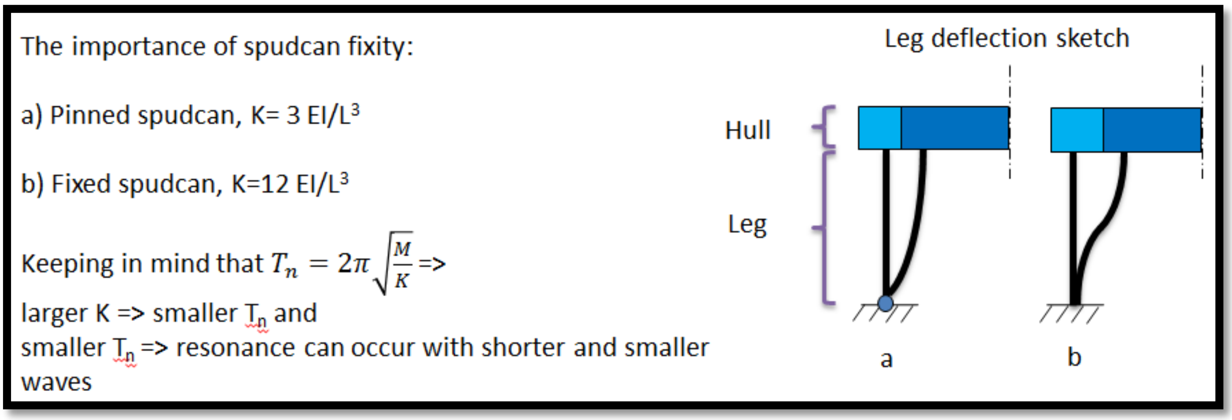

Figure 30 The importance of spudcan fixity for Dynamics

Bigger natural periods imply that resonance could occur with waves of larger periods. In general those waves can have bigger wave heights and more energy. That could lead to even bigger oscillations and inertia loads. On the contrary a smaller natural period means that resonance occurs with smaller waves with less energy but also more often presence at sea. A high amount of fixity is in general considered beneficial for the dynamics, however a more detailed analysis takes place in Stage 2 in order to understand better the relationship between spudcan fixity on the SSfJ and dynamic behavior for various wave periods.

Moreover the internal stiffness of the SSfJ plays an important role on the dynamics of the SSfJ - jack-up system. If the SSfJ has large stiffness, then the SSfJ will receive loads (from the supported jack-up) in a frequency much lower than its natural frequency and thus it will act quasi statically. Then the natural period of the system will be close to the natural period of the jack-up (Figure 31 case a). To illustrate this, one can imagine that in this case the SSfJ is so stiff that it acts like solid rock and therefore the jack-up on top of it will behave as if it is placed on a ultimately stiff seabed. On the other hand if the SSfJ has a very low stiffness then the natural period of the SSfJ – jack-up system will be close to that of the SSfJ (Figure 31 case b).

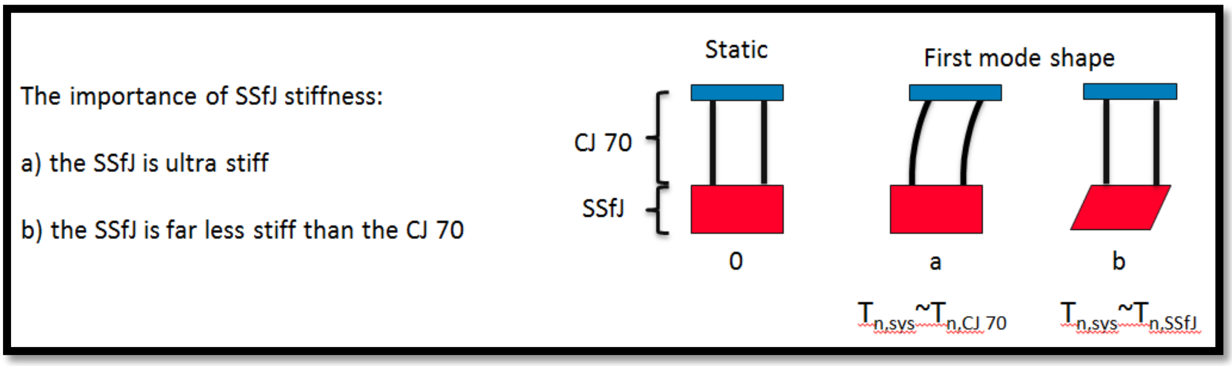

Figure 31 The importance of SSfJ stiffness for Dynamics

Conclusion on the influence of the SSfJ on the parameters related to the structural analyses:

Further research is required with regard to the structural integrity of the jack-up on the SSfJ. The internal SSfJ stiffness and the amount of fixity of the spudcans on the SSfJ determine the dynamic behavior of the jack-up on the SSfJ and shall be addressed quantitatively. This behavior can be critical for the feasibility of the concept because it can lead to intense loading of the legs at the leg-to-hull interface (as presented in Step 1.1). Therefore the structural checks are considered important for a jack-up on the SSfJ.

4.2.1.6.4 Foundation integrity checks

The main parameters in the foundation integrity check are:

- External loading (due to wind, waves and current)
- Foundation fixity
- Soil properties
- Foundation stress history
- Structural stiffness of the jack-up
- Spudcan geometry
- Spudcan displacements
- Other (Geohazards, hard sloping strata, footprints etc.)

The effect of using a SSfJ on each of this parameters is explained below:

4.2.1.6.4.1 External loading

As mentioned above (see 4.2.4.2.2.1) the environmental loads do not differ significantly when using the SSfJ. It is suggested at this point again, that the SSfJ should be designed to make use of a wide area of contact with the seabed, so that the loads are distributed over a wider area compared to the area of the spudcans. In this way the seabed will be able to receive more loads without failing and the SSfJ with the jack-up on top will be more stable. It is very important to take this into account if after this thesis the design of the SSfJ is performed.

4.2.1.6.4.2 Foundation Fixity

Foundation fixity at this point, refers to the spudcans' fixity on the SSfJ and not on the foundation of the SSfJ on the seafloor which is assumed ultimately stiff as explained in 4.2.4.1. The effects of spudcan fixity are presented in 4.2.4.2.2 and 4.2.4.2.3.

4.2.1.6.4.3 Soil properties

The use of the SSfJ will eliminate the dependence of the jack-up foundation integrity from the local soil conditions because the jack-up will no longer be placed on the seafloor but on the SSfJ. However the soil conditions should be taken into account during the design of the foundation of the SSfJ.

4.2.1.6.4.4 Foundation stress history

See 4.2.4.2.4.3

4.2.1.6.4.5 Structural stiffness of the jack-up

See 4.2.4.2.4.3

4.2.1.6.4.6 Spudcan geometry

The spudcan geometry is not related to the foundation integrity for a jack-up that sits on a SSfJ because the SSfJ will have to deal with the local soil conditions. In other words the soil will accommodate the SSfJ and the SSfJ will accommodate the spudcan and therefore the soil is not affected by the geometry of the spudcan.

4.2.1.6.4.7 Spudcan displacements

See 4.2.4.2.4.6

4.2.1.6.4.8 Other

Jack-ups are called to face various situations such as geohazards, hard sloping strata, footprints etc. It is possible that some of these situations can be dealt with the use of a SSfJ. However at this point the SSfJ is aimed only at increasing the water depth specification, assuming that all the other challenging foundation situations are not present.

Conclusion on the influence of the SSfJ on the parameters related to foundation integrity:

The use of the SSfJ can have a positive effect on the foundation integrity of the jack-up. To do this, the design of the SSfJ (which is out of the scope of this thesis) should achieve:

1. sufficient fixity of the spudcans (to be specified in Stage 2)
2. a stiffer base for the jack-up (compared to the soil stiffness under the spudcans)
3. better (broader) transfer of the loads to the soil

The most critical part of this check is the fixity of the jack-up on the SSfJ, which is addressed in Stage 2. <u>This is considered the most critical aspect for a jack-up on the SSfJ.</u>

4.2.1.7 Step 1.3 conclusion

The influence of the use of the SSfJ on the parameters included in the main checks related with the "bottle necks" of jack-up suitability for a site is addressed in step 1.3. The outcome of step 1.3 is that **the most important checks to be performed are the structural checks. These checks are related to the stiffness of the SSfJ and the amount of fixity that can be achieved between the SSfJ and the spudcans of the jack-up.**

It is understood that the increase of the spudcan fixity leads to decrease of moments at the leg-to hull interface level (beneficial for the forces on the leg chords at that level) and also to decrease of natural period and sway amplitude (which in many cases leads to improved dynamic behavior). It is therefore important to assess and give recommendations on how much spudcan fixity and how much SSfJ stiffness is required so that the jack-up can be safely and economically on the SSfJ. These recommendations for the design of the SSfJ are presented in Stage 2 of the technical study.

1.5.17 Step 1.4

In this step the assumptions taken in step 1.3 with respect to environmental loading are to be validated. In 4.2.4.2.2 it is assumed that the jack-up will not be challenged more by the environmental loads while placed on the SSfJ compared to when it stands on the sea floor. Simplified checks took place and the results that prove this assumption are presented below.

4.2.1.8 Method

The following method is applied in order to address the difference in the effect of wave, current and wind load on the jack-up between the situations presented below and in Figure 32:

A) the jack-up stands on the seabed in 150m water depth
B) the jack-up stands on the SSfJ in water depth 160m
C) the jack-up stands on the SSfJ in water depth 170m and
D) the jack-up stands on the SSfJ in water depth 180m

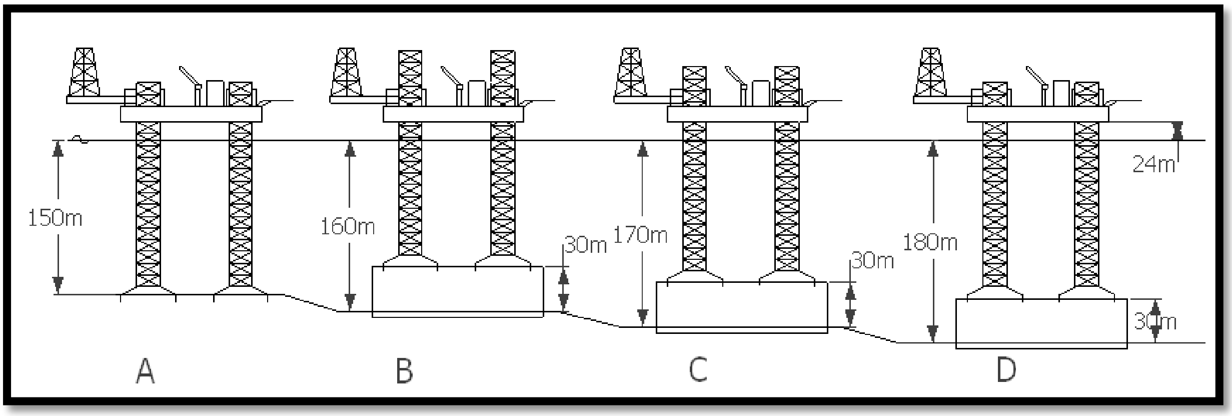

Figure 32 The four situations addressed in step 1.4

One model for each situation is created in the structural analysis software SACS. Then wind, wave and current loads are applied on each model. As mentioned in the note at 4.2.4.2 the environmental conditions that apply in all situations are the same. Then static analyses take place for all situations and the values of some characteristic parameters are compared.

It must be noted that the analyses at this step are not performed in order to calculate the precise displacements or moments but in order to show the change in the effect of the environmental loads on the jack-up when it is placed on the SSfJ in deeper water.

4.2.1.9 Modeling the GustoMSC CJ 70 jack-up

To make the models, data is acquired from commercial brochures of the CJ 70 designers (GustoMSC, 2009), CJ 70 owners (Maersk Drilling, 2012) and additional information or indications about specific values are obtained from relevant scientific publications such as (Williams, et al., 1999) and (Cassidy, et al., 2001). The modeling of the CJ 70 on the seafloor is presented in Figure 33.

The jack-up model consists of nine prismatic beams that represent the legs (according to ISO 19905-1, paragraphs A.8.3 and A.7.3.2.3.) and three prismatic members that represent the hull (Figure 33). The characteristics of the model are presented in the next paragraph. Detailed information for the development of the models can be found in Appendix 1.

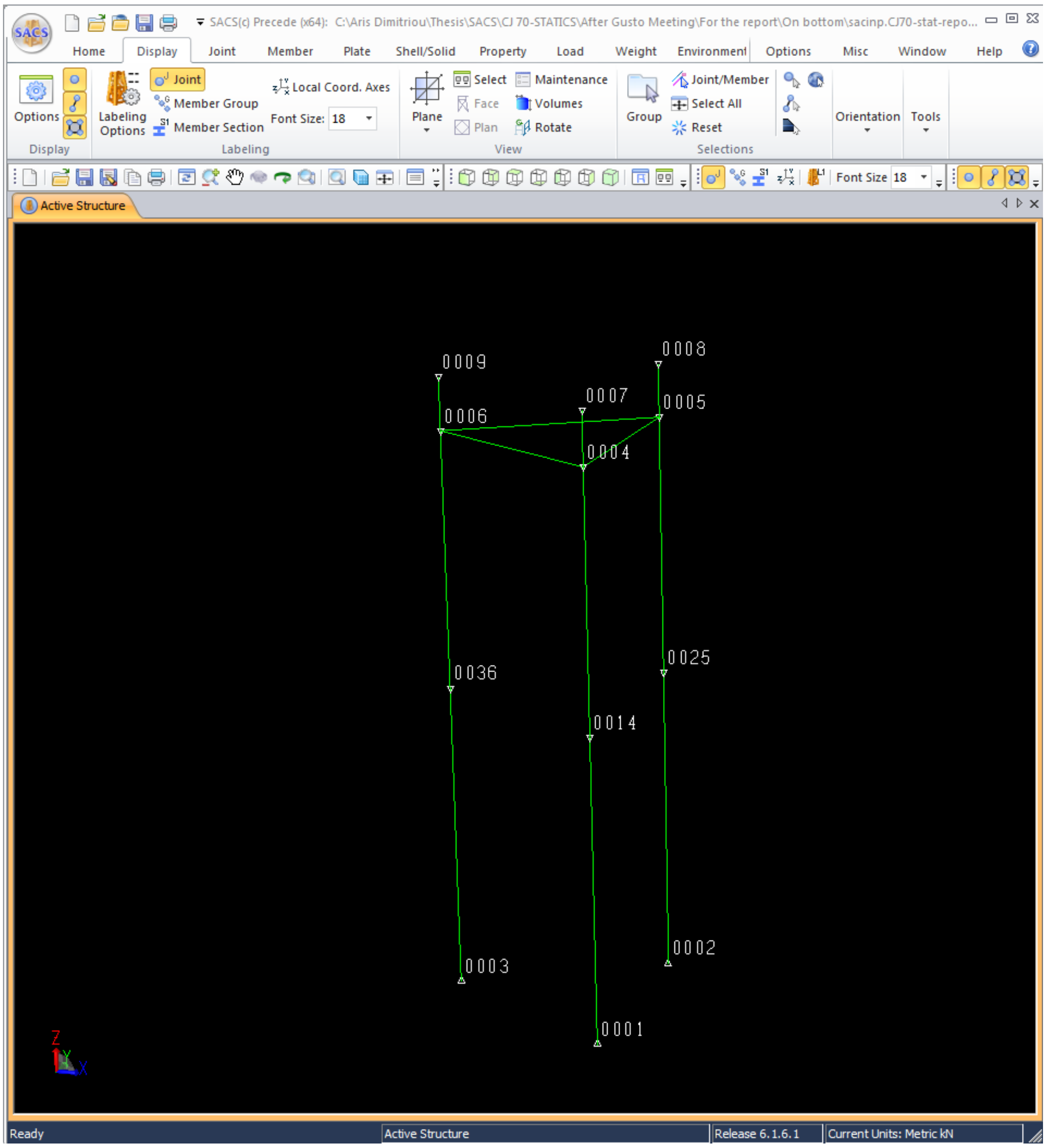

Figure 33 The model of the CJ 70 in SACS

The model of the CJ 70 on the SSfJ is the same as the above with the only difference that the spudcans are assumed pinned at 30 m above mudline and the water depth is also increased by 10, 20 or 30m for cases B,C and D respectively. In this manner the "ideal" SSfJ is regarded infinitely stiff and also "hydro-dynamically" transparent in the sense that it does not affect the movement of the water particles.

4.2.1.9.1 Model characteristics

4.2.1.9.1.1 Main dimensions

The air gap is considered 24m for all cases. The hull beams are fixed to the legs at the elevation of the fixation system which in this case is assumed 13m above the keel.

The distance between the legs is 70m.

4.2.1.9.1.2 Cross section properties

The cross section properties, used for the structural checks, for the members in the model are presented below (Table 5). The procedure for the "equivalent stick model" was followed for the legs according to ISO 19905-1 paragraph A.8.3. For the derivation of these characteristics one should refer to Appendix 1. It must be noted that the cross section properties of the legs were overridden in order to calculate the hydrodynamic load (see 4.2.5.2.1.3)

Table 5 Cross Section properties used in SACS

Member type		Leg	Hull
Cross section type		Prismatic	Prismatic
Cross section height	[m]	4.82	8.00
Cross section width	[m]	4.82	7.03
Shear area	[m^2]	0.1425	auto*
Area	[m^2]	0.8348	auto*
Torsional moment of inertia	[m^4]	7.7	auto*
Moment of inertia around major axis	[m^4]	45.08	auto*
Moment of inertia around minor axis	[m^4]	45.08	auto*

*Auto denotes that the value was calculated by SACS

4.2.1.9.1.3 Hydrodynamic Characteristics

The legs were modeled as "equivalent sticks" for the calculation of the hydrodynamic loads by following the procedure described in paragraph A.7.3.2.3. The resulting equivalent diameter and area are:

D_e=2.14m and A_e=3.60m^2

The equivalent drag and inertia coefficients for every flow direction are presented in

Table 6:

Table 6 Equivalent drag and inertia coefficients

Wave direction [^{o}]	Cdi	Cmi
0	3.25	1.6
15	3.55	1.6
30	3.71	1.6
45	3.55	1.6
60	3.25	1.6

4.2.1.9.1.4 Weight

4.2.1.9.1.4.1 Hull weight

The mass of the hull is assumed to be 30000 tonnes including variable loads. Due to lack of information it was assumed that this mass is equally distributed over the hull and therefore an equivalent distributed load was applied throughout the beams that represent the hull. The distributed load for each hull beam is:

$q_{w,hull}$=30000/3/70*9.81=1401 kN/m

4.2.1.9.1.4.2 Leg weight

The leg mass is assumed to be 3000 tonnes. For an explanation of this assumption one should refer to Appendix 1. For a leg length of 204.3 m the distributed weight for the leg is:

$q_{w,leg}$=3000*9.81/204.3=144 kN/m

4.2.1.10 Analyses and checks

Analyses are inspired by checks described in ISO-19905-1. This code refers to the site specific assessment of jack-ups. Some of the checks included in this code seem applicable to the needs of this study and therefore are performed with some small modifications/simplifications. The type of analysis done at this step is a basic static analysis for the most extreme environmental conditions.

4.2.1.10.1 Analysis set up

A summary of the directions used throughout the thesis is presented below (Figure 34). Due to the symmetry of the structure only 5 directions where used in total throughout this thesis.

The analysis at this phase is done for wave, current and wind direction 0. The load characteristics are explained at 4.2.5.3.2.1. In all the analyses, wind wave and current are co-directional.

