TPG4560 - Petroleum Engineering, Specialization Project

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Project report

Subsea System for CO2 Injection

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Preface

This project thesis has been carried out at the Department of Geoscience and Petroleum as a cooperation with Department of Marine Technology, Faculty of Engineering and Science at the Norwegian University of Science and Technology (NTNU). The project report has been written as a study to further assist with the endeavors of a master thesis.

We would like to thank our supervisors at the Department of Geoscience and Petroleum, Tor Berge Stray Gjersvik and Sigbjørn Sangesland for their guidance and advice throughout the course of this project. We would also like to thank Audun Faanes from Equinor for providing necessary data and his assistance with the thesis.

Summary

This project represents an exploration of a subsea injection system, aiming to establish a more complete understanding of the included components and surrounding infrastructure. The primary goal is to break down the various aspects of the industry, challenging prevailing standards and seeking opportunities for improvement. This is done by presenting various enhancements and concepts which can yield both financial and environmental benefits compared to solutions utilized today.

The research has yielded a spectrum of conceptual ideas and potential modifications, forming the basis for the subsequent development of further work. The presented concepts mainly revolve around modularization, integrational or size alterations. Calculations is done to present early-stage design estimations for the various concepts to evaluate its potential advantages and limitations. The findings indicate that implementing the discussed concepts could offer advantages in terms of both financial and environmental considerations when compared to current industry standards.

Given the wide scope of the study the necessity for further analysis of a complete system will be necessary to establish reliable results of these concepts. This task will be undertaken as part of the upcoming master thesis.

Sammendrag

Dette prosjektet presenterer en omfattende undersøkelse av Subsea injeksjon systemer, hvor formålet er å oppnå en god forståelse for hvordan komponenter og tilhørende infrastruktur fungerer. Hovedmålet av rapporten er å se på forskjellige aspekter innen denne type industri, utfordre dagens standarder og søke muligheter for endringer. Dette er oppnådd ved å presentere forskjellige forbedringer og konsept som kan gi et positivt bidrag til både økonomiske og miljøvennlige utfordringer knyttet til en slik operasjon.

Oppgaven har lagt grunnlag for et vidt spekter av konsepter og medfølgende modifikasjoner som legger grunnlaget for senere arbeid. Konseptene dreier seg hovedsakelig om modulisering, integrering og størrelsesendringer. Grunnleggende beregninger er gjort for å etablere tilhørende fordeler og utfordringer for hvert konsept i en tidlig design fase. Funnene gjennom prosjektet indikerer at en implementering av diskuterte konsept potensielt kan være både økonomisk og miljøvennlig sammenlignet med dagens bransjestandard.

Som et resultat av det vide spekteret til oppgaven er det et klart behov for ytterligere analyser for å etablere pålitelige og utfyllende resultater for hvert konsept. Denne oppgaven vil bli utført senere som en del av den kommende masteroppgaven.

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List of Abbreviations

CCS – Carbon Capture and Storage

CO2 – Carbon Dioxide

LCO2 – Liquid Carbon Dioxide

BOP – Blowout Preventer

MTPA – Million Tons per Annum

XT – X-Mas Tree

VXT – Vertical X-Mas Tree

HXT – Horizontal X-Mas Tree

ROV – Remotely Operated Vehicle

PMV – Production Master Valve

PWV – Production Wing Valve

DHSV – Downhole Safety Valve

PSV – Production Swab Valve

WH - Wellhead

HC – Hydrocarbon

LMRP – Lower Marine Riser Package

ITS – Integrated Template Structure

FBS – Flow Base Structure

HOST – Hinge over Subsea Template

IMR – Inspection, Maintenance and Repair Vessel

MODU – Mobile Offshore Drilling Unit

RLWI – Riserless Light Well Intervention

BF – Buoyancy Factor

FEM – Finite Element Method

VIV – Vortex Induced Vibrations

1. Introduction

1.1 Background

In the face of climate change and the need to reduce greenhouse gas emissions, Carbon Capture and Storage (CCS) can provide an important contribution to this. CCS technology offers a promising avenue to capture, transport, and permanently store CO_2, thereby preventing their release into the atmosphere. Recently CCS has gained momentum for large-scale industrial applications and is a growing sector both locally and globally. The ability to be on the leading edge of this technology can contribute to both lowering emissions and financial gain.

1.2 Objective

The main objective of this study is to look at the development of cost-efficient methods and equipment. This is aimed at substantially lowering the overall installation, production and operational costs associated with CCS implementation. Specifically looking closer at the equipment standing at the seabed, such as the template structure, subsea Christmas tree and blow out preventer (BOP). As the industry yet is missing equipment design for pure CO_2 injection applications, traditional production solutions are used. This results in the use of equipment that is heavily over dimensioned in certain areas. The study will therefore discuss different solutions to simplifying or reduce the number of components needed for pure CO_2 injection compared to traditional oil production equipment.

1.3 Report Structure

The report is organized to initially outline background information on CCS, followed by an exploration of key components utilized in the industry to establish a foundational understanding for later discussions. The subsequent chapter will introduce new concepts for each equipment category, exploring potential design modifications for a pure injection system. The following chapter will feature calculations, shedding light on the advantages and challenges associated with the implementation of the presented concepts. The final chapter will engage in a discussion, evaluating all presented concepts and ultimately narrowing it down to the most viable solution.

2. Previous Published Knowledge

2.1 Carbon Capture and Storage - CCS

Carbon Capture and Storage is a process that involves capturing carbon dioxide (CO2) emissions from industrial processes, transporting the CO2 to a storage location and eventually storing it underground. This process is to be considered important for a sustainable future, by preventing the gasses to enter earth's atmosphere and contribute to global warming.

The Norwegian government has approved a project for CCS called Langskip. The initiative will involve investments of over 25 Millon NOK in the first phase, where the government will cover about 2/3 of the total costs and the industry covers the remaining. [1]

Norway's total emissions per 2022 totaled at 48,9 Million tons CO2 [2], and Equinor have decided that their goal by 2035 is to capture and store between 30-60 Million tons per annum (MTPA) [3]. This achievement will cover the entirety of Norway's CO2 discharge resulting in a net zero emission.

2.1.1 How does it work:

CCS consists of three main phases:

1. **Capture:**
   Separation of CO2 from other gases that are produced at big processing facilities, for example coal- and gas power plants, metal plants or refineries.
2. **Transportation:**
   After the separation of CO2 has occurred, the gas is compressed and transported to a suitable location using direct piping, trucks, ships or other suitable transportation.
3. **Storage:**
   The CO2 gas will then be injected into a reservoir deep below the surface, usually at a depth of 1000 meters or more.

2.1.2 How is it stored?

Storage of CO_2 will utilize the same mechanism that has stored oil and natural gas underground for countless years. This involves injecting CO_2 into a saltwater formation, requiring the presence of a porous and permeable reservoir formation, along with a sealing rock, for effective storage. Consequently, the structures designed to contain the gas must closely resemble the reservoirs that traditionally host hydrocarbons. [4]

2.2 Northern Lights

The Northern Lights project is a part of the full-scale carbon capture and storage (CCS) initiative Langskip, that aims to reduce carbon emissions from industrial sources and store CO_2 in a safe and permanent manner. The project is being developed by Equinor, which currently have partnered with Shell and Total.