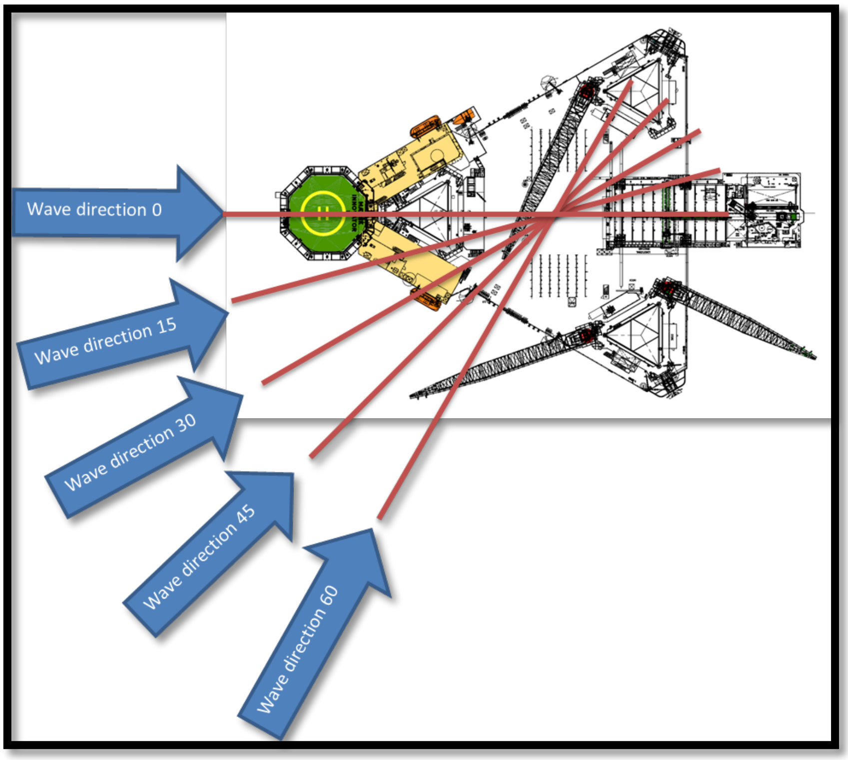

Figure 34 Directions used w.r.t. CJ 70

Pinned foundation is assumed for the spudcans. The assumption of pinned foundation is conservative because the CJ 70 has spudcans with skirts, which in most of the sites introduce some fixation. However for the purpose of comparing the effect of environmental loads between the two situations a pinned foundation can lead to a good result. P-Δ effects and shear deformation of the legs were taken into account.

4.2.1.10.2 Input

4.2.1.10.2.1 Loads

The environmental conditions that are assumed in the calculations are prescribed in Chapter 3 where the design input is presented. It is noted again that the environmental conditions to be faced by the CJ 70 on the SSfJ match the design environmental of the CJ 80 type jack-up and are also the same as the environmental conditions used for the design of the CJ 70 for the on bottom situation (Situation A) (see also Chapter 3). The values of the design loads used in the analysis are presented below. For the purpose of this chapter the loads were combined with a load factor of 1, and it is known that this might not be the case in the calculations for the actual ultimate limit state for this jack-up, however it is considered a conservative load combination.

4.2.1.10.2.1.1 Wind

A wind velocity of 10 m/s at 10m above the mean sea level was used. The wind load on the jack-up is calculated in Appendix 1 based on ISO 19905-1 paragraphs A.6.4.6.2. and A.7.3.4. The resulting values for the wind load are presented in Table 7. One third of the wind load is applied as a concentrated load on each leg at the elevation of the resultant wind action. This elevation is produced as a weighted mean of the elevations of the wind forces on each building block.

Table 7 Wind load in direction 0 for all situations

	Water depth	Total Wind load in direction 0	Elevation of the resultant wind force w.r.t. SWL
Situation	[m]	[MN]	[m]
A) On bottom	150	8.90	48.2
B) On the SSfJ	160	9.76	49.6
C) On the SSfJ	170	9.31	48.7
D) On the SSfJ	180	8.90	48.2

It must be noted that the wind load differs due to the difference in the part of the leg that extends above the hull. For a support structure with the height of 30m the part of the leg that extends beyond the hull for conditions A and D is the same (reminder - all situations have the same air gap, see Figure 32). For condition B an additional part of 20 m of leg is subjected to wind load compared to situations A and D. This part is above the hull and obviously the wind velocities at that altitude are larger, leading to a bigger wind load. Similarly for condition C an additional part of 10 m is subjected to wind load above the hull compared to conditions A and D.

4.2.1.10.2.1.2 Wave

The design wave height is 29m and the associated wave period is 16s (based on Chapter 3). In the analyses, the wave is passed through the structure with steps of 10 m and at each step the static forces are calculated. No dynamic amplification factor is used at this stage.

Based on ISO 19905-1 paragraph A.7.3.3.3.1. the applicable wave theory for the analysis performed at this stage is selected.

For H=29m , T=16s and g=9.81 m/s^2 the determination of the appropriate wave theory follows.

Table 8 Input for the determination of the appropriate wave theory

Situation	depth [m]	H/gT^2	d/gT^2
A) On Sea bottom	150	0.012	0.060
D) On SSfJ (at 180m WD)	180	0.012	0.072

Using the above input for the smallest and largest value of water depth and Figure 35 it is decided to use a third order stream function.

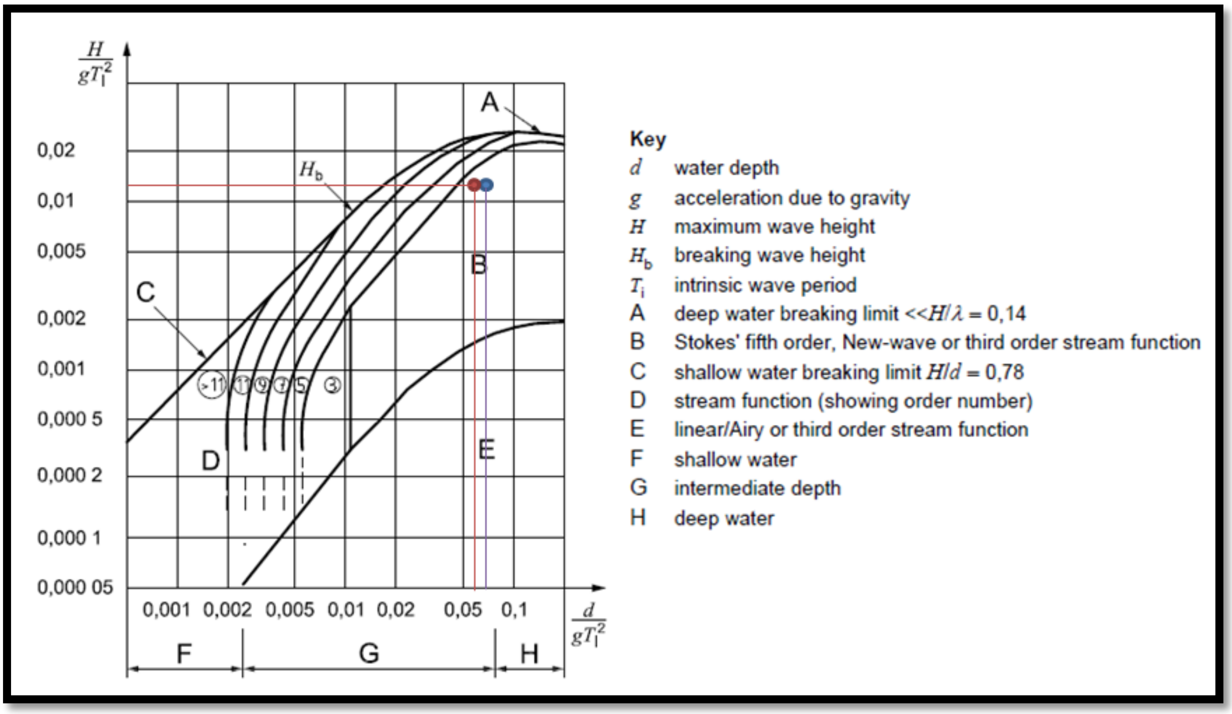

Figure 35 Selection of the appropriate wave theory. (ISO 19905-1, 2012)

A kinematic factor was applied based on ISO 19905-1 paragraph A.6.4.2.3 “in order to obtain realistic estimates of the actions for the extreme storm event”. The formula for the calculation of the kinematic factor is:

$\phi = 1.0193 - 0.00208\ |\psi|$

where

ψ latitude in degrees

In this analysis the value of $\psi = 58^{o}$ was applied which corresponds to a mean value for latitude in the North Sea. Therefore ϕ= 0,9

4.2.1.10.2.1.3 Current

ISO suggests a profile as described in 4.2.4.2.2.1.1. However in this analyses a more conservative profile is used that has a current velocity of 1m/s throughout the whole depth. Although the current velocities are the same for both a) and b), current is taken into account because of the nonlinearity of the hydrodynamic load. To explain this one should recall the Morison equation where the drag force is dependent on the velocity of the water particles to the power of 2. This means that by ignoring the current the result can be very different and the comparison between the various situations can be inaccurate.

4.2.1.10.3 Results comparison for static analyses with extreme weather conditions

In this paragraph the results for the analyses in SACS of the models for all the situations are presented and compared. The comparison is done between specific parameters. The parameters chosen are:

1. Max total base shear
2. Max hull displacement
3. Max bending moment at the level of the fixation system
4. Max overturning moment

In Table 9 the values for the selected parameters are presented.

Table 9 Comparison of the results of Static analyses

	Water depth	Total Base Shear	Hull displacement	Max moment (at the fixation system)	Max OTM
Situation	[m]	[kN]	[m]	[MNm]	[MNm]
A) On bottom	150	30942	3.206	1947	5414
B) On the SSfJ	160	30139	2.972	1800	4530
B) On the SSfJ	170	29897	3.044	1844	4882
B) On the SSfJ	180	29850	3.131	1899	5296

4.2.1.10.3.1 Base shear comparison

As it can be seen in Table 9, the max base shear is maximum for situation A and decreases in cases B to D. This shows that the environmental loads (wind, wave and current) in situation A (where the CJ 70 stands on the sea bottom) are bigger compared to all the other cases (where the CJ 70 stands on the SSfJ). Keeping in mind that the wind load in situations B and C is greater than that in situation A (Table 7), one can conclude that the hydrodynamic loads are smaller in cases B and C compared to case A. This is actually true and it is related to an issue that is well known in the area of hydromechanics. An explanation and a proof for this follow:

The explanation for the decrease in hydrodynamic load with increase of water depth relates to the change in the movement of water particles as water depth increases. **When the water depth increases**, and provided that it is not considered deep water, **the water particles' horizontal velocities and accelerations decrease** (according to linear wave theory). According to (Journee & Massie, 2001), the conditions of deep water apply when the water depth at a location is bigger than half of the wave length. In the analyses performed at this stage, for a wave of 29m height with a period of 16s the wave length varies from 438.5m at 150m water depth to 443.5m at 180m water depth. This immediately means that the water depths from 150 to 180m are considered "intermediate waters" for this wave, since half of the wave length is more than the water depth (440/2=220>180). Therefore the water particles horizontal velocities and accelerations max values decrease from situation A to situation D. This is illustrated in Figure 36 which is produced by the output of SACS.

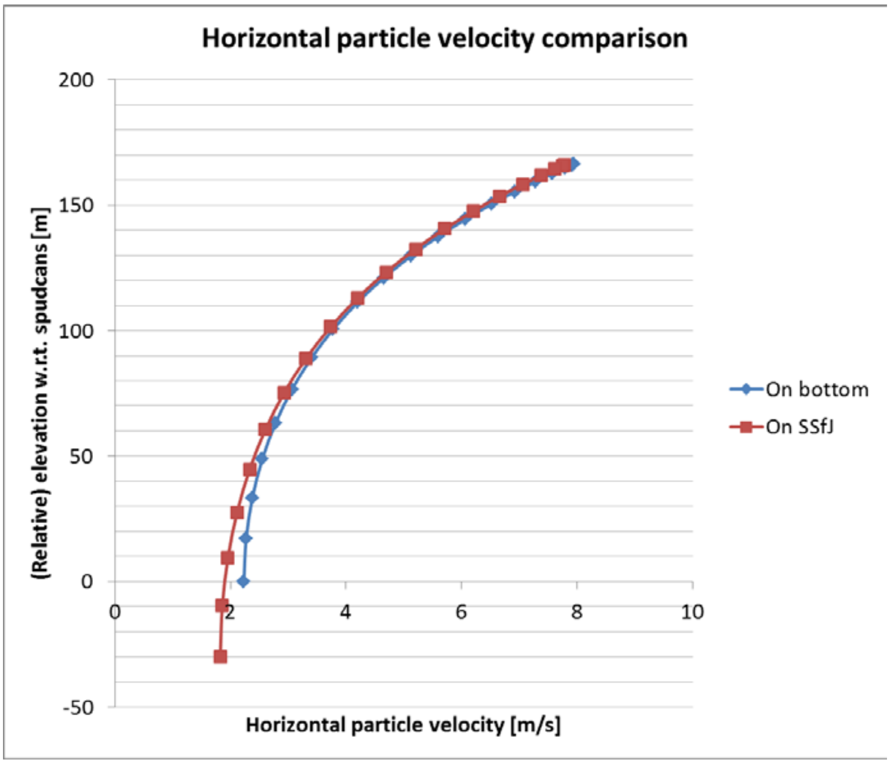

Figure 36 Max horizontal particle velocity comparison for situation A and D

The water particle velocities and accelerations are involved in the hydrodynamic load in a way that is represented in the well-known Morison equation. Obviously, bigger particle velocities and accelerations lead to bigger hydrodynamic loads.

4.2.1.10.3.2 Hull displacements and max moments comparison

The overturning moment (OTM) is measured with respect to the lower end of the legs and not with respect to the foundation of the SSfJ on the sea bottom. The max hull displacement, the max leg bending moment and the max overturning moment increase with the **increase** of water depth for the situations B,C and D **but never exceed** the values that correspond to situation A. In the comparison between situations A and D this is caused by the fact that the hydrodynamic loads are smaller in deeper water. However, the results for situations B, C and D are not only related to the decrease of hydrodynamic load as explained in 4.2.5.3.3.1 but also to the fact that when the CJ 70 stands on the SSfJ, the distance between the application of the wind load and the bottom of the legs is smaller (see Figure 38).

From basic mechanics it is known that the deflection of a cantilever beam is given by the next formula and Figure 37:

$$\delta = \frac{F\,L^3}{3EI}$$

Where

δ is the deflection of the tip
F is the force

L is the distance between the tip and the fixation point
E is the modulus of elasticity
I is the moment of inertia of the cross section of the beam

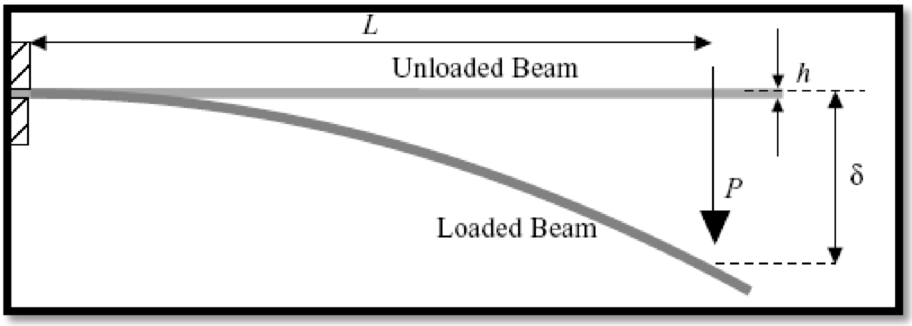

Figure 37 Beam deflection

A jack-up can be simplified into a beam like that on Figure 37. Therefore for a given air gap and varying water depths the distance between the wind load application point (on average about 48m above SWL as shown in Table 7) and the lower fixation point for each situation varies from 178m for situation B to 198m for situations A and D as shown in Figure 38:

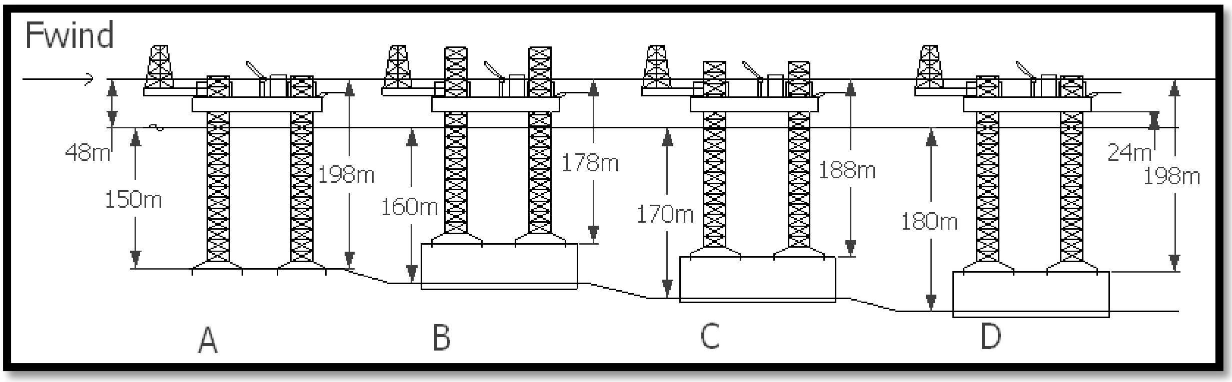

Figure 38 Distance between wind force application level and lower fixation level

In the formula presented in this paragraph the distance between the load and the fixation point is at the power of 3 and this signifies that the importance of this distance is greater than the importance of the magnitude of the force (which is at the power of 1). Therefore it makes sense that the displacements for situations B and C are smaller than those of conditions A and D. This is illustrated with the following simple comparison of the simple beam deflections between situations B and D:

$$\frac{\delta_B}{\delta_D} = \frac{\frac{F_B\, L_B{}^3}{3EI}}{\frac{F_D\, L_D{}^3}{3EI}} = \frac{F_B\, L_B{}^3}{F_D\, L_D{}^3} = \frac{9.76 * 178^3}{8.90 * 198^3} = 0.796$$

The above comparison shows that the deflection due to wind load in situation B is approximately 80% of the deflection due to wind load in situation D. In a similar manner the deflections due to hydrodynamic loads can be compared. The behavior of deflections is in line with the behavior of bending moments at the elevation of the fixation point.

4.2.1.11 Step 1.4 Conclusion

After performing static analyses with the wind, wave and current loads for the CJ 70 on the sea bottom and for the CJ 70 on the SSfJ as explained above, the following can be stated:

Indeed the assumption made in 4.2.4.2.2.1 is valid and the jack-up will not be challenged more by the environmental loading when it is placed on the SSfJ compared to when it stands on the sea bottom.

This means that **from statics point of view** the environmental loads are less challenging for a CJ 70 on a SSfJ than for the same rig on the sea bottom.

1.5.18 Stage 1 Conclusion

In Stage 1 the effect of the use of an “ideal” SSfJ on the critical aspects of the design and the operation of jack-ups is treated.
First the critical aspects in the design and operation of jack-ups for the normal on bottom operation are identified. It is understood that the most important “bottle necks” are the dynamics and the leg-to-hull moment which are very much dependent on the foundation characteristics (which can also be critical). Then the effect of the use of a SSfJ on these critical aspects was assessed via assumptions which were also validated with simple checks.
It is understood that the use of the SSfJ will cause reduction in the (static) effect of environmental loading of the jack-up and therefore **the jack-up integrity when it is placed on a SSfJ is improved (from statics point of view)**.
During the assessment of the influence of the use of a SSfJ on the critical aspects of dynamics and leg-to-hull moment, it appears that some checks are very important for addressing the technical feasibility of the concept. These checks are related to the stiffness of the SSfJ and the amount of fixity that can be achieved between the SSfJ and the spudcans of the jack-up. It is therefore decided to deal with these checks more thoroughly at the next stage (Stage 2) and to give indications about the required values of SSfJ stiffness and fixity of the spudcan on the SSfJ.

4.3 Stage 2

This stage deals with the important checks identified in Stage 1 and aims to produce numerical values for the structural requirements of the SSfJ that should be used in case the concept reaches the design phase. To address these values a look in the dynamics of the concept is required. In this stage the situation at which the CJ 70 stands on the SSfJ at a water depth of 180m is only taken into account since as shown in Table 9 this is the most challenging condition for the jack-up on the SSfJ.

1.5.19 Introduction

It is important to first present the problem and the research question before addressing the procedure that is followed.

4.3.1.1 The research question – problem description

The research question is: "Which are the optimal values for the stiffness of the SSfJ and the stiffness of the interface between the SSfJ and the spudcans of the CJ 70 jack-up".

The effect and the importance of these values is explained well in 4.2.4.2.3.3.2.

However it is important to define what is considered as "optimum". To define the "optimum" it is useful to consider what is the current practice in the design of spudcans. As explained in Step 1, the designers of jack-ups usually aim to increase the fixity of the spudcans as much as possible (for this reason the designers developed spudcans with skirts). Based on that one could say that the optimum stiffness is the maximum technically achievable one. However to increase the stiffness it is most of the times necessary to use more material, thus to design a heavier and more expensive structure. It seems therefore that the "optimum" will be defined by the balance of two "opposing forces": the need for as big stiffness as possible and the need for as low cost as possible. For the particular case of this thesis it is considered enough to consider as "optimum" the combinations of SSfJ stiffness and interface stiffness that precisely secure the bottle necks against the most extreme environmental conditions (with a utilization of as close as possible to 100%). Any bigger stiffness would just be a waste of materials. The optimum is defined quantitatively in step 2.1.

4.3.1.2 Important assumptions

The SSfJ is assumed perfectly fixed to the sea floor. Also it is regarded stiffer as a structure compared to the CJ 70 because it will most likely be constructed as some sort of truss structure. In addition, it is assumed that the SSfJ is very stiff in the vertical direction, i.e. it will not deform significantly in the vertical direction when loaded by the jack-up. Under these assumptions the dynamic behavior of the SSfJ can be assumed to be quasi-static when it is subjected to loading from the jack-up. This means that the oscillations of the jack-up (therefore of the loads passed to the SSfJ) will have much lower frequency than the natural frequency of the SSfJ.

4.3.1.3 Structural System

Using the assumptions stated at 4.3.1.2 the structural system of the CJ 70 on the SSfJ can be simplified so that instead of a SSfJ structure, only the interface is modeled. In this case the interface can be modeled with 2 (horizontal) translational springs and 2 rotational springs per spudcan (no torsion is allowed for the spudcans). The translational springs account for the internal stiffness of the SSfJ and the rotational springs account for the fixity of the spudcans. The translational springs' stiffness will be called k_t and the rotational spring stiffness will be called k_r. Figure 39 shows a side view sketch of the structural system (only half of the springs per leg are depicted). Figure 40 shows the arrangement of the translational and rotational springs in space. As a reminder x direction is direction 0 degrees for environmental loads.

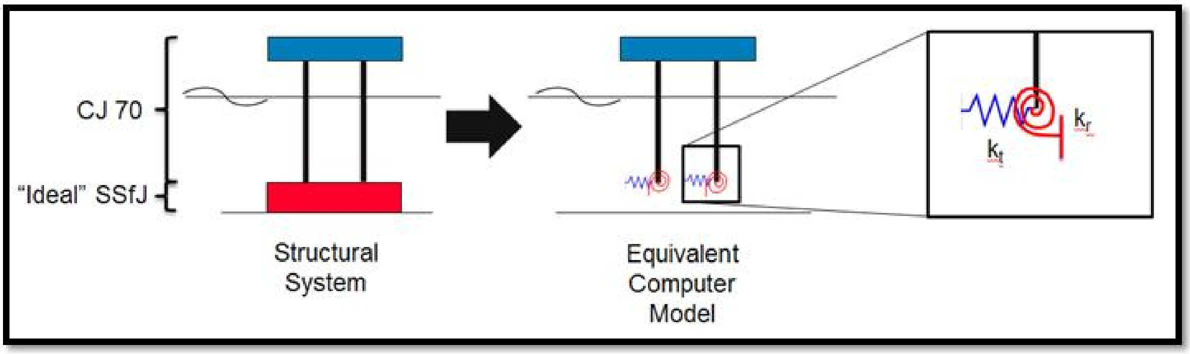

Figure 39 The structural system in Stage 2

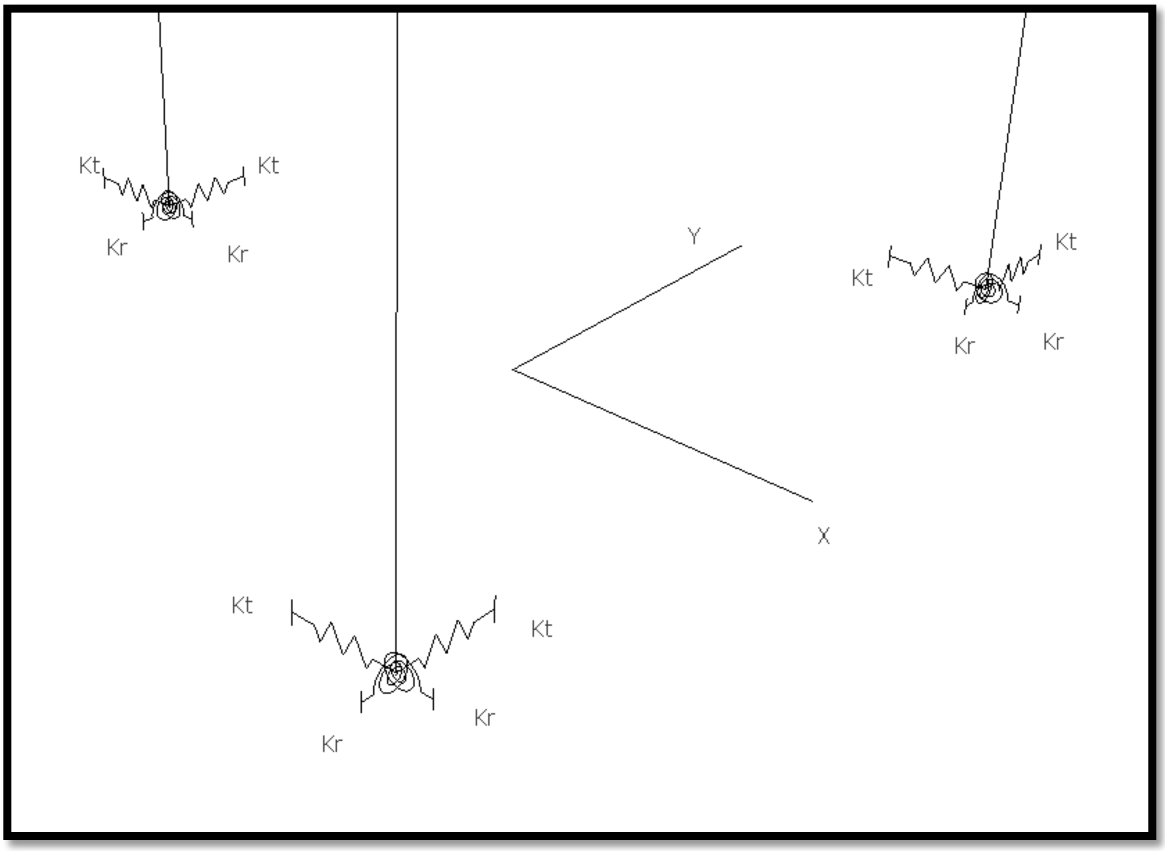

Figure 40 The arrangement of translational and rotational springs in space

1.5.20 Approach

Stage 2 is divided in 4 steps. A brief description of the steps is presented in Figure 41.

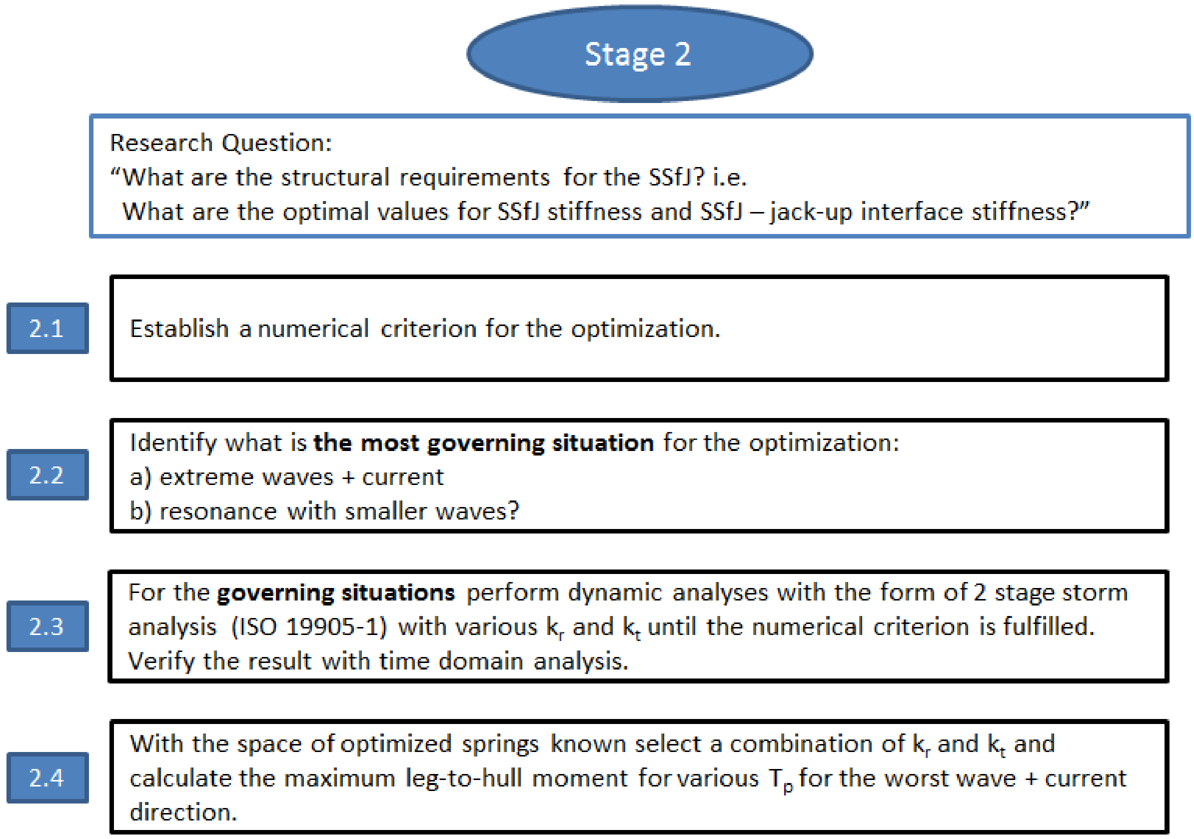

Figure 41 Stage 2 Approach

A more detailed explanation of each step of Stage 2 of the technical study follows:

2.1 In this step a numerical criterion is established for the optimization. As mentioned in 4.3.1.1 the optimum is defined as the combination of k_r and k_t that give a utilization of as close as possible to 100% at the bottle neck. Therefore it is decided to regard as criterion for the optimization the moment at the leg-to-hull interface, which should never exceed the leg bending moment capacity.

2.2 In this step the most difficult situation for the jack-up on the SSfJ is identified. It is understood that the most challenging conditions can be either the combination of extreme waves with current or the excitation of the jack-up from the waves at its natural period. Obviously, the most difficult situation must be used in the optimization

2.3 This step includes the calculations of the optimization. In order to quickly approach the optimum values of k_r and k_t a method of dynamic analysis that uses a dynamic amplification factor to calculate the inertia loads is applied according to ISO 19905-1 paragraph A.10.5.2. Various wave and wind directions are taken into account. Then the result of the optimization is verified with a time domain analysis which is considered more accurate.

2.4. The final step is to perform a sensitivity check with respect to wave period.

1.5.21 Step 2.1

In this step, the numerical criterion for the optimization is calculated. The objective is to calculate the maximum bending moment the leg of the CJ 70 can hold. To calculate the bending moment capacity of the leg, simple knowledge of statics is applied. It must be noted that since the dimensions of the members of the leg are estimated and not known in full detail, the resulting moment capacity might be different than the real one.

The shape of the cross section of the leg of the CJ 70 is known and presented in Figure 42 below:

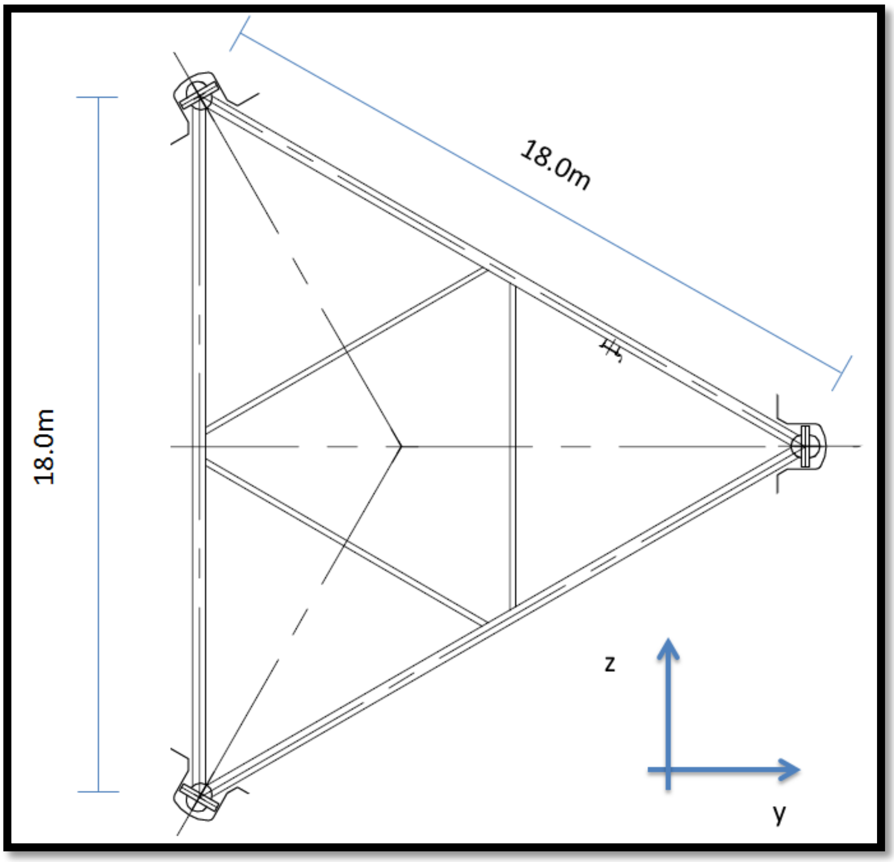

Figure 42 Cross section of the leg of the GustoMSC CJ 70 jack-up (Maersk Drilling, 2012)

The cross section properties are assumed in Appendix 1. The area of the chord is estimated to be A_C=0.2783 m^2 and the yield stress is known to be σ_y=690 MPa (ISO 19905-1, 2012). This gives a maximum compression capacity of $F_{u,c}$= 0.2783 * 6.9*10^8 = 192 MN

The bending moment capacity for the moment around the y axis equals the maximum compression in a chord multiplied with the distance of that chord from the opposite side. This is illustrated in Figure 43.

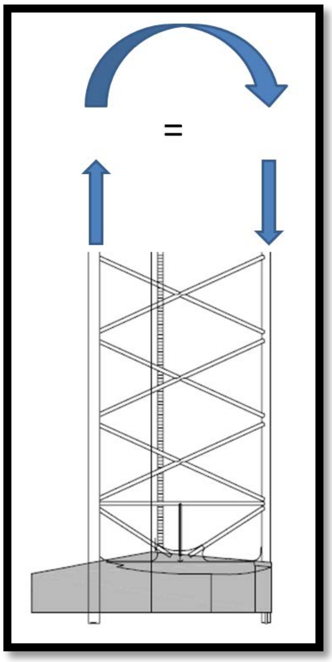

Figure 43 The bending moment can be substituted by 2 parallel opposite forces

The lever arm for the moment in z-direction is the distance between the chord at the right of Figure 42 and the brace at the left:

d = 18 * sin60^o= 15.588m

For the moment around the y axis the lever arm is the actual distance between the chords (18m).

Before calculating the max bending moment capacity it is necessary to deduct the compression due to weight of the hull and the leg. This is dependent on the level at which the check focuses and therefore two capacities are calculated: one for the elevation of the leg-to-hull interface and one for the elevation of the spudcans (bottom of the leg).

4.3.1.4 Moment capacity at the leg-to-hull interface

Based on the assumption of equal distribution of hull weight to the three legs (see 4.2.5.2.1.4), every leg has to carry 10000 mT of hull and 3000 mT of leg weight. An assumption is made that hull weight, due to the movement of the jack-up, will at some point be carried more by the rear chord than by the other chords and in a proportion of 75% for the rear and 25% for the rest:

$F_{c,hull\ weight}$ =10000*0.75*9.81/1000 = 73.57 MN

In these analyses the hull is fixed to the leg at the elevation of 187m from the lower end of the leg and the leg length is 204.3m. Thus the weight of the leg that is carried at this point is:

$F_{c,leg\ weight}$ = (204.3-187)/204.3*3000/3*9.81/1000 = 0.83 MN

This gives an individual compression per chord of:

$F_{c,weight}$ = 73.57+0.83 = 74.4 MN

Thus the spare compression capacity left for receiving the leg z-moment is:

$F_{c,z,eff}$ = 192 – 74.4 = 117.6 MN

The z-moment capacity of the leg can now be determined as:

$M_{u,z}$ = 117.6 * 15.588 = 1833 MNm.

For the calculation of the moment capacity in y direction the same weight distribution is assumed, thus:

$M_{u,y}$ = 117.6 * 18 = 2116.7 MNm

Note: In the above calculations, conservative assumptions about the hull weight distributions are made.

4.3.1.5 Moment capacity at the lowest part of the leg

At this point the weight carried includes the whole leg weight. Therefore

$F_{c,leg\ weight}$ = 3000/3*9.81/1000 = 9.81 MN

Again it is assumed that at some point 75% of the hull weight will be carried by one chord thus:

$F_{c,hull\ weight}$ =10000*0.75*9.81/1000 = 73.57 MN

This gives an individual compression per chord of:

$F_{c,weight}$ = 73.57+9.81 = 83.38 MN

The spare compression capacity left for receiving the leg z-moment is:

$F_{c,z,eff}$ = 192 – 83.38 = 108.62 MN and is obviously smaller than the one calculated for the higher level due to the addition of the whole leg weight.

The z-moment capacity of the bottom of the leg can now be determined as:

$M_{u,z}$ = 108.62 * 15.588 = 1693 MNm.

For the calculation of the moment capacity in y direction the same weight distribution is assumed, thus:

$M_{u,y}$ = 108.62 * 18 = 1955 MNm

It is useful to collect the above values in one table:

Table 10 Bending moment capacities

	Leg-to-hull	Bottom of the leg
	[MNm]	[MNm]
$M_{u,z}$	1833	1693
$M_{u,y}$	2117	1955

In the calculations this value should be reduced with the appropriate resistance factors. It is decided to use a partial resistance factor of 1.1 for the bending strength and this is explained in 4.3.5.3.1.4.

1.5.22 Step 2.2

It is obvious that the optimization should be performed for the most governing loading situation. In this way the solution can be applicable in all the circumstances the jack-up might face while placed on top of the SSfJ. In this step a decision is made based on calculations and reasonable assumptions about which are the most governing conditions.

4.3.1.6 Possible governing situations

It is believed that the most challenging circumstances for the survival of the jack-up on the SSfJ will be either the extreme wave with current or the resonance with smaller waves. From the one hand, extreme waves and current contain a very big amount of energy which passes on the jack-up and creates large internal forces. The significance of extreme wave and current is illustrated by the fact that the GustoMSC product sheets show the values of the extreme weather conditions as survival design conditions, while they do not show the dynamic characteristics of the jack-up, nor they refer to resonance.

From the other hand, for a concept like the SSfJ where the static system of the jack-up will not be the one checked by the jack-up designers, it is important to check the dynamic behavior and especially to identify if the effect of resonance can be significant. Just to introduce the possible challenge, one can imagine that since the jack-up will be placed on a support structure (most likely made of steel), there will be less damping in the oscillation of the jack-up, compared to when it is placed on soil, due to the lack of soil damping. Of course there will be some soil damping due to the fact that the SSfJ is placed on soil, but in this analyses it is conservatively regarded that soil damping is not present. The decrease in damping can lead to a significant increase of the inertia forces due to the oscillation of the jack-up and it could possibly be the case that resonance can be a more challenging condition compared to extreme weather.

It is not straight forward what the governing situations will be because the importance of both possibly governing situations is determined by the values of k_r and k_t. For example, low values of k_r and k_t can lead to large natural period of the structure and thus to resonance with larger waves which can lead in bigger leg-to-hull moment compared to the moment produced with slightly bigger waves but no resonance. This is explained further below.

4.3.1.7 Step 2.2 approach

To find the most governing conditions, the two conditions [a) extreme wave + current and b) resonance] must be compared. An easy way to compare the two conditions would be to just compare the static and dynamic loads for each one of them. If this comparison would not yield a clear difference, then another more specific criterion should apply, for example the moment at the elevation where the leg is connected to the hull, i.e. the so called leg-to-hull moment.

At this point a rough but quick method to address the relative significance of the different conditions was applied. The physical problem of jack-up dynamics is simplified and it is treated as a single degree of freedom mass-spring-damper system. The solution of the physical problem in its simplified version is then validated with a more accurate method which makes use of time domain analyses. For the simplified problem, it is decided to make use of the Dynamic Amplification Factor (DAF) as described in ISO 19905-1 paragraph A.10.5.2. because it can give a quick insight in inertia loads with varying natural period and wave period. However this method has some limitations which are explained in 0.

The comparison is done for natural periods varying from 6s to 10.5s and is based on the 2 stage deterministic storm analysis as described in ISO.

The procedure is presented in and explained below .