The project includes transportation, injection, and permanent storage in the North Sea by the "Troll" field, where the first exploration well has been developed and confirmed to have storage capacity for both phase 1 and 2 of the project. [5] This first Northern Lights field is called Eos where the reservoir is located 100 km off coast and 2600 meters below the surface. Per 2022 a detailed well- and drilling plan was concluded and confirmed completion programs for the first injection well and assembly of well C-1 was finalized. [6]

Phase one of the initiative includes a desired storage capacity of up to 1,5 million tons of CO_2 per year, where constructions both on- and off-shore started in 2021 and is planned to be operational by mid-2024 [7]. The second phase of the program aims at over 5 million tons per year and introduces a capacity increase as demand within CCS develop across Europe.

2.3 SMEAHEIA

Smeaheia is a CO_2 development project intended to help Europe meet its climate goals. The initiatives ambition is to develop a transport and storage infrastructure for up to 20 Million Tons CO_2 per year, which will ultimately lead to a major increase in CCS capacity on a much more global scale. The Smeaheia license shall bring together a large-scale link of CO_2 transportation between Northwestern Europe to massive storage reservoirs in the North Sea. The License will be 100 percent operated by Equinor and will utilize a large portion of the existing Troll-field off the west coast of Norway. [8]

2.3.1 Licenses

Per 5. April 2022 Equinor was awarded two licenses for development of CO_2 storages, Smeaheia in the North Sea as well as Polaris in the Barents Sea [9], but by early 2023 they decided to no longer take part in the Polaris project [10]. Both licenses are huge steps in the development of CCS and making Norway a leading province in CO_2 storage in Europe.

2.3.2 Infrastructure

Within the mainframe of this initiative two different means of transportation have been discussed and are being evaluated. These include transportation via ships and by direct pipelines, where both concepts are being matured in parallel and are referred to by Equinor as the following:

1. **Norwegian Hub:**
   A ship transportation solution with onshore receiving terminal on the west coast of Norway, where the terminal has access to well injection at Smeaheia via direct pipelines.

2. **CO_2 Highway Europe:**
   A pipeline solution connecting North-West Europe directly to the wells at Smeaheia. This solution could reduce costs of transportations by as much as 50% compared to ship transportation and could include other benefits such as higher operating consistency and reduced lifecycle emissions. [8]

3. Technical data

In this chapter, some initial data is presented to describe the suspected condition for an injection well and the accompanying equipment. This is done to showcase the main differences compared to a traditional oil production well and demonstrate which parameters can be important to consider for the early design phase.

3.1 Wellhead

The temperatures and pressure experienced at the wellhead will differ for that of a production well. Due to the external influence of the environment the temperature of the injected fluid will be equivalent to the ambient temperature surrounding the well. For a typical offshore well site this will mean an ambient temperature of between 4-8 degrees Celsius.

The pressure experienced at the wellhead will depend on the specific reservoir conditions combined with the injection pressure from topside. Reservoirs suitable for injection and storage must have a large amount of cleared space. This in turn will result in a typically lower pressure compared to a producing reservoir. Referring to the PT-diagram illustrated in Figure 1 below, the operational pressure must be adequate for the injected LCO2 to remain in liquid form down to the reservoir. This is represented by the red line in Figure 1, indicating a minimum pressure of approximately 30 bars for a temperature equal to 6 degrees.

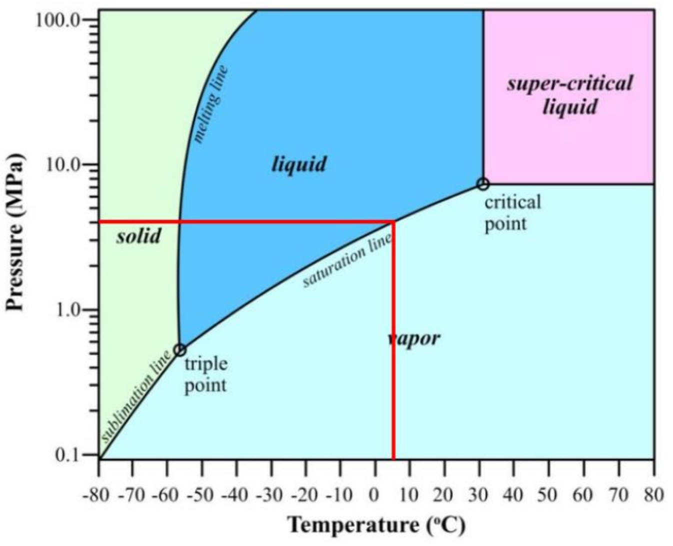


Figure 1: PT-diagram for CO2 [11]

Examining the Northern Lights project as an example, an injection well has already been drilled at the Eos field. In this location, the water depth is approximately 300 meters [12], leading to an external pressure of:

$$P_{ext} = \rho gh = 1025 * 9.8065 * 300 = 30.2 Bar$$

Equation 1: External Pressure at a Water Depth of 300 meters

To calculate the injection velocity through the injection tubing, the density of the injected fluid is required. For simplicity, it is assumed that pure LCO2 is injected, neglecting possible contamination. Utilizing the estimated ambient temperature of 6 degrees and an injection pressure of 50 bar, this results in a density of 897.3 kg/m^3 for the LCO2 [13]. The design injection capacity for one well will be 1-1.5 million tons per annual. Calculating for the maximum amount of 1.5 MTPA the injection velocity will be:

$$1.5 MTPA = 47.55 kg / s$$

$$Flow = \frac{mass / s}{density} = \frac{47.55 \frac{kg}{s}}{897.3 \frac{kg}{m^3}} = 0.05299 m^3 / s$$

Equation 2: Mass Flow through Injection tubing

$$A = \pi r^2 = \pi * 0.0762^2 = 0.01824 m^2$$

Equation 3: Cross Section Area of 6-inch Tubing

$$V = \frac{Flow}{A} = \frac{0.05299 \frac{m^3}{s}}{0.01824 m^2} \approx 2.9 m / s$$

Equation 4: Injection Velocity

3.2 Reservoir

Reservoir conditions will depend on the selected site and the duration of the injection process. In contrast to a production reservoir, the injection process will lead to a gradual pressure increase due to the expanded volume in the reservoir. The primary criterion for the reservoir to be suitable for injection is that the pressure and temperature are adequate to maintain the CO2 in its liquid phase throughout the descent into the reservoir [14].

For the injection well drilled for the Northern Lights project, the estimated reservoir pressure and temperature are 200-300 bar and 100 degrees Celsius, respectively [12]. It is considered that these conditions are sufficient to maintain the CO2 in its liquid phase. The reservoir is situated approximately 2600 meters below the seabed.

4. Overview of Components

The primary goal of this study is to streamline the injection system for pure CO_2 injection. To achieve this, each core component relevant to this study will be discussed in terms of their primary functions. This assessment will involve creating an overview of each major component before conducting a final evaluation based on the data obtained. The final discussion will challenge the NORSOK and industry standards on possible design improvements that do not jeopardize well integrity, safety, cost-efficiency, or the installation process.