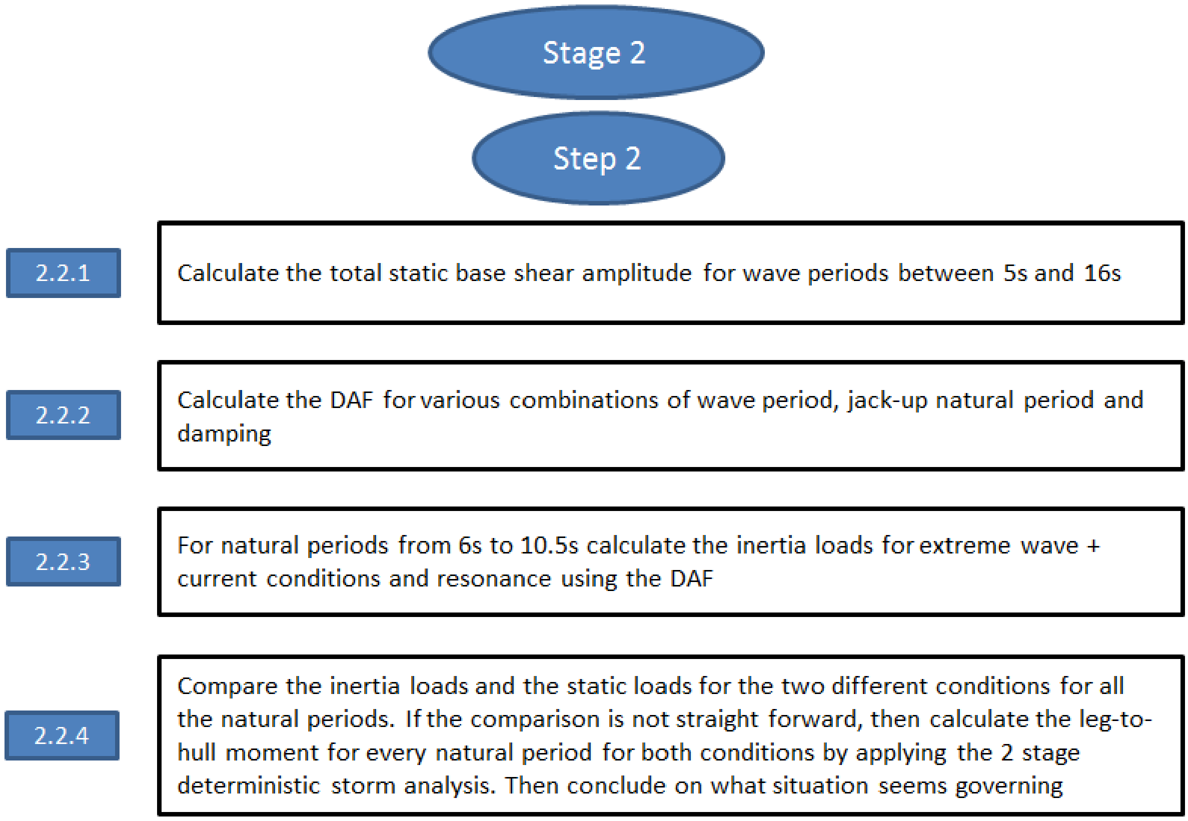

Figure 44 Stage 2-Step 2 approach

Initially static analyses are performed for one direction (0 degrees) and one deterministic wave per analysis combined with the extreme current. The analyses are carried out for wave periods ranging from 5s to 16s and the wave heights for the respective periods are calculated based on ISO 19905-1 paragraph A.6.4.2.3. The analyses produce the total base shear amplitude which is necessary for the calculation of the inertia loads with the DAF.

The DAF can be specified for various combinations of wave period, natural period of the jack-up and damping. At this stage the natural period of the jack-up is unknown and therefore the DAF is calculated for natural periods of jack-up between 6s and 10.5s as these are the expected boundaries for the natural period (see 4.2.2).

The next step is to compare the inertia loads for every natural period between the 2 conditions. If the differences are not significant calculate for several potential natural periods of the jack-up the leg to hull moment for both the condition of resonance and extreme weather (wave and current only). The calculations shall be done based on the 2 stage deterministic storm analysis described in ISO 19905-1 paragraph A.10.5.2.2.2. This will eventually determine what situation is governing.

4.3.1.8 Calculations

4.3.1.8.1 Step 2.2.1

The static analyses are performed in SACS. The model used is the same as in Stage 1 Step 4 Situation D (180m water depth). The analyses are carried out for wave and current direction of 0 degrees as specified in Figure 34. A deterministic wave is used per analysis and the wave characteristics are specified as follows.

For wave periods from 5s to 16s with a step of 0.5s the wave height was calculated. ISO 19905-1 suggests that the period of a deterministic wave shall be related with the significant wave height, in absence of any site specific data, as follows [simplified formula is used here]:

$$3.44\sqrt{(H_s)} < T < 4.42\sqrt{(H_s)}$$

Where

H_s is the significant wave weight in meters
T is the intrinsic wave period in seconds

From the design input presented in Chapter 3 it is known that the maximum wave height is 29m and has a period of 16s. This, according to formula (A.6.4-1) of ISO 19905-1, implies a significant wave height of: H_s = 29 / 1.86 = 15.59m

Therefore the relationship between wave period and wave height is:

$$\frac{T}{\sqrt{H_S}} = \frac{16}{\sqrt{15.59}} = 4.052$$

In the analyses performed in this thesis it was decided to use the above relationship for the wave height and period, i.e.:

$H_s=(T/4.052)^2$

This produces the following wave characteristics (Figure 45):

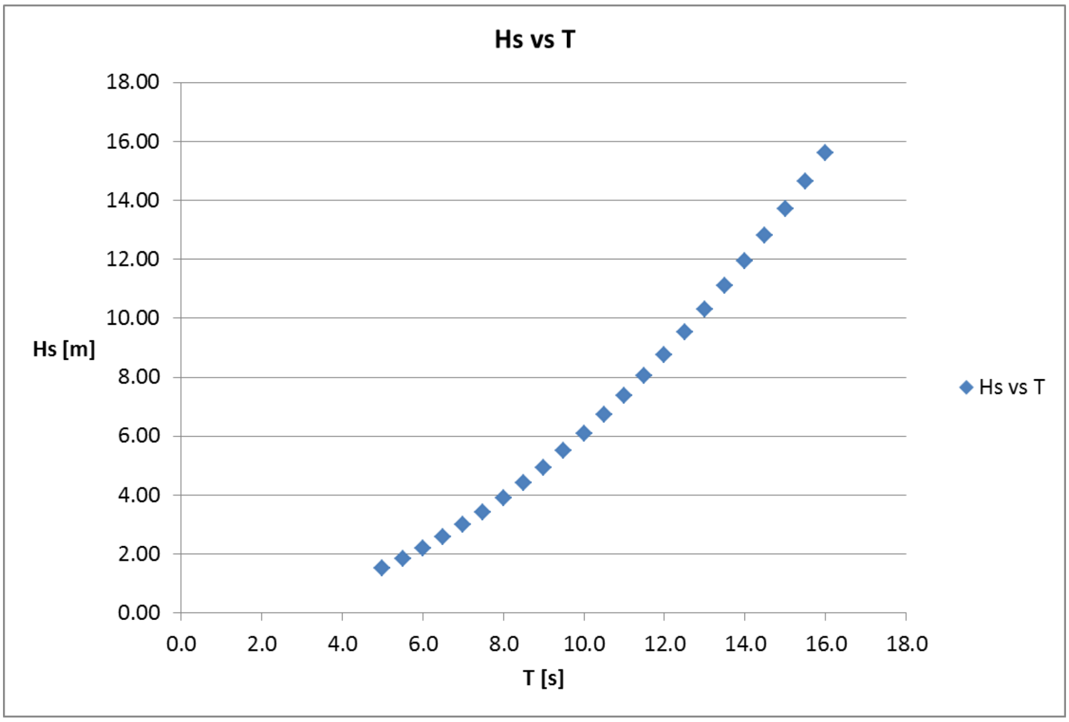

Figure 45 Wave height vs Wave period used to determine the static base shear

A static analysis is carried out for each wave combined with a uniform current of 1 m/s at the same direction. The static analysis is performed by stepping a wave through the structure in many steps and by calculating the static forces at each step using the Morison equation. The structure is considered still at every step and therefore no dynamic amplification takes place. The resulting total base shear values are presented below and the value needed in the calculations further below is the one of the static base shear amplitude which is defined as the difference of the maximum and the minimum value divided by 2.

Table 11 Static Base Shear for various waves in direction 0

T	H_s	BS_{max}	BS_{min}	BS amplitude
[s]	[m]	[kN]	[kN]	[kN]
5.0	1.52	1749	1570	89.5
5.5	1.84	1819	1449	185
6.0	2.19	2028	1336	346
6.5	2.57	2140	1277	431.5
7.0	2.98	2173	1284	444.5
7.5	3.43	2225	1356	434.5
8.0	3.90	2267	1469	399
8.5	4.40	2329	1504	412.5
9.0	4.93	2423	1367	528
9.5	5.50	2559	1220	669.5
10.0	6.09	2640	1062	789
10.5	6.71	2850	919	965.5
11.0	7.37	3159	773	1193
11.5	8.05	3530	645	1442.5

12.0	8.77	3939	504	1717.5
12.5	9.52	4416	353	2031.5
13.0	10.29	4934	208	2363
13.5	11.10	5522	46	2738
14.0	11.94	6177	-2	3089.5
14.5	12.81	6884	-241	3562.5
15.0	13.70	7642	-386	4014
15.5	14.63	8486	-533	4509.5
16.0	15.59	9391	-673	5032

It is helpful for the reader to present a graph of the amplitude of the total static base shear. Such a graph is presented in Figure 46.

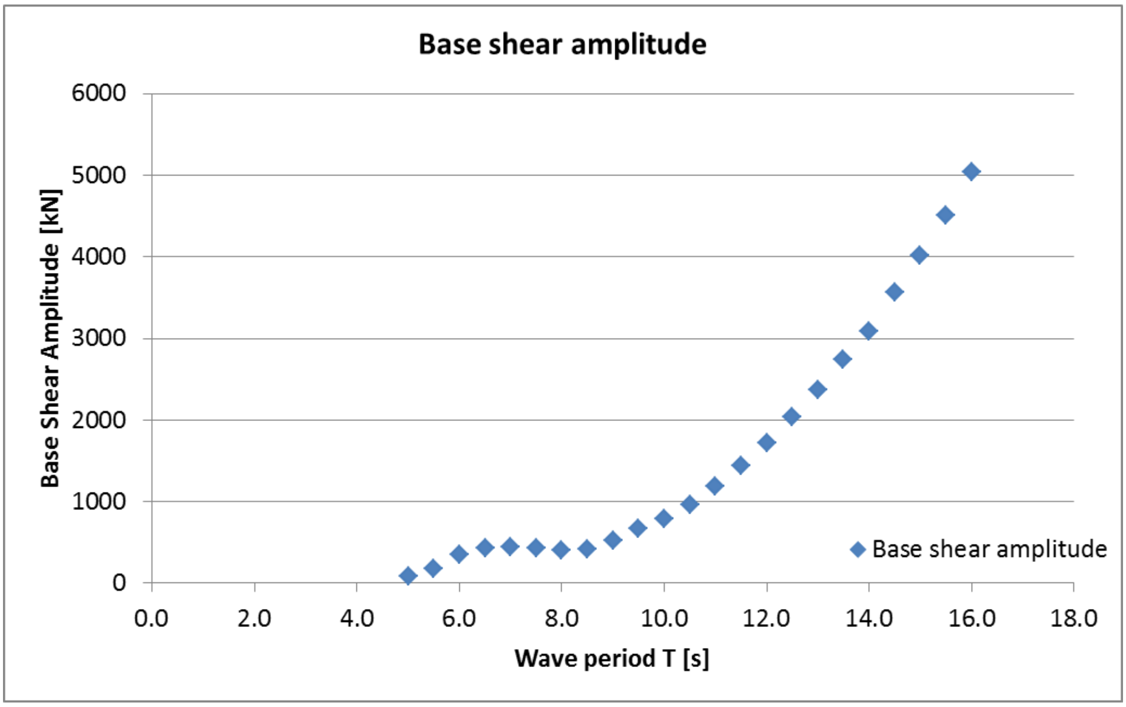

Figure 46 Amplitude of the total static base shear for various waves in direction 0

The above figure shows an interesting characteristic of the jack-up structure. It is visible that the amplitude of the base shear for waves with period of 7s is bigger than for waves with period of 8 seconds, even though the wave height of waves with 8s is bigger. This phenomenon is called reinforcement and is caused by the different phase at which the waves hit the legs of a jack-up. It can be easily explained as that the waves' crests hit the bow leg and the rear legs of the jack-up at the same moment. The opposite is called cancellation and can lead to small base shears.

4.3.1.8.2 Step 2.2.2

At this step the DAF is calculated for various values of wave period and jack-up natural period.

4.3.1.8.2.1 DAF limitations

4.3.1.8.2.1.1 General DAF limitations as stated in ISO

Before showing the calculations it is important to mention the limitations of this method as stated in the ISO code paragraph A.10.5.2.2.2:

"This representation assumes that the jack-up on its foundation can be modeled as an equivalent single degree-of-freedom mass-spring-damper mechanism.[]The torsional mode and corresponding three-dimensional effects cannot be included in this representation.

The SDOF method is fundamentally empirical because:
- the wave/current action does not occur at the hull;
- the excitation is non-periodic (random) and non-linear.

The method generally leads to an approximation of the jack-up's real behavior that has been calibrated against more rigorous methods. The following cautions are noted when using the SDOF method.

a) If the ratio of the jack-up natural period to the wave excitation period, Ω, is in the range 0,4 to 0,8 and the current velocity is small relative to the wave particle velocities, the SDOF method can give reasonable results, subject to items b) to d) below.

b) The SDOF method does not account for reinforcement and this can make the method unconservative, particularly when Ω > 0,5. When Ω > 0,5, there can be significant energy in an irregular sea at the jack-up natural period, and this is not accounted for in the SDOF method because the DAF is not affected by any periodicity other than the excitation at 0,9Tp. This lack of excitation is particularly important when the jack-up natural period is close to a wave reinforcement point. In this case, the resonant response, combined with reinforcement, can result in a significantly higher action than that calculated from the SDOF method. []

c) The SDOF method can be unconservative for cases where the current velocity is large relative to the wave particle velocities. If the results of the assessment are close to the acceptance criteria, further detailed analysis is recommended.

d) The SDOF method can be unconservative and should not normally be used in an extreme storm

assessment when Ω is greater than 1,0, i.e. when Tn > 0,9Tp. However, the SDOF analogy may be used when the calculated Ω is greater than 1,0 providing Ω is taken as 1,0.

When using the SDOF method, a minimum value of 1,2 should be taken as the DAF in an extreme storm assessment, regardless of the DAF calculated using the SDOF method."

4.3.1.8.2.1.2 DAF limitations specific for this thesis

In this thesis the DAF was calculated for the natural period in surge direction only. This could lead in an inconsistency when calculating the inertia forces for loading in directions other than the surge direction (Direction 0 in this thesis). However, as shown in 4.3.5.2.1, for the jack-up model of this thesis the first two natural periods are almost equal, due the symmetry of the model and the mass distribution. This means that the DAF should be the same for oscillation in direction 0 (surge) and direction 90 (sway). Since the whole procedure of using the DAF is simplistic, this inconsistence is accepted at this stage but it is considered necessary to validate the results with more accurate methods such as time domain simulations.

4.3.1.8.2.2 DAF formula

The DAF can be calculated using formula A.10.5-1 of ISO 19905-1. The formula is presented below:

$$K_{DAF,SDOF} = \frac{1}{\sqrt{(1-\Omega^2)^2 + (2\zeta\Omega)^2}}$$

Where

Ω	is the jack-up's natural period (T_n) divided by the excitation period (T_w), $\Omega = T_n/T_w \leq 1$
ζ	is the damping ratio or fraction of the critical damping, $\zeta \leq 0.07$
T_w	=0.9T
T	is the wave period
T_n	is the natural period of the jack-up

4.3.1.8.2.3 Damping

The importance of damping in dynamics is very significant. As known from basic knowledge of dynamics, damping determines the importance of resonance in a way that for low values of damping, resonance produces large inertia forces and thus large internal loads. Since resonance with waves cannot be avoided as the natural period of jack-ups always falls within the period range of sea waves, special care should be taken in the estimation of the damping value. ISO suggests the following values for various sources of damping in percentage of the critical damping:

- 2% for the structure and the holding system etc.
- 2% for the foundation
- 3% for hydrodynamic damping

For the SSfJ concept it is believed that the only influenced value of the above mentioned will be that of the foundation damping. Since the SSfJ is expected to be a steel structure and since it is assumed to be perfectly fixed on the sea bottom it is believed that a value of 0% for foundation damping is a safe choice for the analyses done in this thesis. This means that the damping used is 5% of the critical.

4.3.1.8.2.4 DAF calculation

With the value of damping selected in 4.3.4.3.2.3, the DAF can be calculated as a function of wave period and jack-up natural period. Therefore a range for each parameter was selected.

The range for wave period is selected to be from 5s to 16s. It is known that waves with period smaller than 5s have quite small wave heights and thus do not contain significant amount of energy. On the other hand waves with period above 16 s are not taken into account because it is known that the CJ 70 jack-up is designed with an extreme wave that has a period of 16s.

The range for jack-up natural periods is selected to be from 6 to 10.5 seconds. As described in 4.2.2, (Hoyle, et al., 2006) mention that the natural period of typical deep water jack-ups ranges from 6 to

10s depending on the level of foundation fixity. Since the jack-up used in the technical study is currently the biggest in the market, it was decided to consider for the calculations of the DAF a range of natural periods from 6 to 10.5s.

The DAF was calculated and plotted in a contour plot that follows Figure 47.

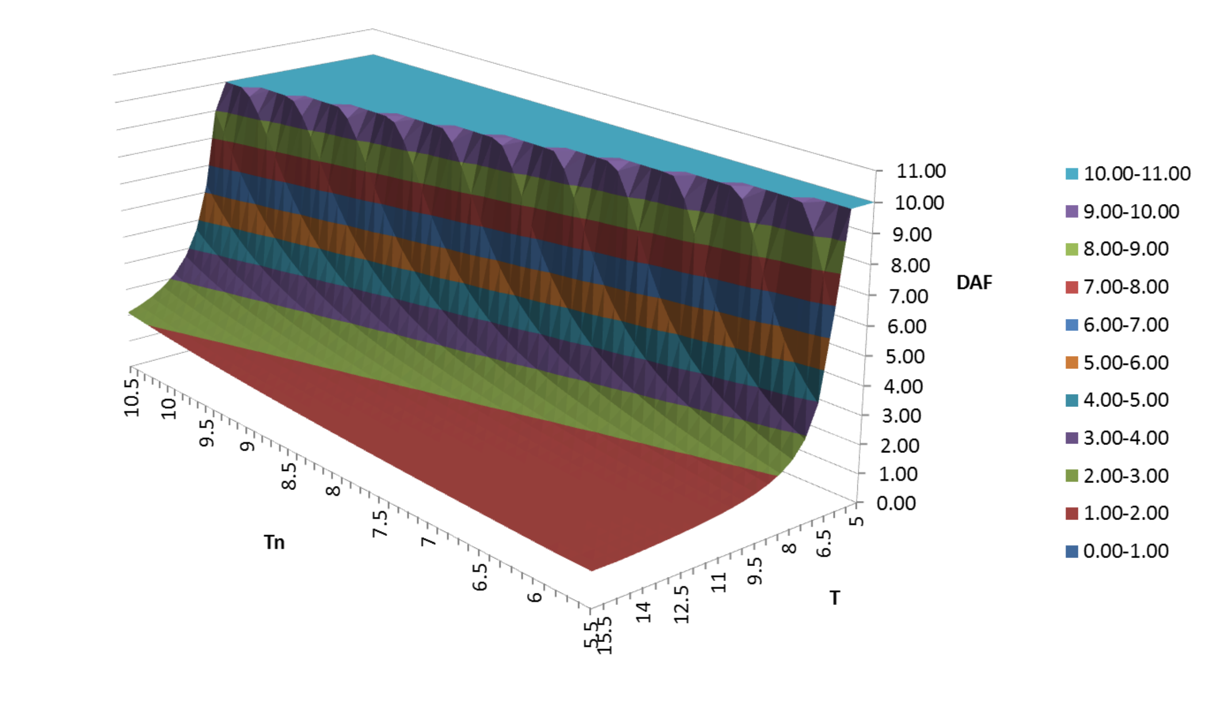

Figure 47 DAF for various wave periods (T) and jack-up natural periods (T_n)

In Figure 47 the effect of the limitations of the DAF method is visible. For instance, when $T_n > 0.9T$ then $\Omega = 1$ and therefore the DAF gets its maximum value which is 10! The DAF gives a rough impression of how the static forces, caused by the environmental loads, are amplified due to the oscillation of the structure. The DAF is also used to calculate the inertia loads that act on the structure due to its oscillation and this is explained in 4.3.4.3.3.

4.3.1.8.3 Step 2.2.3

At this step the inertia loads will be calculated for a range of natural periods and for two conditions per period: a) extreme wave and current and b) resonance.

4.3.1.8.3.1 Method

The method followed is the one described in ISO 19905-1 paragraph A.10.5.2.2.2

At first the inertia forces are calculated. The inertia forces represent the contribution of dynamics over and above the quasi-static response. The formula for the inertia force is:

$F_{in} = (K_{DAF,SDAF} - 1)\ F_{BS,Amplitude}$

Where

F_{in} is the magnitude of the inertia force

$F_{BS,Amplitude}$ is the single amplitude of quasi-static base shear over one wave cycle (calculated at 4.3.4.3.1)

$K_{DAF,SDAF}$ is the DAF (calculated in 4.3.4.3.2.4)

Then, according to the method, the inertia load is applied at the center of gravity of the hull in the direction of wave propagation. Finally, if it is needed to calculate the leg to hull moment taking into account both dynamic and static response, it is possible to do so with a simple static analysis with wave, current and the inertia loads.

Important note: Every natural period is related to different foundation characteristics (k_r and k_t) which apart from the natural period determine also the distribution of moments on the legs as explained in 4.2.4.2.3.3.2. Therefore it is useful to connect the values of k_r and k_t with the natural period. This is done in this step and explained below (4.3.5.2).

4.3.1.8.3.2 Calculation of inertia loads

4.3.1.8.3.2.1 Condition a) max wave and current

The condition for max wave and current is defined as a seastate with a wave height equal to 29m and a wave period of 16s combined with a current of 1 m/s, uniform over depth (see 4.2.5.3.2.1.2). A quasi static analysis is done to identify the base shear for this loading using the same model that was used in Step 1.4 situation D and the result is

BS_{max} = 25701 kN

BS_{min} = -2957 kN

Therefore $F_{BS,Amplitude}$ = (25701-(-2957))/2 = 14329 kN

The DAF and the resulting inertia forces for each natural period are presented below:

Table 12 Inertia loads for condition of extreme wave + current

T_n	T	DAF	$F_{bs,amplitude}$	F_{in}	SUM
[s]	[s]	[-]	[kN]	[kN]	[kN]
6	16	1.21	14329	2988	17317
7	16	1.31	14329	4396	18725
8	16	1.44	14329	6330	20659
9	16	1.63	14329	9063	23392
10	16	1.91	14329	13101	27430
10.5	16	2.11	14329	15904	30233

4.3.1.8.3.2.2 Condition b) resonance

In this study the effect of resonance is checked from the view point of the jack-up survival and not from the view point of serviceability. In other words the checks are performed in order to assess whether the jack-up can survive on the SSfJ and not whether it can operate. As a reminder it is mentioned that in severe metocean conditions the jack-up configuration is changed to elevated storm configuration and in this case the jack-up is just waiting for the storm to pass without performing drilling or any other activity.

For every natural period of the jack-up there is a specific wave period at which resonance occurs. As explained in 4.3.4.3.2.2 the wave period that causes resonance is equal to $T_n/0.9$. The base shear amplitude is calculated for waves with periods from 5s to 16s with a step of 0.5s (Figure 46). These values are used in order to estimate the base shear amplitude for the wave periods that cause resonance with the selected natural periods. An interpolation was done when the requested wave periods were not used in the calculation of the static base shear. For resonance the DAF takes its maximum value which is 10. For the condition of resonance and for the selected natural periods the inertia forces are presented below:

Table 13 Inertia loads for condition of resonance

T_n	T	DAF	$F_{bs,amplitude}$	F_{in}	SUM
[s]	[s]	[-]	[kN]	[kN]	[kN]
6	6.67	10.00	436	3923	4358
7	7.78	10.00	415	3733	4148
8	8.89	10.00	502	4521	5023
9	10.00	10.00	789	7101	7890
10	11.11	10.00	1248	11236	12484
10.5	11.67	10.00	1534	13808	15342

4.3.1.8.4 Step 2.2.4- Conclusion of Step 2.2

Based on the simplified approach followed in step 2.2 which takes into account only the first natural period of the jack-up, it becomes very obvious that the condition of resonance with the first natural period of the jack-up is for all the possible natural periods less challenging for the jack-up compared to the condition of extreme wave + current. The only point at which the resonance gives a bigger value compared to the extreme condition is at the natural frequency of 6s where the inertia load is 3922.5 kN compared to 2988 kN of inertia load due to extreme condition, but this is not considered significant since the base shear for the extreme wave is 14329 kN.

What adds more to the conclusion is that even without the use of the amplification factor, the base shear for the extreme conditions (14329 kN) almost matches the sum of inertia load and quasi-static base shear of the condition of resonance for a natural period of 10.5s. With such a big difference between the two conditions it is considered safe to omit a two stage deterministic storm analysis for the calculation of the actual leg-to-hull moment for every natural period. **Therefore it is decided to perform the optimization for condition of extreme wave + current.**

However at a later stage, when the natural period of the jack-up is calculated for the optimum set of k_r and k_t, a check is performed for the condition of resonance with smaller waves (see 4.3.6).

Note: During the preparation of this thesis a meeting was held with the designers of the CJ 70 jack-ups and the issue of relevant importance between resonance and extreme conditions was brought up. The designers expressed the opinion that extreme weather conditions should be governing since the energy contained in smaller waves is a lot smaller and even with resonance it is not significant compared to the extreme wave conditions. What the designers noted was that smaller waves with periods of around 8s would be more governing for the assessment of the fatigue life of the jack-up, but such an analysis is beyond the scope of this thesis.

1.5.23 Step 2.3.

With the most governing conditions identified in Step 2.2 it is possible to perform the optimization for the SSfJ stiffness and the SSfJ - Jack-up interface stiffness. As explained in 4.3.1.1 the objective is to locate the combinations of k_r and k_t for which the utilization at the bottle neck becomes equal to 1, i.e. when the moment at the leg-to-hull interface reaches the M_u as calculated in 4.3.3 and reduced with a safety factor.

In order to quickly arrive at a combination of k_r and k_t that satisfies the numerical criterion it is decided to perform the simplest method of dynamic analysis which is the two stage deterministic storm analysis according to ISO 19905-1 paragraph A.10.5.2. According to this method the jack-up is simulated as a single degree of freedom mass-spring-damper system and a DAF is used to calculate the inertia forces due to the oscillation of the jack-up. For this method the DAF is already calculated in 4.3.4.3.2.4. When the optimal combination of k_r and k_t is found, a validation of the results with a method that describes better the phenomenon of the oscillating jack-up takes place. This method uses random wave time domain analyses.

The procedure followed is presented below:

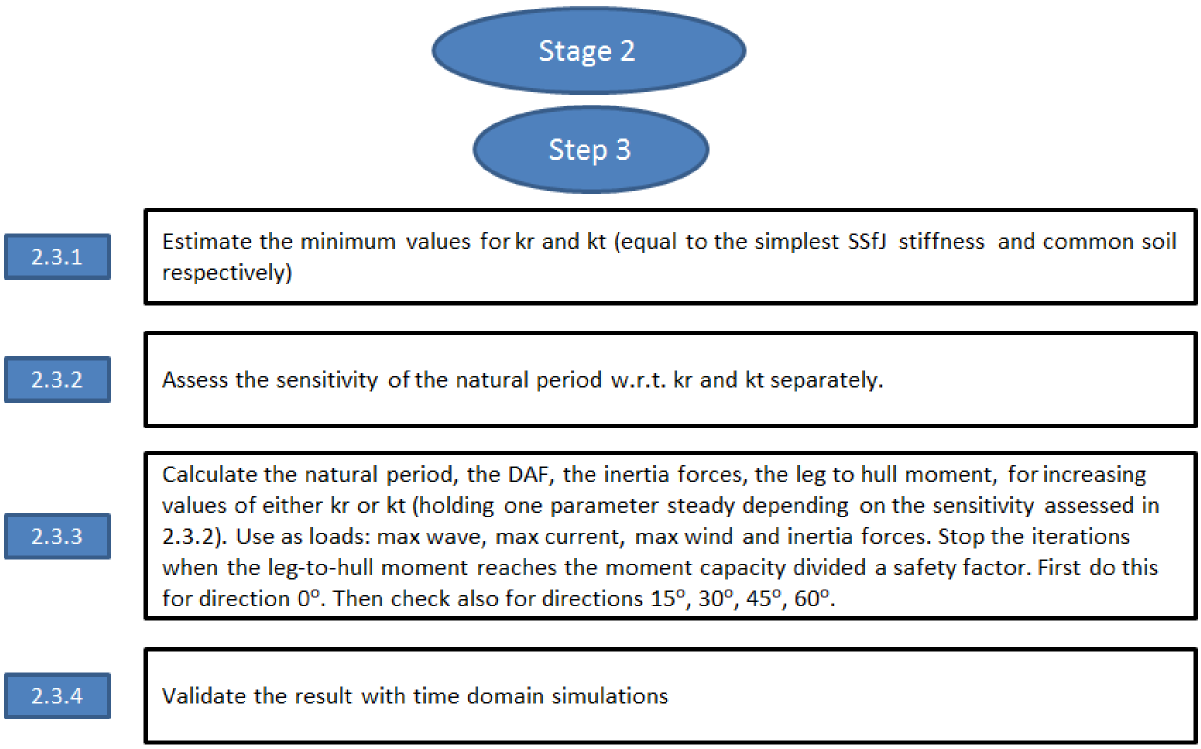

Figure 48 Stage 2 Step 2 approach

4.3.1.9 Step 2.3.1

At this step the minimum values for k_r and k_t are calculated. The reason for this step is to set the starting point for the optimization. The reason why the minimum values for k_r and k_t are sought instead of the maximum is that there are hints about the minimum values as it can be explained below.

4.3.1.9.1 Minimum value for k_t

In order to have a quick and solid argument about what the minimum SSfJ stiffness (k_t) can be it is decided to calculate the stiffness of the simplest possible arrangement for the SSfJ. This arrangement is sketched as a space frame with one diagonal. To calculate the stiffness, a load of 10 MN is applied in the direction of k_t. The value of the load is in the order of magnitude of the loads present in reality for structures of such scale. The arrangement is presented in Figure 49:

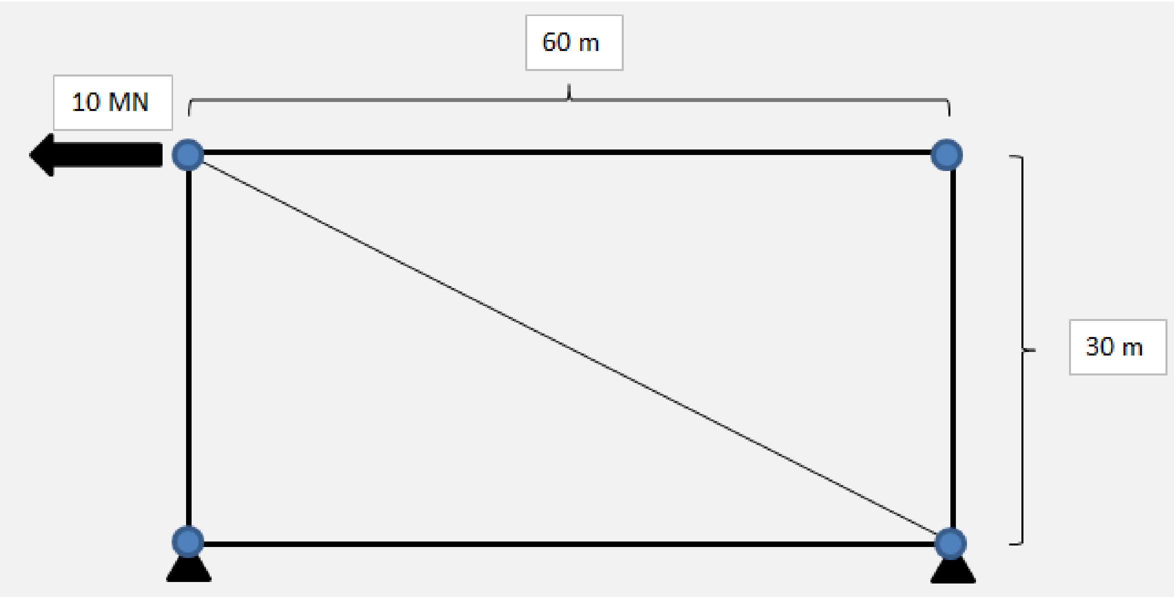

Figure 49 Calculation of the minimum SSfJ stiffness (k_t)

The dimensions used are derived simply. The vertical dimension is the supposed dimension for the SSfJ height (30 m) as decided in Chapter 3. The horizontal dimension is the distance between the bow leg and the axis that connects the rear legs of the CJ 70 (see Appendix 1). The length of the diagonal can be calculated as follows:

$L_{diagonal} = \sqrt{60^2 + 30^2} = 67.08m$

Static calculations are done in order to calculate the axial load in the diagonal. With this arrangement the axial load is:

$F_{diagonal} = 10 * (67.08/60) = 11.18$ MN

Assuming that the diagonal will be used at its full capacity (because the cheapest alternative is sought), the stress in the diagonal will match its yield stress which is assumed 355 MPa. Assuming a modulus of elasticity equal to E = 210 GPa the strain of the diagonal can be calculated as:

$\varepsilon = \sigma_y / E = 3{,}55 * 10^8 / 210 * 10^9 = 0{,}00169$

With this strain and with the length of the diagonal known the elongation in the direction of the diagonal can be calculated as:

$\delta = \varepsilon * L_{diagonal} = 0.00169 * 67.08m = 0.113$ m

The deformation in the direction of the load is estimated as:

$\Delta x = \delta * 60/67{,}08 = 0{,}113 * 60/67{,}08 = 0{,}1014$m

This means that for a force of 10 MN, a SSfJ, with the least amount of steel possible, will deform in the direction of the force by 0.1014 m. Thus the minimum SSfJ stiffness is estimated:

$\mathbf{k_{t,min}} = F / \Delta x = 10000/0{,}1014 = 9{,}86 * 104$ **~ 10^5 kN/m**

In addition, the required area of the cross section for the diagonal can be calculated in order to check if a common cross section can be used for the diagonal. Assuming that the same force applies in compression and that no buckling will take place (because in reality there will be more members that reduce the buckling length) a cross sectional are can be calculated using the yield stress and the calculated force:

$A_{min,req} = F / \sigma_y = 11.18$ MN / 355 MPa = 0.03m^2

This value of cress sectional area is within the range of the areas of the steel members used in offshore industry. In fact a tubular with an outer diameter of 762mm and a wall thickness of 15.88mm has a bigger cross sectional area.

It must be noted that this is just an indication of the order of magnitude as no load or resistance factors are applied. This estimation just gives an impression of the cross sectional area requirements and shows that with the current available material it is easily achieved.

4.3.1.9.2 Minimum value for k_r

It is considered more complicated to assume a value for the rotational stiffness in the same way it is done for the SSfJ stiffness. Therefore the starting value of k_r for the iterations is taken equal to a value that has been used in the presentation of (Rimmer, et al., 2013). In this presentation the results of the monitoring of a similar jack-up are presented and some values about the rotational fixity of the spudcans are presented. It is decided to start the iterations for the optimization using a value of k_r equal to 10^7 kNm/rad.

4.3.1.10 Step 2.3.2

In this step the sensitivity of the natural period of the jack-up for changes in the values of k_t and k_r is assessed.

4.3.1.10.1 Calculation of the natural period

To calculate the sensitivity, it is necessary to be able to calculate the natural frequency of the CJ 70 on the SSfJ taking into account the spring coefficients k_t and k_r. In this thesis two ways to calculate the natural period of the jack-up on were applied:

a) Using SACS
b) Using formula 7.3.5.3. of (SNAME, 1994)

Using both ways to calculate the natural period of the jack-up a validation of the calculation was possible. It is remarkable that the hand calculation of the natural period (with SNAME formula) gives results comparable with the software SACS for the first natural period. However a lot of effort was given in order to calibrate the formula. This involved many assumptions especially for parts of the jack-up with little information known (such as the fixation system and the hull). This is explained in Appendix 2. In the analyses that follow, the natural period calculated with SACS is considered the correct one.

Moreover, it must be mentioned that the hand calculation only shows the first natural period while SACS was used to calculate the first 10 natural periods and thus gives a better view of the dynamic behavior of the jack-up. For illustration purposes, in Table 14 the first 10 natural periods that were calculated with SACS using for $k_r = 10^7$ kNm/rad and $k_t = 10^5$ kN/m:

Table 14 The natural periods for the first 10 modes for minimum k_r and k_t

Mode number	Period
#	[s]
1	12.41
2	12.41
3	9.16
4	0.92
5	0.92
6	0.87
7	0.87
8	0.86
9	0.83
10	0.69

It is interesting to note that the first 2 modes correspond to almost the same period. Those modes correspond to the sway and surge motions respectively. This happens due to the symmetric shape of the model, the symmetric distribution of the mass on the model and also due to the fact that all the legs have the same stiffness. The 3rd mode corresponds to the yaw motion of the hull and has a natural period of 9.16s. It is also very important to note that the natural periods for modes 4 to 10 are very small and therefore their importance is considered to be very low since they can be excited by waves with such small period that have very small wave heights and contain small amount of energy.

4.3.1.10.2 Sensitivity of the natural period w.r.t. k_t

In order to assess the sensitivity of the natural period with respect to k_t the value of k_r should be kept constant and the natural period should be calculated for various values of k_t. The natural period was calculated for a constant $k_r=10^7$ kNm/rad and for k_t ranging from 10^3 kN/m to $5*10^6$ kN/m. The result is presented in Figure 50:

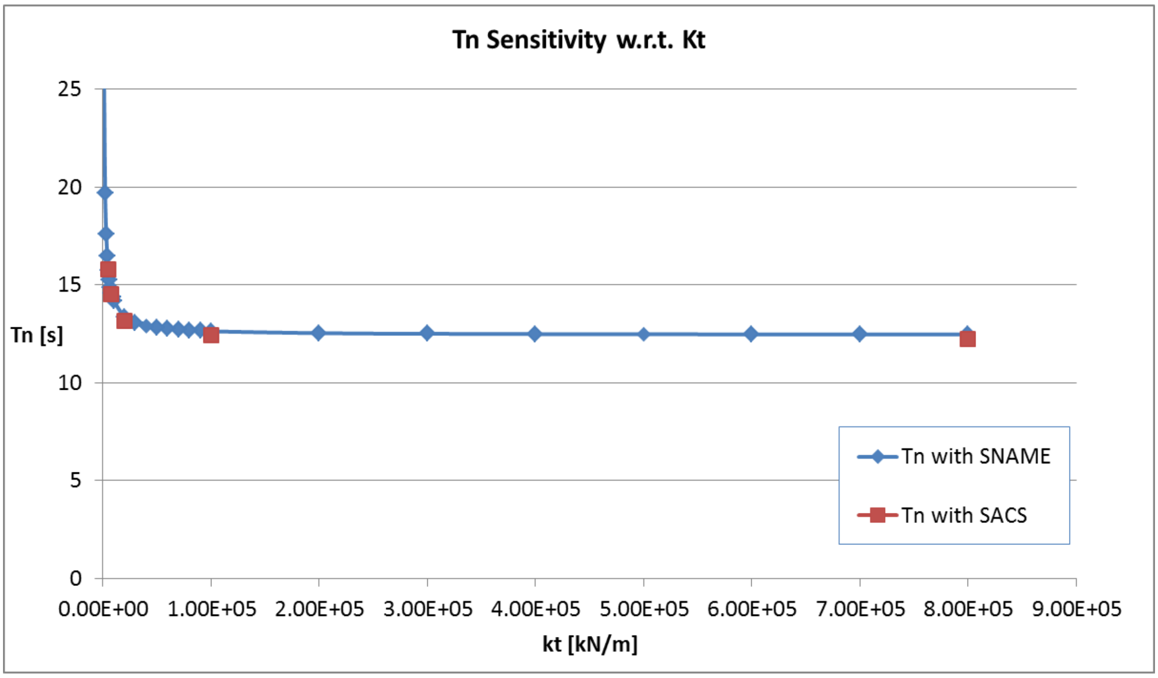

Figure 50 T_n sensitivity w.r.t. k_t values for constant $k_r=10^7$ kNm/rad

In Figure 50 the resulting natural period calculated with both the SNAME formula and SACS is presented. Since the SNAME formula is programmed in excel it is easier and faster to produce results. Therefore the SACS calculations were done just for verification.