4.1 X-Mas Tree

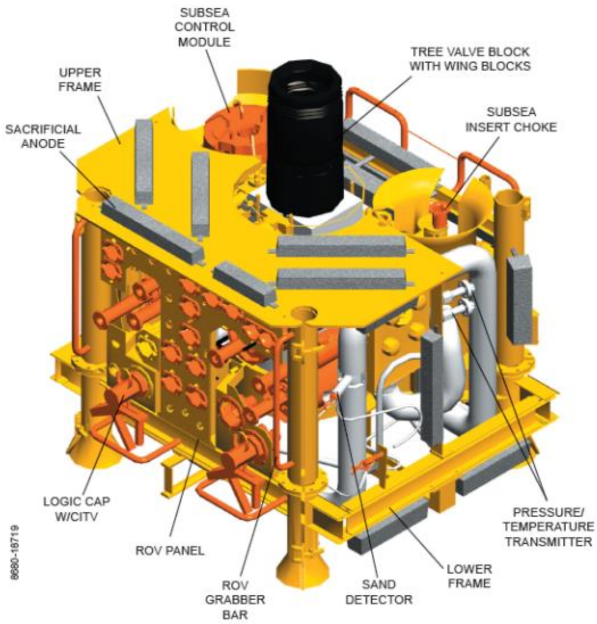


Figure 2: Illustration XMAS Tree [15]

The subsea X-Mas Tree (XT) serves as the primary barrier separating the well from the external environment. Its core function is to regulate the fluids and gases produced or injected into the well, achieved through various control valves and chokes. Subsea Christmas trees come in three main configurations: Vertical X-Mas Tree (VXT) with either a mono- or dual-bore setup, or a horizontal X-Mas Tree (HXT). While the key components of the XT are shared among these configurations, the placement and design approaches can offer unique advantages for specific cases. Additionally, a XT are equipped to collect critical data about flow and environmental factors, including pressure, temperature, sand detection, erosion, and single/multi-phase flow measurements. [16]

The requirements for such a setup are originally tailored for a production tree serving a high-pressure reservoir with a mix of highly combustible fluids and gases. However, specific design guidelines and criteria have not yet been developed for pure CO_2 injection. Given the substantial differences in flow content and operational conditions, there's a compelling need to explore ways to simplify this system for improved cost-efficiency.

Finally, a detailed examination of each major component in a typical subsea Christmas tree is carried out to establish a solid foundation for the discussion of a new designs.

4.1.1 Valves

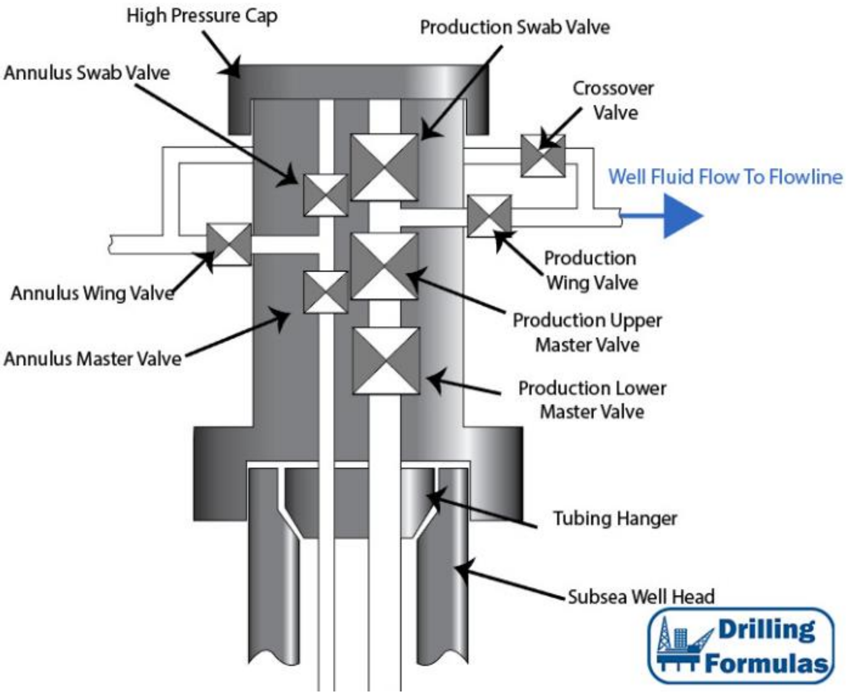


Figure 3: Illustration of Valves [17]

A standard subsea XT shall have a specified number of valves to be able to regulate flow, have controlled interventions or well testing. Each valve can be operated from the surface using hydraulic pressure or electronically, or manually by a remotely operated vehicle (ROV) [17]. The main valves are required to be fail-safe close valves, meaning it requires a hydraulic pressure from topside to keep it in its open state. This means that during a possible emergency where topside loses its connection to the XT the valves will automatically close, securing the well.

The current requirements for valves integrated in an operational subsea XT with regards to the NORSOK D-010 are as follows [18]:

- One fail-safe closed automatic master valve and one fail-safe closed automatic wing valve in the main flow direction of the well.
- If the tree has side outlets, these shall be equipped with fail-safe closed automatic valves.
- One swab valve and tree cap (vertical tree) or two crown plugs (horizontal tree) for each bore at a level above any side outlets.
- Isolation valves on downhole control lines which penetrates the tree block.

Additionally, the valves must be capable of undergoing testing for both low and high maximum differential pressure in the direction of flow [18].

4.1.1.1 Production Master Valve

Figure 4: Production Master Valve [19]

Master gate valves is placed in the bore hole and should provide a full opening to not interrupting flow or hindering running equipment from passing thru. For subsea XT there is typically used two PMV’s, dedicated the upper and lower PMV for redundancy. The PMV should be a high-quality valve that must be capable of containing the full shut-in pressure of the well [20].

The primary requirement for master valves is that they must be "fail-safe close" valves. This designation implies that they need a continuous supply of hydraulic pressure from the topside to remain in the open position. In the event of a potential emergency, such as a loss of communication or connection between the topside control and the XT, these fail-safe close valves will automatically close. This will overall enhancing safety and well integrity.

Given that the subsea injection system's operation pressure is significantly lower than that of a typical production well, it is reasonable to assume that a single master valve will suffice. However, it's important to consider the substantial Joule Thomson (JT) effect that occurs with CO_2 in its gaseous phase [21]. This effect can cause extremely low temperatures during pressure alterations. This necessitates the use of materials designed for extremely low temperatures in certain flow conditions, especially during startup or shutdown procedures. Consequently, the cost of the valve will increase, making a one master valve-based design particularly appealing.

4.1.1.2 Production Wing Valve

The Production Wing Valve (PWV) will be installed within the horizontal flow path of the production line. Typically, it takes the form of a gate or ball valve, sharing the same Flow fail-safe close features as described for the PMV. Its primary purpose is to halt the flow during shutdown procedures. The Production Wing Valve is the preferred choice for this function since it allows monitoring of production tubing pressure through pressure/temperature gauges positioned between the PMV and PWV [20].

4.1.1.3 Swab Valve

The Swab Valve is located beneath the tree cap and remains dormant during regular production activities. Its primary purpose is to create a vertical opening to the well, enabling the potential for well interventions or other operations that requires direct access to the production line. The Swab Valve is exclusive to the VXT system, as the HXT system utilizes plugs along with the tree cap [20].

4.1.1.4 Choke Valve

The choke valve is positioned downstream of the PWV in the production flowline. Its primary purpose is to regulate fluid flow and pressure from the well and is typically not intended for complete well shut-off. To withstand the high-speed flow of potentially corrosive fluids over an extended period, it must be crafted from high-quality steel. The design of the valve should be optimized to minimizes wear on critical components, ultimately extending the valve's lifespan and reducing the need for frequent well interventions.

The choke valve typically features a needle valve or port valve configuration and can be either retrievable or non-retrievable [20]. In favor of maintaining an efficient and cost-effective intervention process, a retrievable configuration can be particularly advantageous for subsea applications.

When dealing with injection wells containing a significant LCO2 content, the Joule-Thomson effect becomes a critical design factor for the choke valve. If the CO2 flow transitions into its gaseous phase, the Joule-Thomson effect becomes pronounced. This implies that the valve can be exposed to very low temperatures while adjusting pressure. While this isn't typically problematic under normal operating conditions, it can become a concern during start-up or shut-down procedures. Therefore, the choke should be designed to handle such operational conditions and ensure the continuous flow of liquids, particularly at lower flowrates [14].