It is remarkable that after a certain value for the k_r the natural period remains unchanged. The physical meaning behind this is that for small values of k_t the oscillation of the SSfJ – jack-up system is dominated by the oscillation of the SSfJ and for values greater than 10^5 kN/m the SSfJ is stiff enough in order for the oscillation of the system to be dominated by the oscillation of the jack-up. This is actually a proof for what is stated in paragraph 4.2.4.2.3.3.2 and especially for what is shown in Figure 31.

What is more important is that for the minimum value of k_t as calculated in 4.3.5.1.1 the natural period is already at the steady part of the graph. This means that **by increasing the value of SSfJ stiffness the natural period of the system will not change significantly**. This is a very important conclusion and shows that **the optimization should focus mostly on kr**.

4.3.1.10.3 Sensitivity of the natural period w.r.t. k_r

In this case the value of k_t was kept constant and equal to $k_t=10^5$ kN/m, while the natural period was calculated for various values of k_r. The result follows:

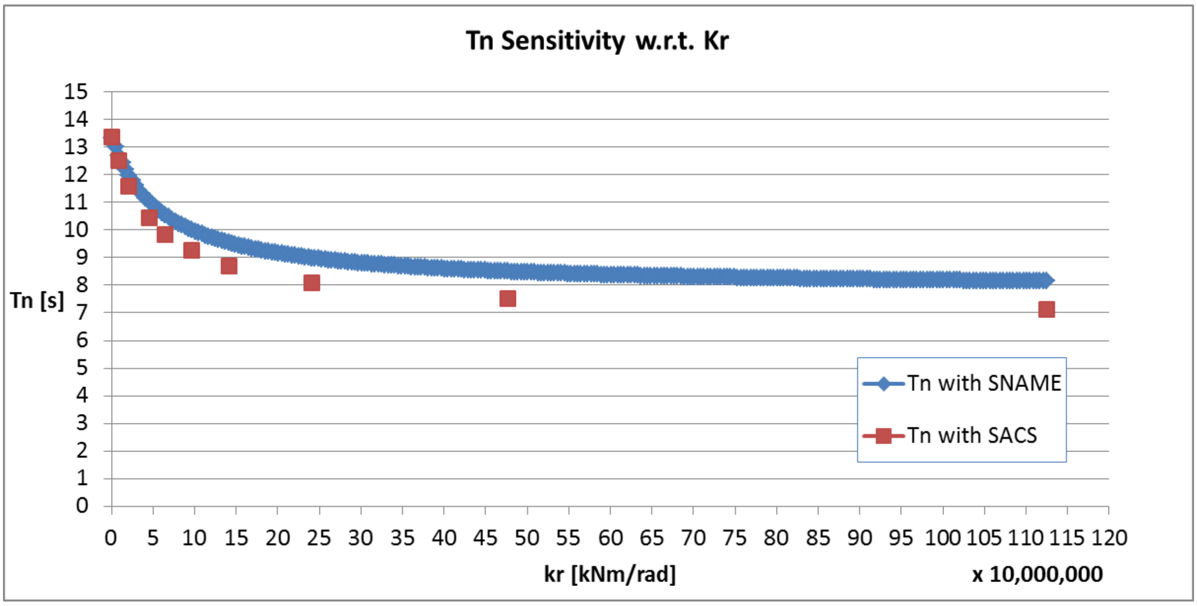

Figure 51 T_n sensitivity w.r.t. k_r values for constant $k_t=10^5$ kN/m

It is obvious in 0 that a mismatch exists between the hand calculation and the calculations performed in SACS. This is possibly related to the estimation of some values that were used in the SNAME formula, for which no accurate information was available. However despite the mismatch a trend is shown and this is that with the increase of k_r the natural period of the jack-up drops exponentially. It was expected that the natural period will drop as explained in 4.2.4.2.3.3.2 but the exact behavior was not known. It must therefore be noted that after increasing the k_r above a certain value, the natural period will not be changed dramatically. One can imagine the limit of the curve presented in Figure 51 as the natural period of a rotationally constrained jack-up on the SSfJ.

The conclusion drawn via the sensitivity check of the natural period with respect to k_r is that the optimization should definitely be done by keeping the value of k_t constant and by changing the value of k_r starting from the value of $k_r = 10^7$ kNm/rad.

4.3.1.11 Step 2.3.3

In this step, the calculations of the optimization take place. The procedure for each iteration is presented below:

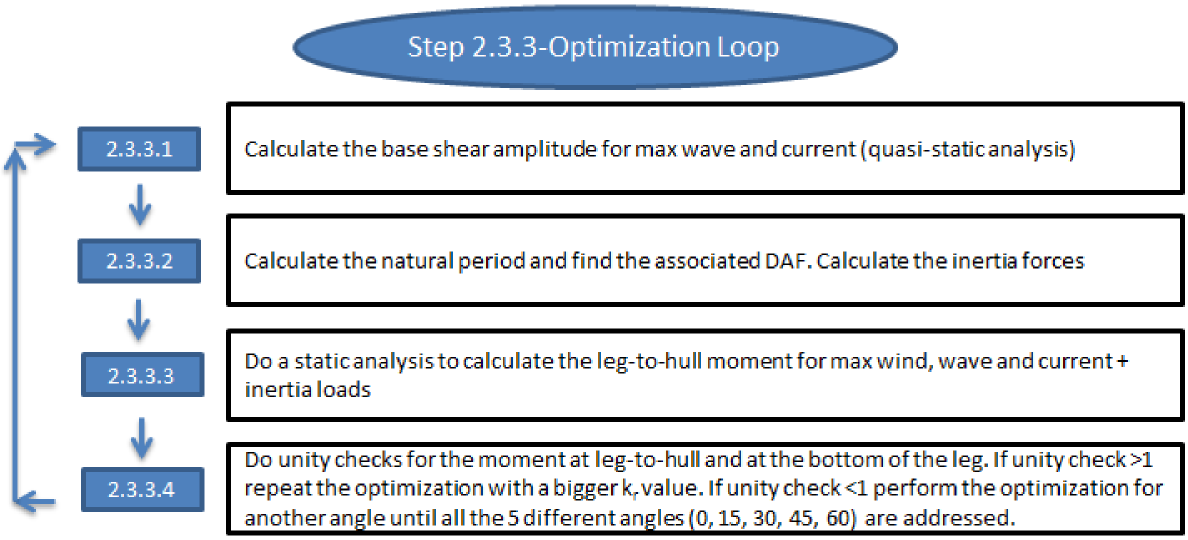

Figure 52 Optimization loop for k_r

Following the procedure, the first run of the loop is presented below.

4.3.1.11.1 1st run

4.3.1.11.1.1 Step 2.3.3.1

A static analysis (one wave pass) is performed in SACS using as loads:

- Weight: as shown in 4.2.5.2.1.4
- Wave: 29m height, 16s period in direction 0^o(as shown in 4.2.5.3.2.1.2)
- Current: Uniform, 1 m/s in direction 0^o

The initial values for k_r and k_t are:

- $k_r = 10^7$ kNm/rad
- $k_t = 10^5$ kN/m

The result is the following:

BS_{max} = 21952 kN

BS_{min} = -2287 kN

Therefore $F_{BS,Amplitude}$ = (21952-(-2287))/2 = 12119.5 kN

4.3.1.11.1.2 Step 2.3.3.2

The natural period is calculated with both methods (SNAME formula and SACS as explained in 4.3.5.2.1). Due to the fact that many assumptions are taken while applying the SNAME formula (see also 4.3.5.2.1) the natural period calculated with SACS is considered the correct one. The calculated first natural period is:

With SACS: T_n= 12.41s

With SNAME formula 7.3.5.3: T_n= 12.62s

The associated DAF can be calculated as explained in 0. For T_n = 12.41s, T = 16s and ζ = 0,05 the result is DAF = 3.67

Hence the inertia forces are: F_{in} = (3.67-1) * 12119.5 = 32363.3 kN

4.3.1.11.1.3 Step 2.3.3.3

In the static analysis to be performed the following are taken into account:

- Weight: as shown in 4.2.5.2.1.4
- Wave: 29m height, 16s period in direction 0^o (as shown in 4.2.5.3.2.1.2)
- Current: Uniform, 1 m/s in direction 0^o
- Wind: 8.9 MN in direction 0^o (as shown in 4.2.5.3.2.1.1)
- Inertia forces: F_{in} = 32363.3 kN at 187m above spudcan level in direction 0^o

Note 1: The inertia load must be applied at the center of gravity of the hull. In this analysis one third of the inertia force is applied at each leg at the elevation where the hull is connected to the leg, which is also the same elevation as the elevation of the center of gravity of the hull in the model. Of course the direction is the same as the direction of the wave and current (0^o).

Note 2: In the static analyses performed at this stage the p-delta phenomenon was taken into account.

Before showing the results it is useful to show the numbering of the legs:

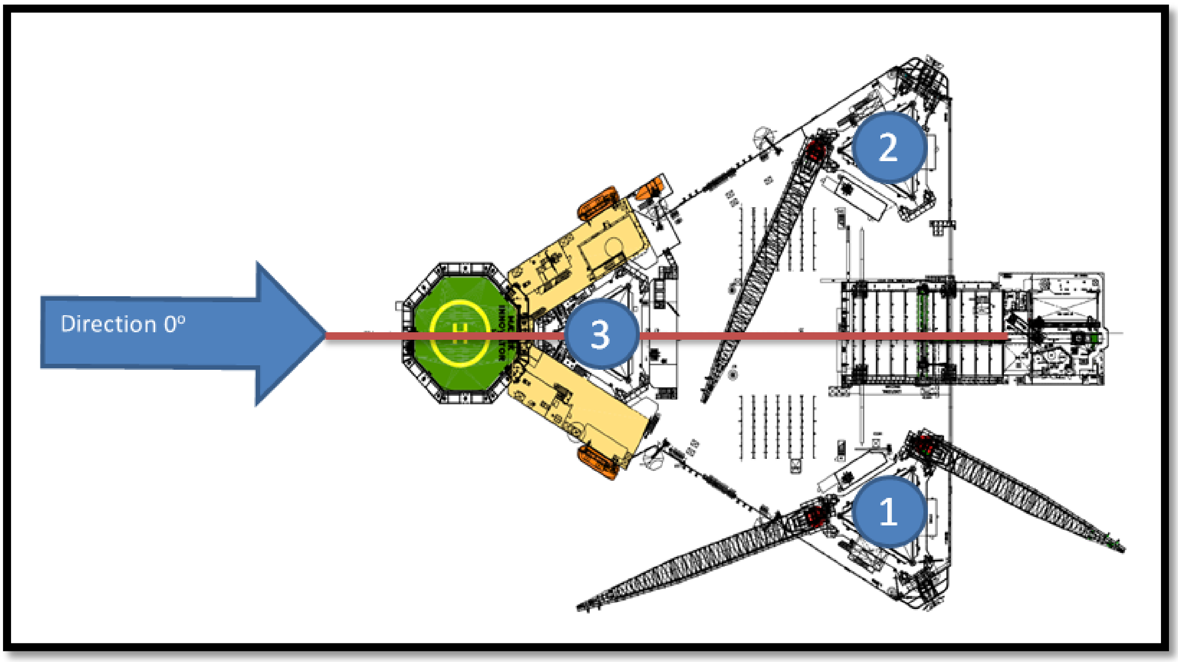

Figure 53 Numbering of legs

The resulting moments are presented in Table 15:

Table 15 1st run results: Leg moments at the leg-to-hull interface and at SSfJ – jack-up interface

	Leg-to-hull		SSfJ - jack-up interface	
	Mz	My	Mz	My
leg #	[MNm]	[MNm]	[MNm]	[MNm]
leg 1	3650.8	137.5	428.5	3.5
leg 2	3650.8	137.5	428.5	3.5
leg 3	3889.9	0.0	418.2	0.0

It is obvious that the moments at the leg-to-hull level are a lot larger than those at the lower part of the legs (the SSfJ – jack-up interface). This means that for this value of k_r the jack-up behaves more like pinned rather than fixed, i.e. the interface stiffness is relatively low and this causes accumulation of the moment at the higher part of the leg.

4.3.1.11.1.4 Step 2.3.3.4

In this final step of the iteration loop the unity checks for the leg moments are calculated.

4.3.1.11.1.5 Resistance factor and factored moment capacity

At first the moment capacity (calculated at 4.3.3) is divided with the resistance factor selected which is 1.1. This resistance factor is selected based on ISO 19905-1 suggestion for the resistance factor of bending non circular prismatic members. This leads to the following factor resistance moments:

For the leg-to-hull level:

$M_{y,d} = M_{u,y} / 1.1 = 2117 / 1.1 = 1924.3$ MNm

$M_{z,d} = M_{u,z} / 1.1 = 1833 / 1.1 = 1666.5$ MNm

For the lower part of the leg:

$M_{y,d} = M_{u,y} / 1.1 = 1955 / 1.1 = 1777.4$ MNm

$M_{z,d} = M_{u,z} / 1.1 = 1693 / 1.1 = 1539.3$ MNm

Collecting these values in a table:

Table 16 Design values for bending moment capacities

	Leg-to-hull	Bottom of the leg
	[MNm]	[MNm]
Mz,d	1666.5	1539.3
My,d	1924.3	1777.4

4.3.1.11.1.6 Load factor

The load factors taken into account are equal to 1 for all loads (wind, wave, current, inertia and gravity). It was decided to apply this load factor because conservative estimation is done for each load. For example a uniform current throughout the whole depth is used and also the areas used to calculate the wind load are overestimated. In addition to this a conservative approach for the combined bending unity check is followed as it is described further below.

4.3.1.11.1.7 Unity checks

Now for every moment a unity check can be done in the form of:

UC = M_y / $M_{y,d}$ for moment around y axis

UC = M_z / $M_{z,d}$ for moment around z axis

Obviously, If the value of UC is greater than 1, the moment due to loads exceeds the moment capacity and failure occurs. The resulting unity checks are presented below:

Table 17 Unity checks for each moment separately

	Leg-to-hull		SSfJ - jack-up interface	
	Mz	My	Mz	My
leg #	UC	UC	UC	UC
leg 1	2.19	0.07	0.28	0.00
leg 2	2.19	0.07	0.28	0.00
leg 3	2.33	0.00	0.28	0.00

Then a combined unity check for the bending in two directions is done as follows. The check applied is:

$$\left[\left(\frac{M_y}{M_{y.d}}\right)^{\eta} + \left(\frac{M_z}{M_{z.d}}\right)^{\eta}\right]^{1/\eta} \leq 1$$

Where

M_y is the moment due to actions around y local member axis (as specified in 4.3.3)
M_z is the moment due to actions around z local member axis (as specified in 4.3.3)
$M_{y,d}$ is the moment capacity around y local member axis divided by the resistance factor 1.1
$M_{z,d}$ is the moment capacity around z local member axis divided by the resistance factor 1.1
η is the exponent for biaxial bending

In these analysis a conservative value of 1 was used for η as explained in ISO 19905-1 at A.12.6.3.2 for bending interaction of members of every geometry.

For the moments calculated at this run the result is the following:

Table 18 Combined unity checks for bending in two axes

	Combined UC	
leg #	Leg-to-hull	SSfJ - jack-up interface
leg 1	2.26	0.28
leg 2	2.26	0.28
leg 3	2.33	0.28

It is very obvious that with this value of k_r and k_t the moment at the leg-to-hull interface exceeds by far the moment capacity. Therefore in the next iteration a bigger value of k_r should be used.

4.3.1.11.2 2nd run

In this run the same procedure as in the previous run is followed but with bigger value of k_r

4.3.1.11.2.1 Step 2.3.3.1

The values for k_r and k_t are:

- $k_r = 4.5*10^7$ kNm/rad
- $k_t = 10^5$ kN/m

The result is the following:

BS_{max} = 21952 kN

BS_{min} = -2287 kN

Therefore $F_{BS,Amplitude}$ = (21952-(-2287))/2 = 12119.5 kN

The results of the static analysis for the determination of the quasi-static base shear amplitude due to wave and current are independent of the k_r and k_t values and therefore they are the same as in the first run. These results will only change if the wave or the current change.

4.3.1.11.2.2 Step 2.3.3.2

The calculated natural period is :

With SACS: T_n= 10.45s

With SNAME formula 7.3.5.3: T_n=11.04s

For T_n = 10.45s, T = 16s and ζ = 0,05 the result is DAF = 2.09

Hence the inertia forces are: F_{in} = (2.09-1) * 12119.5 = 13210.3 kN

4.3.1.11.2.3 Step 2.3.3.3

In the static analysis to be performed the following are taken into account:

- Weight: as shown in 4.2.5.2.1.4
- Wave: 29m height, 16s period in direction 0° (as shown in 4.2.5.3.2.1.2)
- Current: Uniform, 1 m/s in direction 0°
- Wind: 8.9 MN in direction 0° (as shown in 4.2.5.3.2.1.1)
- Inertia forces: F_{in} = 13210.3 kN at 187m above spudcan level in direction 0°

The resulting moments are presented in

Table 19

Table 19 2nd run results: Leg moments at the leg-to-hull interface and at SSfJ – jack-up interface

	Leg-to-hull		SSfJ - jack-up interface	
	Mz	My	Mz	My
leg #	[MNm]	[MNm]	[MNm]	[MNm]
leg 1	1794.7	90.8	753.3	8.2
leg 2	1794.7	90.8	753.3	8.2
leg 3	1873.2	0.0	740.3	0.0

4.3.1.11.2.4 Step 2.3.3.4

The unity checks for each moment separately are presented below:

Table 20 Unity checks for each moment separately

	Leg-to-hull		SSfJ - jack-up interface	
	Mz	My	Mz	My
leg #	UC	UC	UC	UC
leg 1	1.08	0.05	0.49	0.00
leg 2	1.08	0.05	0.49	0.00
leg 3	1.12	0.00	0.48	0.00

The resulting combined unity checks are presented below:

Table 21 Combined unity checks for bending in two axes

	Combined UC	
leg #	Leg-to-hull	SSfJ - jack-up interface
leg 1	1.12	0.49
leg 2	1.12	0.49
leg 3	1.12	0.48

It happens that the combined unity checks again exceed the value of 1. Therefore a bigger value of k_r should be applied in the next iteration. In the same way more iterations are performed. The next iterations are shown in Appendix 3. Below only the input and the output of the iterations is presented.

4.3.1.11.3 Step 2.3.3 results

After several iterations a value of k_r was found for which the leg bending moment capacity at the leg-to-hull level (but also at the interface between the SSfJ and the jack-up) is not exceeded for any direction of the environmental loading. A summary of the input and the output of each iteration is presented below.

Table 22 Optimization Summary

								Max combined UC		
Iteration #	kt	kr	Load Angle	Tn (SACS)	DAF	FBS	Fin	max UC	at leg	at level
	[kN/m]	[kNm/rad]	[degrees]	[s]	[-]	[kN]	[kN]	[-]	[-]	[-]
1	1.0E+05	1.0E+07	0	12.40	3.67	12120	32363	2.33	3	Top
2	1.0E+05	4.5E+07	0	10.45	2.09	12120	13210	1.12	1,2,3	Top
3	1.0E+05	9.7E+07	0	9.27	1.71	12120	8605	0.81	1,2	Top
4	1.0E+05	9.7E+07	15	9.27	1.71	13176	9355	1.04	2	Top
5	1.0E+05	2.4E+08	15	8.08	1.46	13176	6061	0.84	1	Bottom
6	1.0E+05	2.4E+08	30	8.08	1.46	13790	6343	0.96	1	Bottom
7	1.0E+05	2.4E+08	45	8.08	1.46	13306	6121	0.95	1	Bottom
8	1.0E+05	2.4E+08	60	8.08	1.46	12278	5648	0.83	2	Top

In Table 22 the indication "Top" at the column "at level" indicates that the maximum unity check was observed at the leg-to-hull level. Likewise, the indication "Bottom" indicates that the maximum unity check was observed at the SSfJ – jack-up interface, i.e. the lower part of the leg.

Some interesting comments about the results:

The initial value of k_r is a regular value applicable for the CJ 70 on the sea bottom and gives a natural period of 12.4s for the model used in these analyses. For this natural period the DAF is quite big and therefore the inertia forces are quite large. After some iterations the increase of the value of k_r leads to smaller natural period which also leads to a decrease in the DAF and the inertia forces. This way it is achieved to get unity checks smaller than 1 for the combined bending moments in all legs both at the leg-to-hull interface but also at the lower part of the leg.