4.1.2 Tubing Hanger

The Tubing Hanger is fixed to the uppermost tubing joint within the wellhead, typically situated in the tubing head, to provide support for the tubing string. Its primary role is to guarantee hydraulic isolation between the tubing and the annulus. Additionally, in certain instances, the tubing suspension may include provisions for establishing connections that facilitate communication among hydraulic, electrical, and various other downhole functions [20].

4.2 Blowout Preventer - BOP

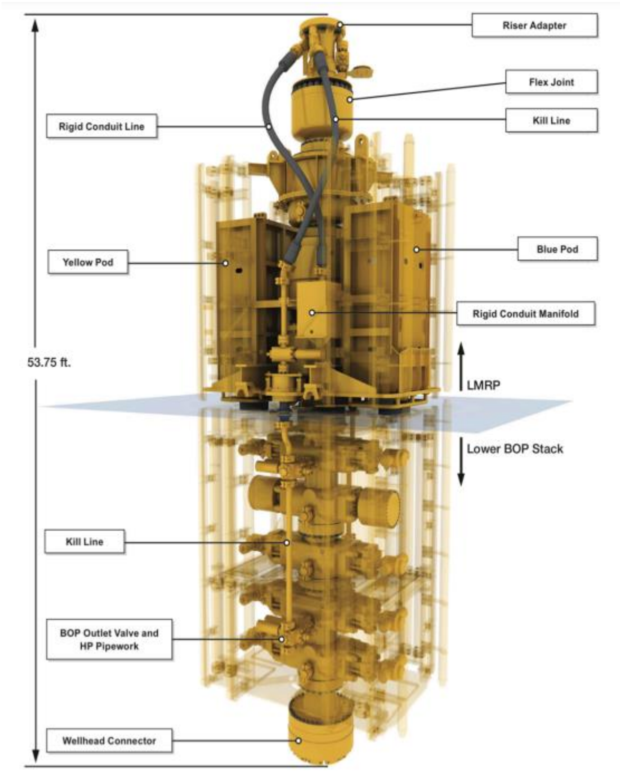


Figure 5: Deepwater Horizon BOP Stack [22]

A subsea blowout preventer (BOP) is a critical piece of equipment used in offshore drilling, oil and gas production and in CO2 injection. BOPs are specialized valve devices, used to seal, control and monitor oil and gas wells. This will prevent uncontrolled release of hydrocarbons, called a blowout. A blowout is an abrupt and uncontrolled discharge of the substances contained within the well, with the potential to result in severe environmental and safety repercussions. [23]

Subsea blowout preventers (BOPs) are designed to endure immense pressures that are encountered in hydrocarbon reservoirs. However, when applied in the context of a CO2 injection well, the extreme conditions they are designed to withstand are not typically present. While the reservoir pressure in a CO2 injection well does rise with the volume of CO2 injected, it is important to recognize that the pressure dynamics differ significantly from those in traditional hydrocarbon (HC) wells.

The variance in pressure profiles between traditional HC wells and injection wells presents an opportunity to explore design modifications that can effectively handle the specific pressures introduced by CO2 injections while maintaining the structural integrity necessary for safe drilling operations.

4.2.1 Ram BOP

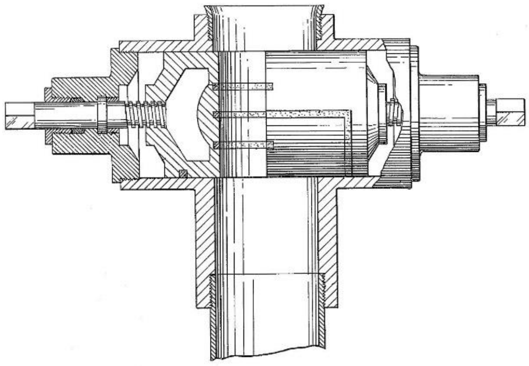


Figure 6: Ram BOP Patent Drawing [24]

A ram-type Blowout Preventer (BOP) functions similarly to a gate valve, employing a pair of opposing steel plungers known as rams. These rams extend toward the center of the wellbore to restrict the flow or retract open to permit flow. The inner section of the ram features packers that press against the wellbore and surrounding tubing. Outlets are positioned on the side of the BOP housing, connecting to choke and valves or kill lines. [23]

4.2.2 Annular BOP

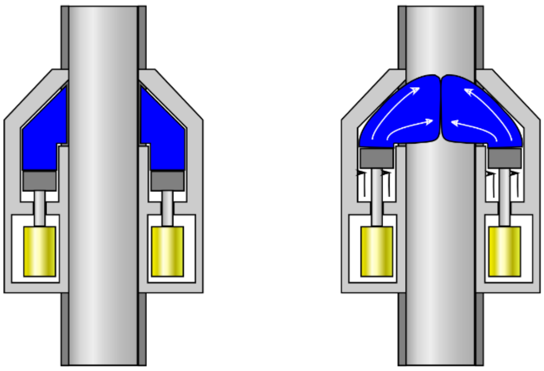


Figure 7: Annular BOP Illustartion [25]

An annular BOP has the capability to close up around the drill string, casing or a non-cylindrical object. This is achieved through hydraulic control of the wedge principle to effectively contain pressure. The BOP features a circular rubber seal strengthened with steel ribs, housed between the head and hydraulic piston. When the piston is actuated, its upward thrust-forces compress the seal unit, effectively sealing the annulus and openhole. This design consists of only two moving components, rendering it a relatively simpler and easier-to-maintain alternative in comparison to ram-type BOPs. [23]

4.2.3 Wellhead System

A subsea wellhead system serves as a pressure-retaining component tasked with both suspending and sealing the casing utilized in well drilling. In essence, it functions as a critical anchor and pressure seal for the casing that runs from the well's bottom, up to the surface pressure control system facilitated by the blowout preventer (BOP). [26] This plays a vital role in establishing a controlled-pressure environment for wellbore access and ensuring the structural integrity of crucial connections and safety elements.

4.2.3.1 Wellhead Connector

The wellhead connector serves as the female component of the wellhead, affixed to the lower portion of the BOP stack. Its primary purpose is to establish a robust, preloaded connection with the wellhead and the LMRP (Lower Marine Riser Package), which constitutes the upper segment of the BOP, particularly during drilling operations. [26].

4.3 Template Structure

The template structure is a specially designed frame created for secure placement of subsea equipment on the seabed. It also serves as structural support for the wellhead when required. To safeguard the equipment from potential risks such as trawling or falling objects, these frames often feature a hinged cover that provides protection without impeding access for ROVs or operations.

There exist various configurations of these templates, differing in size, weight, and usability. Some typical designs include:

- Integrated Template Structure (ITS)
- Flow Base Structure (FBS)
- Hinge over Subsea Template (HOST)

The choice of configuration depends on specific design factors that are influenced by the operational environment and the available installation equipment. To ensure stability on the seabed, these templates are typically equipped with suction anchors, mud mats, or center piles, depending on the soil properties at the installation site.

4.3.1 Northern Lights Template Structure

Looking at the Northern Lights project it is decided to use a satellite type structure, which can be seen in Figure 8. This is due to the low initial investment and low number of planned wells. The structure is a typical ITS configuration with 4 suction anchors to secure it to the seabed. The advantages of adopting this setup include cost-effectiveness during both the production and design phases. However, potential challenges may arise in the form of an oversized construction for its’s intended use, which could complicate the installation process.

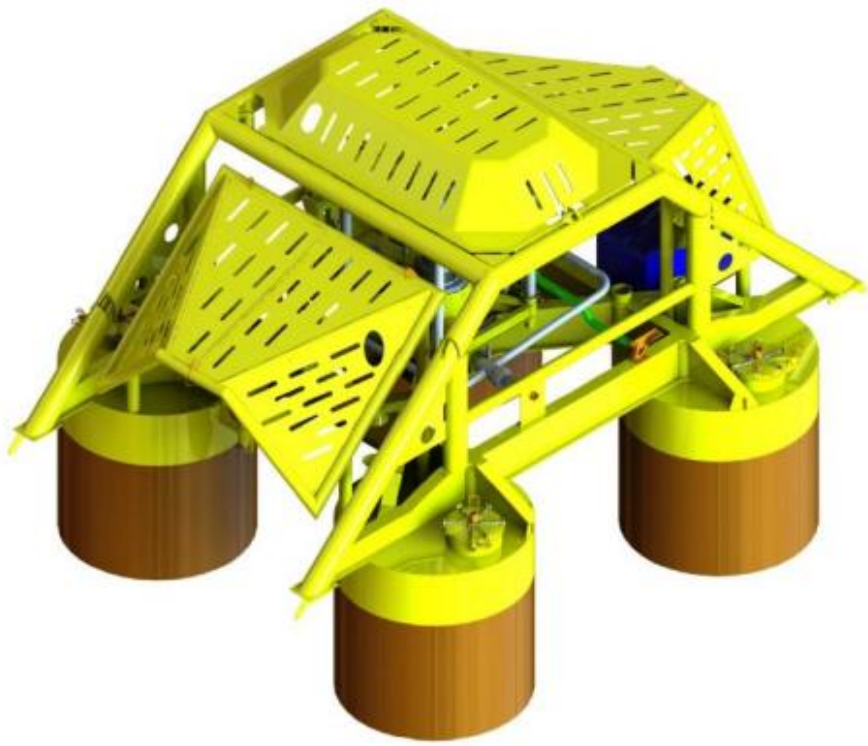


Figure 8: Northern Lights ITS [14]

4.3.2 CAP-X

CAP-X represents a novel initiative by Equinor, aimed at standardizing segments within a conventional subsea template structure. The approach involves sectioning the structure into independent segments, enabling streamlined replacement or reuse. The primary advantage lies in the substantial cost reduction, as it enables the reuse of certain components in subsequent projects. This approach minimizes the need for redesigning and manufacturing the entire structure, as only the segments requiring modification necessitate these efforts. The new components can then seamlessly integrate with the remaining structure. One configuration of this concept is shown in Figure 9 using a compact trawl protection to further minimize the footprint.

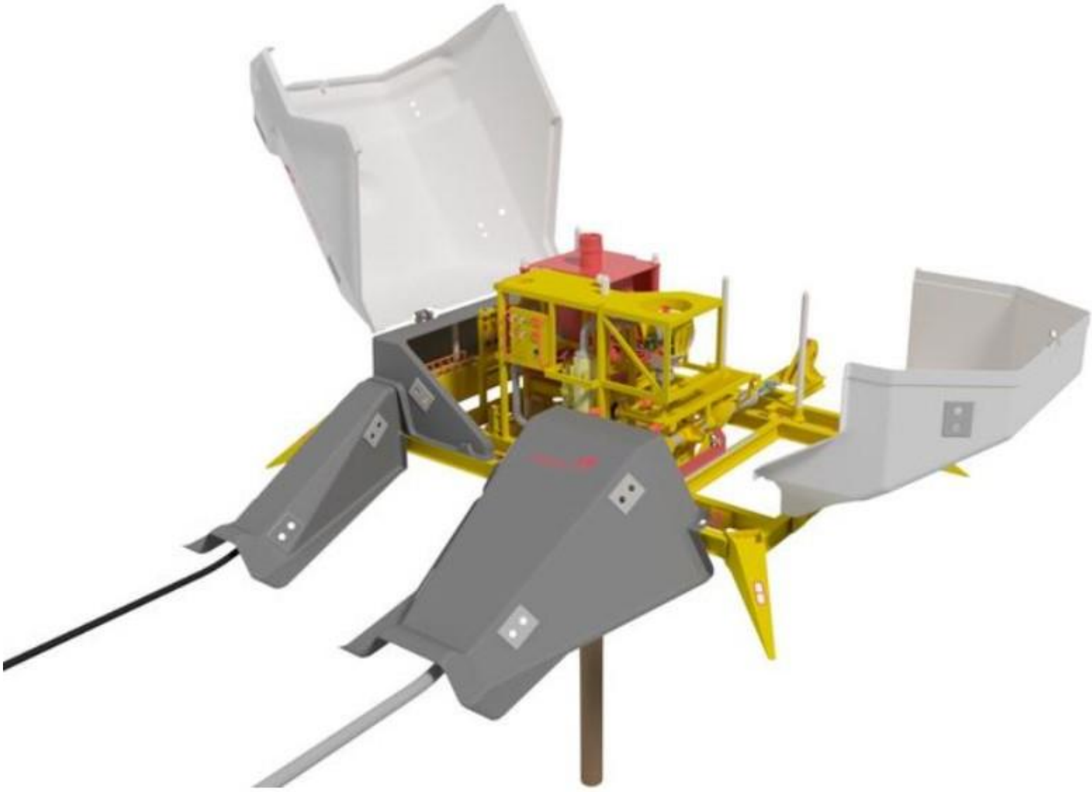


Figure 9: CAP-X Template Structure [27]

5. Concepts and Design Enhancements

This chapter aims to incorporate various design concepts that explore potential simplifications for subsea equipment. The objective is to propose solutions based on existing literature while incorporating innovative perspectives. These considerations will form the groundwork for the development of the final product in the next phase of the master's theses. A variety of concepts will be introduced and deliberated upon before arriving at a conclusive decision regarding the direction to pursue.

5.1 Compact Template Structure

The template structure constitutes a substantial portion of the weight and size of the equipment deployed on the seabed. Exploring methods to minimize the footprint and weight of this structure can lead to notable cost savings in both the production and installation phase. Taking the satellite-well installed for the Northern Lights project as a reference, which employs a conventional ITS structure for satellite-well configurations, the subsequent concepts will explore potential designs for simplifying and standardizing the structure.

5.1.1 Single Centered Suction Anchor

The ITS employed in the Northern Lights project relies on four suction anchors to securely fasten it to the seabed. Given the size and design criteria for the equipment installed on the structure, this can be considered a reliable option in ensuring stability under varying loads. However, it will come with the trade-off of an expanded footprint and increased weight. The current structure is estimated to weigh a minimum of 103 tons, excluding the suction anchors. [14] The weight of these anchors will differ based on their required height and thickness, accounting for the soil conditions at various installation sites.

Exploring ways to minimize the size and height of the X-Mas tree and BOP installed on the template presents an opportunity for a more streamlined template design. One approach involves adopting a centered single suction anchor as the foundation for the structure. This becomes the baseline for the frame, allowing for a more compact design while ensuring adequate protection for the installed equipment. In this configuration, the well would pass through the suction anchor, resembling an FBS-type design.

However, reducing the number of suction anchors to one introduces challenges, particularly regarding the template's stability, especially under lateral loads. This aspect must be carefully considered during the analysis phase to ensure the template can withstand normal operational states and unforeseen loads. Additionally, the increased size of the single centered suction anchor will contribute to greater weight. Therefore, this solution needs to be compared with the four smaller anchor to evaluate potential weight savings.