There is a physical meaning behind the need for increased k_r. The reason is that when the CJ 70 stands on the sea bottom, the soil introduces some damping which leads to a smaller DAF. When the CJ 70 stands on the SSfJ it is assumed that there will be less soil damping and in the analyses performed at this step the soil damping was completely omitted. In order to minimize the dynamic effects the DAF should be decreased in another way than damping and this is only possible by decreasing the natural period. Since the wave that is taken into account has a period of 16s, by decreasing the natural period of the CJ 70 (by increasing the k_r) the Ω decreases and this leads to a decreased DAF.

4.3.1.12 Step 2.3.4

It is necessary to validate the results of the calculations for the optimization shown in 4.3.5.3 with time domain analyses. The approach followed in Step 2.3 is considered rough and conservative because it assumes that the jack-up is a simple mass spring damper system and uses a (mostly conservative) DAF, with its limitations addressed in 4.3.4.3.2.1, for the determination of the inertia loads. As a reminder, the simplified approach of Step 2.3 is followed as a quick indicator of the order of magnitude of the required k_r and k_t values. In general time domain simulations are considered more accurate for analyzing a nonlinear problem such as the jack-up subjected to environmental loading.

4.3.1.12.1 Validation objective

The time domain analyses are used in order to check the accuracy of the calculations performed in 4.3.5.3

4.3.1.12.2 Method Overview

The response of the structure to random waves combined with constant current, for one direction at a time, is calculated with random wave time domain analysis in SACS (module Wave Response). Then the maximum bending moments that occurred in the simulation for the bottom end of the legs and leg-to-hull interface are obtained. Then the moments at the same points due to static (max) wind load in the same direction are added to the moments calculated via the time domain analysis. Finally a unity check is performed for the moments at all the points similarly to the unity check performed in 4.3.5.3.1.4.

Note 1: The time domain analysis is a stochastic procedure and therefore for every run a different sea profile is created depending on the selection of phases (aka seed) of the waves that contribute to the total sea profile. It is noted that ISO 19905-1 suggests to perform at least 10 runs with different seeds and then statistically determine the most probable maximum unity check. However, due to limited amount of time available only one run was performed for every direction. Therefore, it is advised that more runs are performed after this thesis in order to obtain more accurate results.

Note 2: The superposition of the moments due to random wave and constant current with the moments due to constant wind load is done considering that the structure will elastically deform under all these loads. Of course this would not be accurate if plastic deformation takes place. However, in this thesis it is considered that the jack-up structure deflects only elastically.

Note 3: Another imperfection of this approach is that the deflections of the structure due to the combined wave current and wind are not calculated. For this particular structure, where most of its mass is at the top, the simple superposition of moments without the calculation of the total deflections underestimates the moments due to p-delta effect. It should be remembered during the comparison below that the approach followed in 4.3.5.3 includes the p-delta effects.

4.3.1.12.3 Time domain analysis set up

4.3.1.12.3.1 Model

The same model as in the previous steps is used. More information can be found at 4.2.5.2. As for the values of k_r and k_t, the time domain analyses are performed using the values that resulted from the optimization procedure performed in 4.3.5.3, i.e. $k_r = 2.41 * 10^8$ kNm/rad and $k_t = 10^5$ kN/m.

It is clarified that the movement of the structure is taken into account for the calculation of the relative velocities of the water particles. This involves an iterative procedure that is performed by SACS. The structure is considered initially static so that the forces due to wave and current can be calculated with the absolute water particles velocities due to wave and current. Then the movement of the structure is calculated for the applied forces. Then the relative velocities of the water particles due to wave and current with respect to the structure are calculated. With the new particle velocities the forces are recalculated. The new forces are used to determine again the movement of the structure. This will lead to new relative velocities and therefore to another iteration. After several iterations the forces due to relative velocities of the water particles converge.

4.3.1.12.3.2 Wave Spectrum

The random sea state is generated from a summation of many (Airy) waves that have appropriate height and frequency in order to match a spectrum. In this thesis the JONSWAP spectrum is used for waves that propagate in a single direction. This spectrum is considered the most accurate for applications in the North Sea because from the one hand it is applicable for fetch limited or wind duration limited or shallow water depths conditions and from the other hand it was produced by measurements in the North Sea. The parameters used for the JONSWAP spectrum in the calculations are selected as follows:

4.3.1.12.3.2.1 Wave height

SACS required as input the significant wave height. Earlier in the analyses of Step 2.3, the maximum wave height was used as H_{max} = 29m. The relation between the maximum wave height and the significant wave height for the North Sea (non-cyclonic area) is according to ISO 19905-1 paragraph A.6.4.2.2.:

$H_{max} = 1.86\ H_s$

Therefore:

$H_s = H_{max} / 1.86 = 29 / 1.86 = 15.59$m

4.3.1.12.3.2.2 Wave period

SACS requires the dominant period as input for the spectrum. This is calculated as follows:

According to ISO the zero-upcrossing period is dependent on the wave steepness. For deep water the wave steepness often lies within the range of 1/20 and 1/16 and this leads to the following expression for the zero-upcrossing period $T_{z,I}$ related to the significant wave height H_s:

$$3.2\sqrt{H_s} < T_{z,i} < 3.6\sqrt{H_s}$$

In this thesis the value of 3.4 was selected and the zero-upcrossing period. Therefore:

$T_{z,I} = 3.4 * 15.59^{0.5} = 13.43$s

The peak period is dependent on the selection of a parameter called peak enhancement factor (γ). ISO mentions that the most probable values for the γ is 3.3. For this value of γ the relationship between the peak period and the zero-upcrossing period is :

$T_{p,I} / T_{z,I} = 1.286$

Therefore the peak period that is input in SACS is:

$T_{p,l}$ = 13.43*1.286 = 17.3s

4.3.1.12.3.3 Storm duration and analysis time step

The duration of the simulations was set to 3 hours. The time step for the analysis has to be sufficiently small in order to prevent the loss of information. Therefore the time step is selected to be approximately 1/20 of the natural period of the structure which for the selected values of k_r and k_t is around 8s. This time step is small enough to depict the wave environment since the dominant wave period is in the order of 17s.

4.3.1.12.4 Analyses Results

During the analysis it was found that the wind load plays a very significant role and that it determines which direction will be the most critical. Therefore the results are presented below first for the time domain analysis alone and then also including the moments due to wind load.

4.3.1.12.4.1 Results without superposition with wind load

In this paragraph the results of the time domain analyses are presented.

The combined unity checks represent the unity checks for bending in two directions as explained in 4.3.5.3.1.7. The unity checks are performed using as load factors for every load equal to 1 and for resistance factor of 1.1 similarly to 4.3.5.3.1.4

Table 23 Time domain analyses results

	Combined UC per direction					
	leg 1	leg 1	leg 2	leg 2	leg 3	leg 3
	Leg-to-hull	SSfJ - jack-up interface	Leg-to-hull	SSfJ - jack-up interface	Leg-to-hull	SSfJ - jack-up interface
Angle 0	0.34	0.39	0.34	0.39	0.41	0.37
Angle 15	0.41	0.47	0.46	0.53	0.55	0.49
Angle 30	0.49	0.53	0.53	0.60	0.63	0.57
Angle 45	0.51	0.54	0.52	0.58	0.59	0.56
Angle 60	0.46	0.48	0.45	0.50	0.49	0.48

The maximum value in Table 23 is the one of 0.63 for the combined bending moment unity check at the leg-to-hull interface of leg 3 for wave and current direction 30.

It is also remarkable that for the direction of 30 degrees the combined unity checks are bigger for almost all the points of interest compared to those of the other directions at the same points. This shows that by taking into account only the wave and current loading the most governing load direction is 30 degrees.

4.3.1.12.4.2 Results for all loads

In this paragraph the results for the total loading are presented. Those are produced via superposition of the moments obtained through the time domain analyses for random wave and constant current and the moments obtained via static analyses for constant maximum wind load. The latter were calculated with static analyses using as input the wind load as presented in Appendix 1.

Again the unity checks are performed using as load factors for every load equal to 1 and for resistance factor of 1.1 similarly to 4.3.5.3.1.4.

Table 24 Time domain analyses results superposed with wind

	Combined UC per direction					
	leg 1	leg 1	leg 2	leg 2	leg 3	leg 3
	Leg-to-hull	SSfJ - jack-up interface	Leg-to-hull	SSfJ - jack-up interface	Leg-to-hull	SSfJ - jack-up interface
Angle 0	0.56	0.57	0.57	0.58	0.58	0.54
Angle 15	0.64	0.69	0.76	0.77	0.78	0.72
Angle 30	0.75	0.78	0.85	0.86	0.88	0.82
Angle 45	0.79	0.81	0.87	0.87	0.86	0.83
Angle 60	0.71	0.72	0.76	0.76	0.72	0.71

4.3.1.12.4.3 Validation analysis results

The maximum value in Table 24 is 0.88 and represents the combined bending moment unity check at the leg-to-hull interface of leg 3. However, for most of the points of interest, direction 45 has bigger UC than direction 30. This result is much influenced by the fact that the wind load in the direction of 45 degrees is the biggest as shown in Appendix 1. Also for the moments at the SSfJ – jack-up interface, direction 45 is governing in this case.

An important comment is that with the selected values of k_r and k_t the unity checks of every leg at the SSfJ – jack-up interface and at the Leg-to-hull interface are similar. This means that the moments are almost evenly distributed between the top and the bottom of the useful leg. This is in line with what is mentioned as desired situation regarding the effect of spudcan fixity in 4.2.2 and Figure 24.

4.3.1.12.4.3.1 Comparison between validation analysis and optimization procedure (4.3.5.3)

The validation analysis showed that the most governing direction is that of 30 degrees. This is the same as the results of the method presented in 4.3.5.3.

Moreover, the method used for validation (which makes use of time domain analyses) gives smaller unity checks compared to the method that treats the jack-up as a mass-spring-damper system. However the results are not extremely different. To illustrate this, it is important to mention that the maximum unity check calculated with the validation method was 0.88 while the first method (see 4.3.5.3) produced a maximum unity check of 0.96. This implies that, if the time domain analyses is considered more accurate, then the method followed in 4.3.5.3 is conservative.

It must be noted that the maximum unity checks were not found at the same spot for both methods, even though the maximum unity check was found for the same loading direction (30 degrees). The optimization procedure followed in 4.3.5.3 showed that the maximum unity check is at the leg-to-hull interface of leg 1 while the method used for the validation showed that the maximum unity check is at the leg-to-hull interface of leg 3. One possible reason for this the validation method describes better the natural problem of the oscillating jack-up because it takes into account several mode shapes. For a loading direction of 30 degrees the rotational mode is also important. As it can be seen in Figure 54 when the loading is in the direction of 30 degrees it is in line with legs no2 and no3. This means that the loading is non-symmetric and therefore rotational oscillation of the hull is expected. This rotational oscillation will create inertia loads that are different from the inertia loads determined with the use of the DAF in 4.3.5.3. For this reason the use of time domain analysis is considered more accurate.

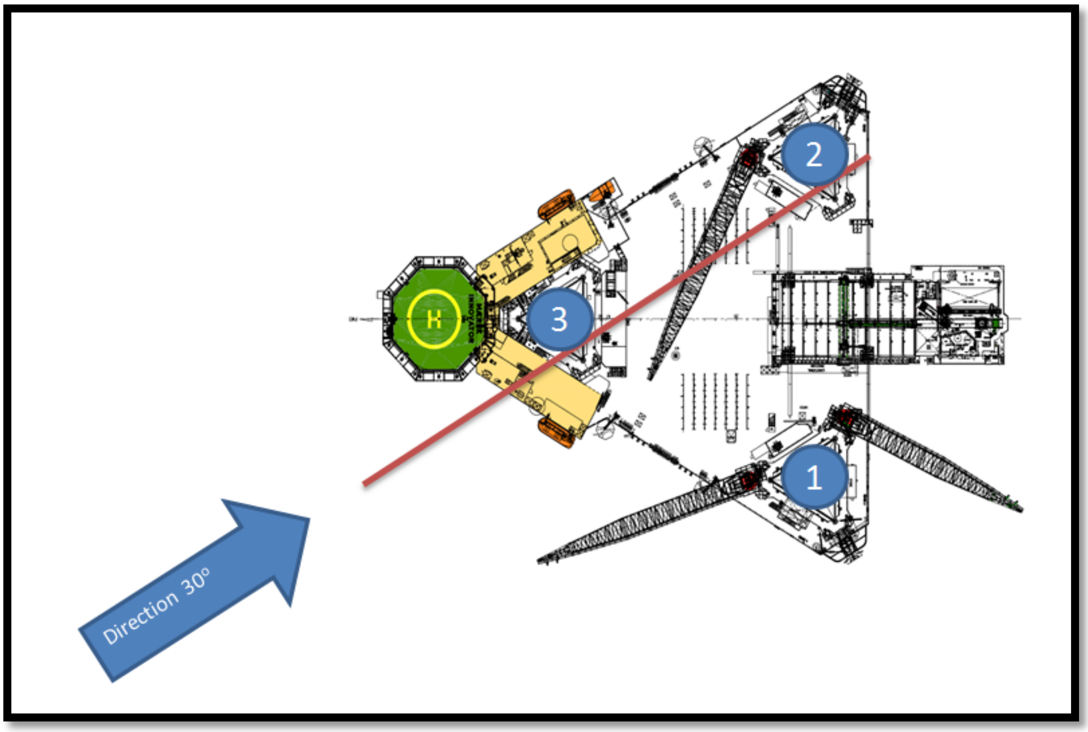

Figure 54 Loading direction 30

4.3.1.12.4.4 Validation general conclusion and recommendations

In general since the method that includes time domain analyses produced smaller values for the unity checks, thus it is concluded that the optimization procedure that used the DAF is considered conservative. Therefore, the values for k_r and k_t calculated in 4.3.5.3 are considered valid even though they are conservative.

It is strongly recommended to use the time domain analyses in order to obtain accurate results in case further research is done. Moreover while performing time domain analyses it is advised to perform several runs for every calculation and then process statistically the results in order to obtain the most probable maximum extremes. A guideline for the statistical processing of the time domain analyses results can be found in ISO 19905-1 paragraph A.10.5.3.4.

1.5.24 Step 2.4

In this step the maximum leg-to-hull moment are calculated for other wave periods apart from the one of the max wave. In particular the most interesting check is to calculate the maximum leg-to-hull moment for the condition of resonance and for the worst direction of environmental loads. The responses are calculated with the method used in 4.3.5.3 which as said in 4.3.5.4.4.4 is considered conservative.

The natural period for the optimum values of k_r and k_t is T_n = 8.08s. The wave period that leads to resonance with this jack-up natural period can be calculated from the formula for the Ω by setting Ω = 1. Thus:

$\Omega = 1 \Rightarrow \frac{T_n}{0.9T} = 1 \Rightarrow T = \frac{T_n}{0.9} = 8.08/0.9 = 9s$

With this period the DAF takes its maximum value which is:

DAF = 10

Since the phenomenon of resonance takes some time to evolve it is believed that the value of significant wave height is more applicable than the 100 year max wave that corresponds to this period. Therefore the value of wave height to be used is the one calculated in 4.3.4.3.1, i.e. :

H_s = 4.93m

The current and wind forces will be used with the same (extreme) values as used in the optimization.

The wave, current and wind direction used in this analysis are those that produced the biggest unity check in Step 2.3.3, i.e. direction 30°

4.3.1.13 Calculations

At first the inertia loads need to be determined. Therefore a static analysis (one wave pass) is performed in SACS using as loads:

- Weight: as shown in 4.2.5.2.1.4
- Wave: 4.93m height, 9s period in direction 30°(as shown in 4.2.5.3.2.1.2)
- Current: Uniform, 1 m/s in direction 30°

The values for k_r and k_t are:

- $k_r = 2.41*10^8$ kNm/rad
- $k_t = 10^5$ kN/m

The result is the following:

BS_{max} = 2469 kN

BS_{min} = 1560 kN

Therefore $F_{BS,Amplitude}$ = (2469-(-1560))/2 = 454.5 kN

The inertia forces are: F_{in} = (10-1) * 454.5 = 4090.5 kN

In the static analysis to be performed for the calculation of the moments due to all the loads, the following are taken into account:

- Weight: as shown in 4.2.5.2.1.4
- Wave: 4.93m height, 9s period in direction 30^o (as shown in 4.2.5.3.2.1.2)
- Current: Uniform, 1 m/s in direction 30^o
- Wind: 9.75 MN in direction 30^o (as shown in Appendix 1 Table 11)
- Inertia forces: F_{in} = 4090.5 kN at 187m above spudcan level in direction 30^o

The resulting moments are presented in the following table:

Table 25 Leg moments including resonance loading

	Leg-to-hull		SSfJ - jack-up interface	
	Mz	My	Mz	My
leg #	[MNm]	[MNm]	[MNm]	[MNm]
leg 1	478.0	217.7	417.3	227.8
leg 2	492.9	340.5	408.8	252.8
leg 3	432.2	252.1	400.9	228.2

The unity checks follow:

Table 26 Separate and combined unity checks

	Leg-to-hull			SSfJ - jack-up interface		
	Mz	My	Combined	Mz	My	Combined
leg #	UC	UC	UC	UC	UC	UC
leg 1	0.29	0.11	0.40	0.27	0.13	0.40
leg 2	0.30	0.18	0.47	0.27	0.14	0.41
leg 3	0.26	0.13	0.39	0.26	0.13	0.39

The unity checks are a lot smaller than 1 as expected according to 4.3.4.3.4. What is interesting to note is that even though the wave height is 4.93m which is almost one sixth of the maximum wave used in the optimization iterations, the unity checks are close to 0.5. This shows the importance of the DAF. That being said, there is no reason to check for other wave periods because from the one hand, for periods larger than 9s the DAF will be smaller than 10 and from the other hand for periods smaller than 9s (even with a conservative DAF = 10) the wave heights will be smaller, thus the hydrodynamic loads will be smaller.

Notes regarding 4.3.4.3.2.1:

It should be kept in mind that some of the limitations of the use of the DAF may be important at this stage. For example for this analysis the current velocity is not much smaller than the water particle velocity due to waves and this is depicted in the (small) difference of the max and the min base shear. However ISO suggests to perform a more detailed analysis in such cases provided that the result is close to the acceptance criteria which is not the case for the calculations performed here as the max unity check is much smaller than 1.

Another important issue could be cancellation and reinforcement (see 4.3.4.3.1) since Ω > 0.5. However as it can be seen in Figure 46, reinforcement occurs at wave period of 7s so there is not much chance of underestimating the response with the DAF (refer to 4.3.4.3.2.1).

1.5.25 Stage 2 Summary and Conclusions

In this stage some important structural requirements for the SSfJ are addressed and recommendations for the design values are given. Particularly the design values for SSfJ stiffness (k_t) and SSfJ-jack-up interface (k_r) are calculated.

At first the leg moment capacity was calculated using the assumed properties of the leg as presented in Appendix 1.

Then it was identified whether extreme weather conditions or resonance with smaller waves is the most governing situation. The result was that the extreme weather conditions are more important and produce higher static and inertia loads.

For the extreme weather conditions an optimization procedure for the values of k_r and k_t took place. Initially it was discovered that the stiffness of the SSfJ (k_t) does not affect the natural period when it passes the threshold of k_t=10^5 kN/m. It was also proven that this stiffness is easily achieved by the simplest steel space-frame design. Therefore the optimization focused only on the value of the rotational fixity of the jack-up legs on the SSfJ. The optimization was done in several iterations by increasing the values of k_r until the moment capacity was not exceeded at any point of the legs and for any direction of environmental loads. The final k_r value that satisfies the bending moment criterion is k_r = 2.41*10^8 kNm/rad. The optimization was validated with time domain analyses and it was found to be slightly conservative but it is considered acceptable. **It is recommended therefore that the design of the SSfJ should aim to provide a SSfJ stiffness of kt = 10^5 kN/m and a rotational fixation of the jack-up legs on the SSfJ of k_r =2.41*10^8 kNm/rad**.

Finally with the values of k_r and k_t and with the respective jack-up natural period known, a check was performed for the condition of resonance with waves with period that could cause resonance and significant wave height that corresponds to that period. The result of this check was that the moments at any point of the legs are a lot smaller than the moment capacity.

4.4 Stage 3

This is the final and concluding stage of the technical study. A first objective in this stage is to revisit the main assumptions taken in the previous stages and to assess their influence in the final result. After that recommendations are given for further technical study. Finally, another objective is to recapitulate the technical study and conclude on whether there are solutions to the critical aspects for the survival of the jack-up on the SSfJ.