5.1.2 Module Based Template

The previous discussions explore the potential for cost savings through a physical reduction in size, leading to decreased material usage, shortened production times, and simplified installation processes. Another possibility for cost optimization involves modularizing the template structure into independent segments. While this approach may not yield additional cost reductions in line with the scenarios discussed earlier, it allows for the reusability of components for future implementations with similar requirements.

For this strategy to be advantageous, the template structure must be segmented in a manner that allows for diverse configurations to be mounted without necessitating structural alterations to the reused segments. Achieving this involves implementing a standardized solution for mounting points between different segments, facilitating seamless connections for various modules within defined size limits. Figure 10 below illustrates this concept, showcasing a template divided into four primary segments.

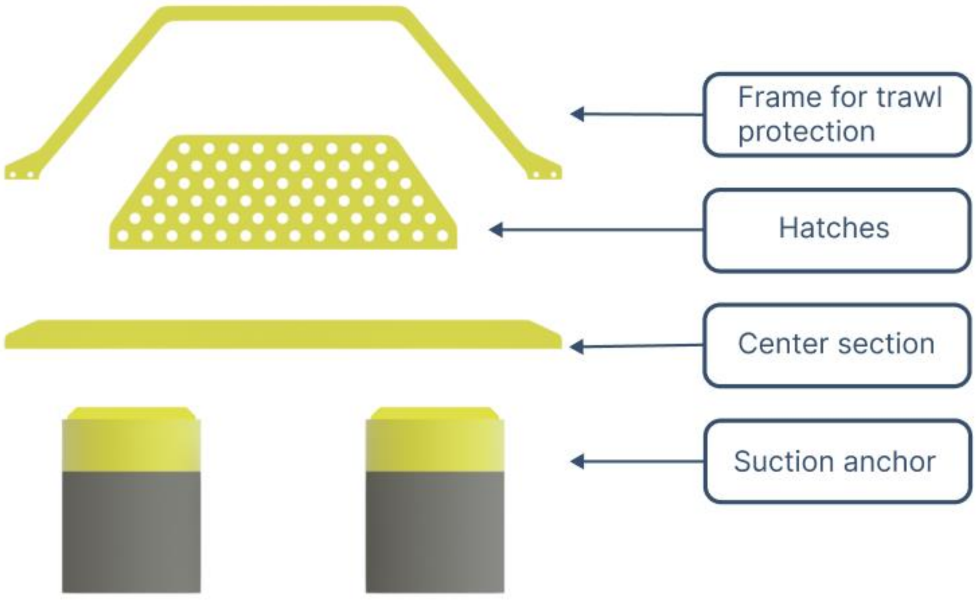


Figure 10: Module Based Template

Examining various installation sites and requirements, this configuration allows for the integration of tailored components without necessitating an entirely new template structure. This flexibility extends to accommodating new suction anchors designed for different soil conditions, with the opportunity to store used anchors for later use at a different location with similar conditions. Addressing the need for frame or hatch replacement due to damage during installation or operation, as well as accommodating new equipment with varying size and accessibility criteria, is another notable advantage.

A challenge associated with this modular configuration is that the structural integrity of the template may be somewhat compromised by the modulation of its components. This potential compromise may result in a slightly heavier structure with a larger footprint compared to a fully integrated design. To mitigate this, careful consideration must be given to the design of dividing and mounting points to ensure they maintain the stiffness and strength of the overall structure. Additionally, the template must adhere to its operational criteria, ensuring easy accessibility for remotely operated vehicles (ROV) and intervention capabilities concerning the installed equipment.

5.1.3 Alternative Material

For subsea equipment, steel has traditionally been the dominant choice of material due to its well-rounded qualities and the large amount of research and data from prior implementations. This preference is particularly evident in addressing corrosion concerns, whether submerged in water or buried in soil [28]. Although further research is still needed, aluminum has emerged as a viable alternative to steel for subsea applications. Integrating aluminum into the frame structure can contribute to weight reduction and a diminished environmental footprint.

Considering the previews concept outlined in Section 5.1.2 the framework will allow for the incorporation of new materials such as aluminum. This can be used for specific components of the template structure since the template is divided into separate sections. This hybrid approach can eliminate certain challenges associated with alternative material usage. For instance, one can utilize steel for the suction anchors and center section, while opting for aluminum in the upper section including hatches and the trawl protection frame. This configuration effectively addresses concerns related to the corrosion of aluminum in buried soil and lack of stiffness for the center section.

A consideration for implementing aluminum in conjunction with steel is the potential for corrosion when the two materials are in contact, particularly in a submerged state. This corrosion arises from the aluminum acting as an anode, transferring electrons to the steel, which functions as the cathode [29]. This electrochemical process is intensified when submerged, considering the conductive properties of saltwater acting as an electrolyte. To address this concern, the design of the structure must account for and limit this corrosive behavior. This especially applies for the connection points between the aluminum and steel components.

5.2 Compact X-Mas Tree

When considering the distinct design requirements for an injection-type X-Mas tree in comparison to a production tree, it indicates that there is an opportunity to simplify the integration of fundamental components. Some of the necessary redundancies present in a production tree may be deemed excessive for an injection well, particularly when dealing with a less corrosive injection mixture and operating pressures well below those expected in production wells. Nevertheless, it remains essential to uphold well integrity under all circumstances, including normal operation, shutdown, and well interventions.

Streamlining the components, reducing material usage, and facilitating the retrieval of components and well interventions can result in a substantial cost reduction. This will be done by simplifying equipment production, installation, and operational usage. One approach to achieve this is through the implementation of a module-based concept. This concept involves dividing the X-Mas tree into segments that can be independently retrieved or serviced. This design is already established for production wells, as illustrated in Figure 11.

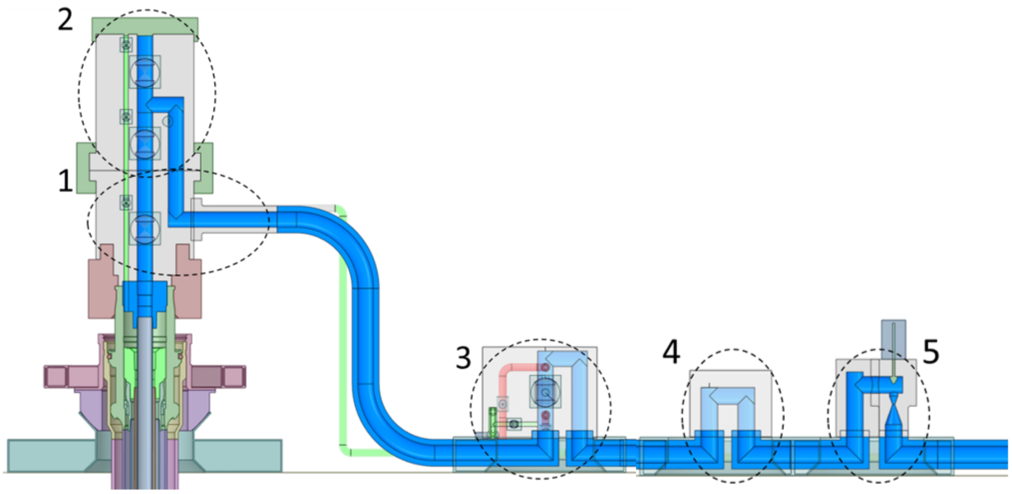


Figure 11: Module-based Concept by Lucas Cantinelli Sevillano [30]

The figure illustrates a typical vertical dual-bore X-Mas tree, where the components are divided into five modules. This design is aimed at enabling the individual retrieval of components while preserving well integrity. As a result, it becomes possible to swiftly replace specific components without requiring heavy equipment topside. This will lead to a significant reduction in costs when compared to the retrieval of an entire tree. Table 1 shows a list of the components within each module.

Table 1: Module-based Concept Component Overview

Module 1	Module 2	Module 3	Module 4	Module 5
Lower Production Master Valve	Upper Production Master Valve	Production Wing Valve	Flow meter	Choke
Lower Annulus Master Valve	Upper Annulus Master Valve	Annulus Wing Valve		
Wellhead Connector	Crossover Valve 1	Crossover Valve 2		
Production Outlet	Production Swab Valve	Chemical Injection Valve 1		
	Tree Cap	Chemical Injection Valve 2		

This configuration enables the retrieval of Module 2 through Module 5 using an Inspection, Maintenance, and Repair (IMR) vessel, eliminating the necessity for a Mobile Offshore Drilling Unit (MODU) for intervention operations. This represents the most significant cost-saving aspect of this concept.

Considering the discussed elements, two design concepts have been developed that follow to this design philosophy while exploring ways to further simplify the concept for a pure CO2 injection well. In the initial stages, these concepts will exclusively focus on the injection process, disregarding annulus access and its associated complications.

5.2.1 Concept 1

The initial concept introduces a X-Mas Tree design that adheres to the module-based design principle discussed earlier. The tree is segmented into four modules, each designed to allow the retrieval of individual components while ensuring the integrity of the well. A visual representation of the planned module and valve arrangement is shown in Figure 12 below. Additionally, Table 2 provides a list of the components included in each module.

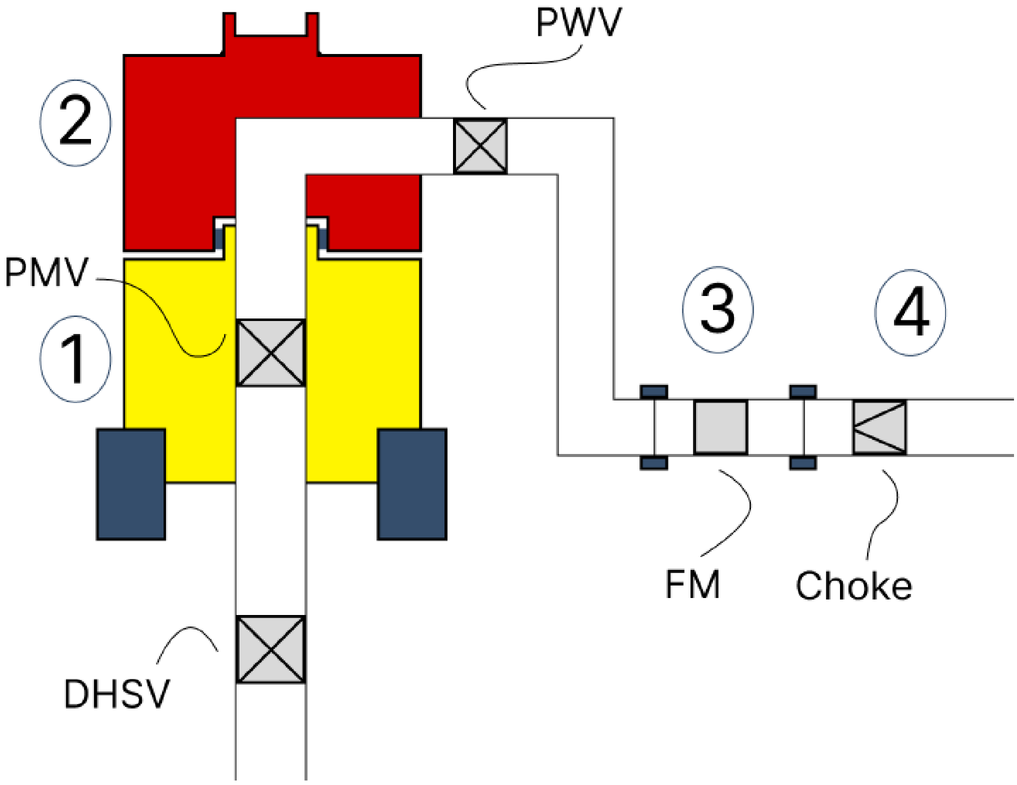


Figure 12: Concept 1 Module and Valve Placement

Table 2: Concept 1 Component Overview

Module 1	Module 2	Module 3	Module 4
Production Master Valve	Production Wing Valve	Flow meter	Choke
Wellhead Connector	Production Outlet		
Module 2 Connector	Riser Connector		
	Hydraulic Pressure Seal for Module 1		

5.2.1.1 *Module 1*

For Module 1, it is chosen to use a single Production Master Valve (PMV). This decision is based on the modified operational criteria for a pure injection well. In such cases, having one fail-safe Master Valve, in conjunction with a Downhole Safety Valve (DHSV) installed in the well, can be considered sufficient. The second PMV can be deemed redundant for injection-type wells, especially when considering the reduced expected operational and shut-in pressures. Consequently, even during the removal of Module 2, the active well will maintain two primary barriers, ensuring a secure seal between the well and the external environment.

Module 1 is connected to the wellhead using hydraulic pressure, similar to a conventional vertical Christmas tree assembly. The removal of this module will necessitate the use of a Riserless Light Well Intervention (RLWI) vessel, thus eliminating the need for a full Mobile Offshore Drilling Unit (MODU).

5.2.1.2 *Module 2*

Module 2 will be locked to Module 1 using hydraulic pressure to ensure an effective seal, accounting for the maximum differential design pressure. This module features the Production Wing Valve (PWV) as the sole primary valve, located at the wing. Retrieving this module thus provides the opportunity to replace the PWV independently, which is not achievable with a traditional vertical X-Mas Trees.

The Swab Valve (PSV) and/or removable tree cap are eliminated and replaced by a solid tree roof that cannot be opened. While this reduces production and maintenance costs for the top module, it limits vertical well access for interventions and maintenance. To address this, the connection between Module 1 and 2 is designed to replicate the top tree connection found in a conventional tree, allowing for equipment to attach during well interventions. Given the simplicity and weight of Module 2, it can likely be retrieved using an Inspection, Maintenance, and Repair (IRM) vessel. Removal of module 2 to gain access to the vertical production line can thus be done without significantly increasing costs compared to a direct access thru a production swab valve.

5.2.2 Concept 2

Concept 2 incorporates three modules, featuring a simplified integration of valves. The design follows a more traditional approach, featuring the main structure of the X-Mas tree as a single unit reminiscent of a traditional tree structure. Notably, the flow meter and choke modules are designed for independent retrieval, enhancing flexibility and maintenance cost. A visual representation of the planned module and valve arrangement is shown in Figure 13 below. Additionally, Table 3 provides a list of the components included in each module.