The steps followed in this stage are presented below:

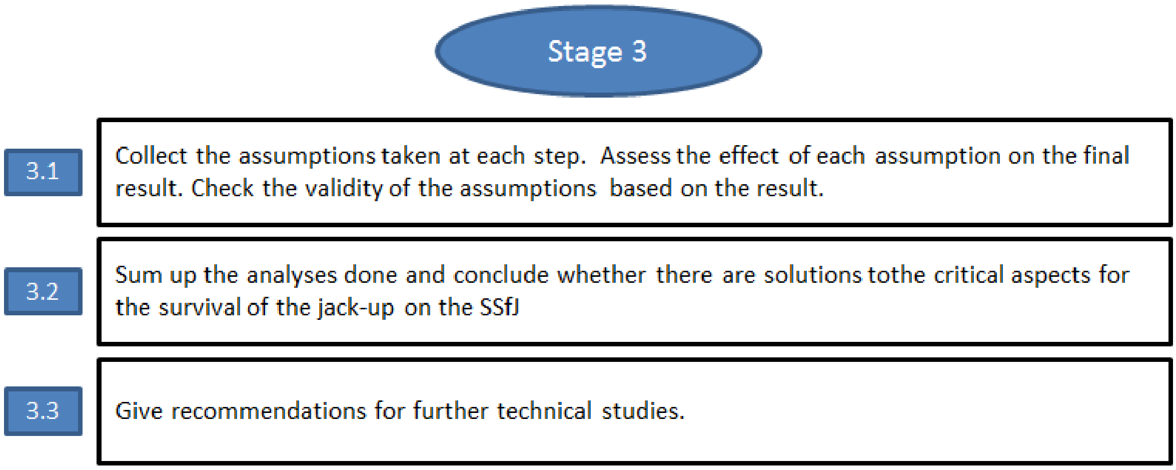

Figure 55 Stage 3 approach

1.5.26 Step 3.1

In this step the assumptions taken at each step of the technical study are revisited, and validated.

4.4.1.1 Revisiting Stage 1

The technical study begins with identifying how the jack-up integrity will be influenced when it is placed on an "ideal" SSfJ. The first step taken in that stage is to look in the literature for weak points, the so called "bottle necks", in the design and operation of jack-ups on the seabed.

4.4.1.1.1 Assumption 1 Lower guide moment

The first identified weak point of the jack-ups in normal operation on seabed is the moment at the lower guide. It is mentioned that at some designs a large lateral force is applied to the leg by the lower guide and this can be crucial for the members of the leg at that point. The assumption taken at that point is that no contact takes place between the lower guide and the leg for the CJ 70 jack-up used in this thesis. This assumption is based on the fact that the CJ 70 uses a fixation system. Therefore the bottle neck is considered the point where the fixation system grabs the leg's chord. It is believed that there will not be any contact between the lower guide and the leg at any moment due to any storm. In other case some additional shear will be introduced at the point of the lower guide, but it is believed that the jack-up designers have taken this into account during the design of the jack-up and therefore this should not be a problem.

4.4.1.1.2 Assumption 2 Jack-up natural period

In Step 1.1 of the technical study it is mentioned that the natural period of typical jack-ups is in the range of 6 to 10 seconds. As a matter of fact, the natural period calculated at the end of Stage 2 is 8.08s which is within this region.

4.4.1.1.3 Assumption 3 "Ideal" SSfJ properties

In step 1.3 many assumptions are taken in order to assess how the parameters that influence the checks related to the bottle necks of jack-ups are influenced by the use of the "ideal" SSfJ. Some properties of the "ideal" SSfJ are presented. It is assumed that the SSfJ will be stably fixed on the seabed, that it will be strong enough to support the CJ 70 jack-up in any circumstances and that it will be "hydro-dynamically transparent". These assumptions are also applicable for the calculations that take place in Stage 2. It is therefore very important that the design of the SSfJ will produce a structure with such properties. However during this thesis it was not possible to deal with the design of the SSfJ. Therefore these assumptions remain to be answered at a later stage after this thesis. What can be said at this point is that from structural point of view it is not very challenging to create a steel space frame that can hold 40000 mT in a water depth of 180m since there have been jacket structures that were installed at water depths of more than 300m in one piece. A steel space frame will also be almost "hydro-dynamically transparent" meaning that it will not disturb the flow around any jack-up parts. The challenging part is considered to be the establishment of a good fixation of the SSfJ at the seafloor in a way that it can be removable. A solution that can be suggested for this is to make use of suction piles along with the steel space frame.

4.4.1.1.4 Assumption 4 Settlement due to storm with the SSfJ

In 4.2.4.2.1.1 an assumption is made that the settlement due to storm will be smaller when a SSfJ is used. This was not addressed in the calculations performed in this thesis but it is considered possible to have less storm settlement when using the SSfJ than compared to normal jack-up operation because the SSfJ will probably be a broad structure with large area in contact with the seabed and this will lead in less stress on the seabed compared to the stress introduced by spudcans. For the same reason the long term settlements and are considered not crucial when a SSfJ will be used.

4.4.1.1.5 Assumption 5 Environmental loads

In 4.2.4.2.2.1 an assumption is made concerning the environmental loads and it states that they will be experienced by the jack-up on the SSfJ in the same way as when the jack-up stands on the seabed. An assumption is made separately for wind wave and current load. All these assumptions are verified in Step 1.4 via simplified checks.

4.4.1.1.6 Assumption 6 Overturning stability

In 4.2.4.2.2.2 it is assumed that the stabilizing moment can be increased with the use of the SSfJ. This can be achieved if a good fixity of the spudcans on the SSfJ is achieved and if a good fixity of the SSfJ on the seafloor is achieved. In Stage 2 a value is calculated about the required spudcan fixity on the SSfJ ($k_r = 2.41*10^8$ kNm/rad). However only the requirement is established so far and no solution as for the implementation of the fixity is given so far in this thesis in terms of design. In Appendix 4 a rough estimation of the rotational fixity that can be achieved with the least use of material is presented. Through that estimation it is shown that the simplest design of the SSfJ can provide enough rotational fixity, assuming again that the SSfJ can be fixed on the sea floor.

4.4.1.1.7 Assumption 7 Geohazards

In 4.2.4.2.4.8 an assumption is stated that refers to the presence of geohazards. It must be noted that geohazards can be dangerous for jack-ups and that the use of the SSfJ can probably decrease that danger. However this was not looked at during this thesis and is left for further research at the design stage of the SSfJ concept.

4.4.1.1.8 Assumption 8 CJ 70 weight and weight distribution

In step 1.4 the validation of the assumption of step 1.3 regarding the environmental load takes place. At this step several assumptions are made due to the fact that not enough accurate data was available for the CJ 70. Due to lack of accurate information and based on (GustoMSC, 2009) and (Kaiser, et al., 2013) the mass of the hull and the legs of the CJ 70 was estimated at 30000 and 3000 respectively. Then the weights were distributed over the beams that represent the hull so that the center of gravity of the hull is at the center of the equilateral triangle formed by the hull beams. In a similar way the weight of the legs was distributed over their whole length. In reality the distribution of the weight can be a lot different but the result of the calculations is not expected to be very different. Nevertheless if at a later stage accurate data about the weight is obtained then the weight distribution should be checked.

It must be noted that no spudcan weight was taken into account in the analyses. It is believed that this does not affect the result of the dynamic analyses since the spudcan center of gravity is close to the fixation of the legs and therefore it does contribute to the oscillating mass of the legs and the hull.

4.4.1.1.9 General assumptions related to the geometry of the CJ 70

The dimensions and various properties of the CJ 70 are estimated from various sources. This is presented in Appendix 1. The effect of these assumptions on the final result is very important. Therefore the intention is to show the method and some rough results. For more accurate results the exact dimensions and structural properties should be used.

4.4.1.2 Revisiting Stage 2

In this stage the important checks that were identified in Stage 1 are performed and emphasis is given at the dynamic behavior of the CJ 70 on the SSfJ.

To perform the checks various assumptions are made and they are collected in 4.3.1.2:

4.4.1.2.1 Assumption 9 SSfJ fixed on the seafloor

Initially the assumption of rigid connection of the SSfJ to the seafloor is made which is also an assumption taken in Stage 1 (see 4.4.1.1.3). Since many calculations rely on this assumption a related recommendation for further research is given later in this chapter.

4.4.1.2.2 Assumption 10 SSfJ is stiffer than the CJ 70 jack-up

This is a reasonable assumption based on another assumption which states that the SSfJ will most likely be made out of steel in the form of a small jacket. It is known that the range of natural periods for jackets at the size of the SSfJ can be around 2s maximum. For example the natural period of a large jacket with a height of around 210m is only 4s (Karunakaran & Haver, n.d.). However without having designed the SSfJ it is impossible to say what its natural period will be, but the assumption of a stiffer SSfJ compared to a jack-up is considered valid.

4.4.1.2.3 Assumption 11 SSfJ very stiff in the vertical direction

It is possible to make the SSfJ very stiff in the vertical direction. For this reason it is recommended to use vertical members just below the points where the chords of the jack-up are attached to the SSfJ. One can refer to Figure 1 of Appendix 4 for a relevant sketch.

4.4.1.2.4 Assumption 12 Chord area

For the calculation of the bending moment capacity of the leg the estimated chord area is used. This estimation has a great influence in the result. However the assumed value is obtained from dimensions provided by ISO 19905-1 and therefore it is close to the actual value. It is suggested that all the calculations that used this value should be performed again if the accurate value of chord area is obtained, but the result is not expected to differ a lot than the one reached at this thesis.

4.4.1.2.5 Assumption 13 Weight distribution between the chords of a leg

For the calculation of the bending moment capacity of the legs a weight distribution is assumed for the chords of each leg. It is assumed that due to the oscillation of the jack-up there will be times that most of the hull weight will be transferred to the lower part of the leg through one chord. A random guess was made that 75% of the weight carried by each leg will at some point be carried by one chord. If there was no oscillation then it is reasonable to assume that each chord will transfer one third (33%) of the weight that the leg is supported to carry. In absence of any data the assumption of maximum 75% of the weight will be transferred by one chord was done. The influence of this assumption in the final result is significant because this assumption determines the leg moment capacity. The leg moment capacity is then used as a criterion for the optimization of the SSfJ stiffness and the rotational fixity of the jack-up spudcans on the SSfJ and this means that if the leg moment capacity is overestimated, then a bigger rotational fixity is needed. It is therefore suggested that at a later stage a valid value for the distribution of the weights to the chords is obtained from the jack-up designers, so that the accurate leg bending moment capacity can be calculated.

4.4.1.2.6 Assumption 14 DAF

The Dynamic Amplification Factor is involved in the dynamic analysis method followed in this thesis. This method was selected because it can give quicker results for the dynamics. However the use of a DAF has some limitations which are explained at 4.3.4.3.2.1. It is stated that the use of DAF can give reasonable results if the ratio of the natural period of the jack-up to the excitation period (Ω) is between 0.4 and 0.8 and if the current velocity is small compared to the water particle velocity due to waves. For the calculations performed during the optimization phase (0) the wave period was 16s and the natural period was between 8.08s and 12.5s . For these periods Ω is between 0.6 and 0.9. Also the water particles velocities due to wave are a lot larger than the current velocity. As seen in Figure 36 the water particles velocities reach a value of 8 m/s while the current velocity is 1 m/s. Moreover the DAF could be unconservative if reinforcement could occur within the range of wave periods used in the analyses, but in the analyses performed in this thesis the periods range between 9 and 16 seconds and as shown in 4.3.4.3.1 the reinforcement period for the CJ 70 jack-up is 7s. Thus reinforcement is not underestimated in this analyses. Concluding, the use of DAF is done within its limits and the related assumptions are considered valid. It can be however true that the DAF is conservative and this was proven with the method that makes use of time domain simulations.

4.4.1.2.7 Assumption 15 Damping

It is assumed that with the use of the SSfJ the damping introduced by soil will be minimized. Therefore in the calculations carried out no soil damping was included. Based on this assumption the damping used was 5% of the critical. The effect of damping on the results is significant. If the damping value that was used in the calculations is smaller than the actual value then the calculations are regarded valid. If the value of damping used in the calculations is greater than the actual value then the resonance effect is underestimated and it can be that resonance introduces bigger loads to the structure compared to the loads introduced by extreme weather. In a check that was done in 4.3.6 the calculated unity checks for the condition of resonance are close to 0.5 thus far from being important. This would not be the case if less damping was used because the DAF would increase dramatically. As an example the DAF for resonance for various values of damping is presented below:

Table 27 The effect of damping on max DAF

Damping %	max DAF
1	50
2	25
3	16.67
4	12.5
5	10
6	8.33
7	7.14

Concluding, it is considered a valid assumption that there will be no soil damping for the jack-up when it stands on the SSfJ, especially when the SSfJ is considered fixed to the seafloor. In reality though the SSfJ will receive some damping from the soil and this will act in favor of the dynamic.

4.4.1.2.8 Assumption 16 minimum k_t value

In 4.3.5.1.1 a rough estimation of the minimum SSfJ stiffness (k_t) is performed. There it is assumed that the diagonal member of Figure 49 will yield when the horizontal load is 10 MN and based on that the minimum SSfJ stiffness was estimated as $k_{t,min}= 10^5$ kN/m. Later many analyses were carried out and it was found that the maximum base shear can reach values in the order of 35 MN. With this forces and for the best use of the material (at its yield stress) the SSfJ stiffness will be:

$k_{t,min\text{-}new} = F/\Delta x = 35000 / 0{,}01014 = 3{,}45 \cdot 10^5$ kN/m

This means that if the design focuses on using the least material to carry the maximum shear then the least k_t provided will be $k_{t,min\text{-}new}$ $3.45 \cdot 10^5$ kN/m. As explained in 0 the natural period is not affected by changes in k_t value as long as it stays above the value of 10^5 kN/m. Therefore the assumption about the minimum k_t value is a valid assumption that does not affect the final result.

4.4.1.2.9 Assumption 17 SNAME formula

The formula 7.3.5.3. of (SNAME, 1994) was used as a quick indicator of the natural period. In that formula many parameters are involved for which no data was available. Many assumptions were taken and they are presented in Appendix 2. Due to the amount of assumptions it was decided to use the values of natural period calculated by SACS. It is believed that SACS can give more accurate results due to the fact that less assumptions are used in the creation of the SACS model and less unknown parameters are involved. As seen in Figure 50 and Figure 51 the results of SACS and SNAME formula are comparable but SACS values are a bit smaller. For the analyses carried out in this thesis where the period of the waves is larger than the natural period of the jack-up, the use of a bigger value for the jack-up natural period leads to bigger inertia loads and therefore to bigger amount of k_r. It is suggested therefore for a later stage to create a very detailed model in SACS where many parameters can be involved and through that to calculate the accurate natural period. Of course the best way to calculate the natural period is by field measurements when the jack-up operates at a site with similar water depth as the one used in the analysis and where the soil conditions can be accurately estimated. Then using these measurements the jack-up model in SACS can be calibrated.

1.5.27 Step 3.2

4.4.1.3 Technical study summary

The technical study performed in this thesis comprises of 3 stages.

In Stage 1 the effect of the use of an "ideal" SSfJ on the critical aspects of the design and the operation of jack-ups is treated. This effect was assessed via assumptions which were also validated with simple checks.

It is understood that the use of the SSfJ will cause reduction in the (static) effect of environmental loading of the jack-up and therefore **the jack-up integrity is expected to be improved when it is placed on a SSfJ (from statics point of view)**.

During the assessment of the influence of the use of a SSfJ on the critical aspects of dynamics and leg-to-hull moment, it appeared that some checks are very important. Those checks are related to the stiffness of the SSfJ and the amount of fixity that can be achieved between the SSfJ and the spudcans of the jack-up. It was decided to deal with these parameters in Stage 2 and to give indications about the required values of SSfJ stiffness and fixity of the spudcan on the SSfJ.

Therefore in Stage 2 the design values for SSfJ stiffness and SSfJ-jack-up interface are calculated. At first the leg moment capacity was calculated using the assumed properties of the leg. Then it was identified whether extreme weather conditions or resonance with smaller waves is the most governing situation. The result was that the extreme weather conditions are more important and produce higher static and inertia loads.

For the extreme weather conditions an optimization procedure for the values of k_r and k_t took place. The optimization was done with several iterations and a quick and rough method was applied, the two stage deterministic storm analysis as described in ISO 19905-1. The optimization was then validated with time domain analyses and it was found to be slightly conservative but it is considered acceptable. **The result of the optimization is that the design of the SSfJ should aim to provide at least a SSfJ stiffness of $k_t = 10^5$ kN/m and a rotational fixation of the jack-up legs on the SSfJ of $k_r = 2.41*10^8$ kNm/rad**.

Finally with the design values of k_r and k_t and with the respective jack-up natural period known, a check was performed with waves that have a period that could cause resonance and a significant wave height that corresponds to that period. The result of this check was that the moments at any point of the legs are a lot smaller than the moment capacity.

4.4.1.4 Technical study conclusions

The procedure followed in this technical study showed that the environmental loads for a jack-up on a SSfJ will be less intense compared to when the jack-up stands on the seabed. Moreover, the structural characteristics of the SSfJ that are required for the survival of the jack-up on it are calculated and it is shown that they can easily be fulfilled with the current design techniques and materials. This study proves that a jack-up can be supported by a SSfJ provided that the SSfJ is fixed on the seabed and has structural properties indicated in this study.

In conclusion, **a jack-up can survive the environmental conditions of the North Sea on a SSfJ if the SSfJ is fixed on the sea floor and has the structural characteristics suggested in this technical study**

1.5.28 Step 3.3 Recommendations for further technical study

In this step a collection of recommendations for further technical studies is provided. These recommendations are based on issues that were either treated via assumptions or not treated at all due to the limited amount of time or the limited scope for this thesis.

It is highly recommended to study how a SSfJ can be designed in a way that it can achieve the maximum fixation to the sea floor. This can be very challenging if the suggested requirements for the SSfJ are to be fulfilled, namely: removability and also reusability.

It is very important to address the issue of the connection of the jack-up and the SSfJ. Although the requirement for spudcan fixity on the SSfJ is quantified, it was not possible to provide a design for the interface. It must be kept in mind that it is suggested to design the SSfJ in such a way that minimum modifications will be required for the jack-up that will be placed on it. This can make the design of the interface quite challenging.

It is also recommended to study how a SSfJ can be designed so that it is adoptable in the seafloor inclinations. In the studies carried out during this thesis an even seabed was assumed. This is not always the case in real sites.

Another important technical issue that needs to be further researched is the installation of the SSfJ on the seabed and also the installation of jack-ups on the SSfJ. During the technical study performed in this thesis only the in-place condition of both the SSfJ and of the jack-up on the SSfJ is considered. It is very important to deal with the installation procedures. To illustrate this it is enough to mention that the installation of a SSfJ next to an existing jacket will definitely be questioned by the owners of the jacket. In the same way the installation of a jack-up on the SSfJ will at least be very carefully checked by the owners of the jack-up.

Apart from the survival conditions that are checked in this thesis, the operational conditions are considered important. It is advised to pay attention to the operations manual for the jack-up that is going to be placed on the SSfJ and check whether the jack-up on the SSfJ is within the specified operational limits.

As a final recommendation it is stated that the checks performed in this study should be repeated and the assumptions taken should be validated if and when accurate detailed data is acquired about the jack-up that will use the SSfJ.

5 Conclusion and recommendations

5.1 General Conclusion

This thesis showed that the jack-up integrity is not influenced negatively when it is placed on a SSfJ and that a jack-up can survive the worst environmental loads in the North Sea on a SSfJ. This is valid under certain assumptions and provided that the SSfJ has structural characteristics as specified in this thesis. These characteristics are the stiffness of the SSfJ and the rotational fixity of the jack-up legs on the SSfJ. The required values for these characteristics that are necessary for enabling a jack-up to survive on a SSfJ were calculated during the technical study of this thesis.

5.2 General Recommendations

Given that there seem to be opportunities for a SSfJ in the North Sea it is recommended to continue studying the concept. At this point a recommendation is given about how the studies should be continued.

Initially the technical feasibility should be further investigated based on the recommendations supplied in the technical study chapter. It is highly recommended that HMC establish good connections or cooperation with jack-up designers so that accurate data and expertise can be used for the assessment of the technical feasibility of the SSfJ.

If it is proven that the concept is technically feasible, an economical feasibility study should take place. According to the feasibility study guidelines presented in Chapter 1 a feasibility study should always conclude after the economics are thoroughly addressed. The suggestion for the economic feasibility study is to estimate the fabrication and operational costs for a SSfJ throughout the whole life cycle of the structure. Then it should be checked if the cost of building and operating a jack-up with water depth capability of 180m is greater than the cost of using a SSfJ with a CJ 70. In that way it can be proven if there is a benefit for constructing and using a SSfJ.

In case the concept is technically but not economically feasible, it could also be valuable to address the feasibility of a support structure that increases the water depth capability of jack-ups even more.

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