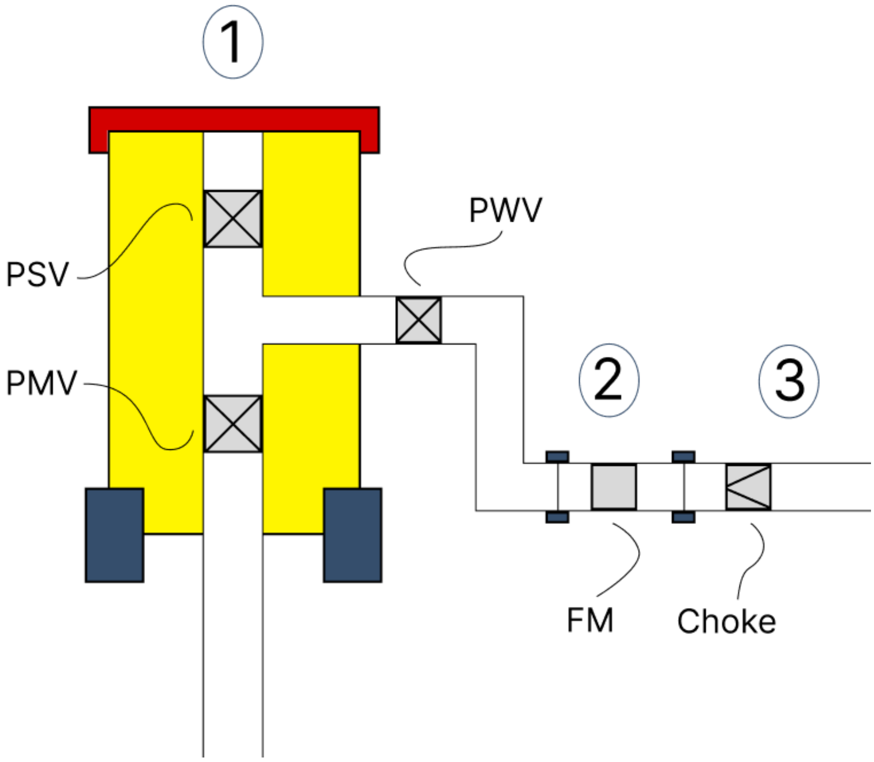


Figure 13: Concept 2 Module and Valve Placement

Table 3: Concept 2 Component Overview

Module 1	Module 2	Module 3
Production Master Valve	Flow meter	Choke
Production Swab Valve		
Production Wing Valve		
Production Outlet		
Wellhead Connector		

5.2.2.1 Module 1

Module 1 adopts a configuration somewhat similar to a conventional vertical X-Mas Tree, but with a minimized number of valves. Within this module, the main structure accommodates the PMW and PWV, both serving as fail-safe close valves. In contrast to concept 1 a traditional swab valve is incorporated into the tree cap. This swab valve facilitates vertical access to the well, enabling safe well operations and interventions.

In the absence of the Downhole Safety Valve (DHSV), the PMV and PWV will serve as the two primary barriers when removing either Module 2 or 3. To guarantee a secure barrier during both regular operational states and interventions, these valves must be designed as fail-safe close valves.

The increased size of Module 1, in comparison to Concept 1, introduces challenges in terms of retrieval for potential replacement of integrated valves. The larger size implies that a complete Mobile Offshore Drilling Unit (MODU) is likely required for retrieval, thereby escalating costs substantially. Considering the prolonged lifespan of these valves the frequency of retrieving Module 1 is decreased. Since module 1 allows direct vertical access for the well for light well intervention thru the swab valve this configuration can maintains its financial advantage compared to the retrieval of the top module in concept 1.

5.2.3 Subsea Silos

Discussions within the Subsea industry around a concept-study exploring the potential of utilizing underground silos. The conventional challenges associated with excavating and burying large components have historically hindered the widespread adoption of such a strategy. However, the introduction of a modular-based concept, as outlined, significantly diminishes construction expenses due to size reduction and easier installation operations. This will thereby present a compelling case for the reduced risks associated with implementing this infrastructure.

The deployment of underground silos holds the promise of alleviating, if not entirely eliminating, numerous environmental factors that contribute to cyclic loads, fatigue, and the need for component replacements. Particularly in cold-water environments, the looming threat of iceberg collisions is a major concern, with the potential to jeopardize well completions in these geographical areas. The proposed conceptual idea not only addresses this concern but also opens possibilities for well completions in regions that may have previously been overlooked for both injection and production fields. This innovation has the potential to extend the boundaries of exploration and development into areas that were once deemed challenging or inaccessible.

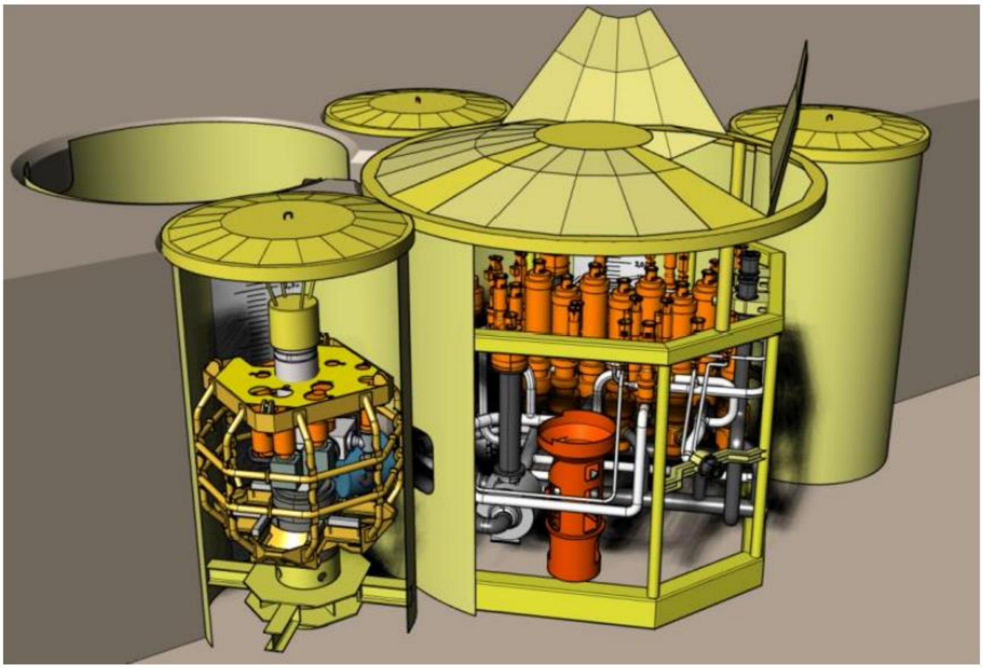


Figure 14: Subsea Silos – Concept [31]

5.3 Reduced BOP Size with compact Wellhead

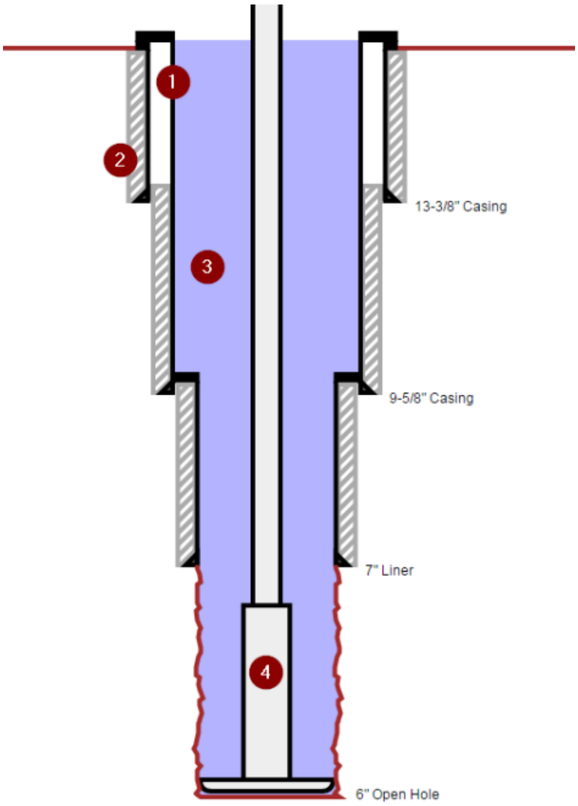


Figure 15: Wellbore Example [32]

During the course of this project, a discussion arose regarding the dimensions of wellheads in traditional HC wells. As the conversation progressed, a concept idea emerged. Unlike HC wells, CO2 injection wells may not experience the same level of environmental strain and in the event of a blowout the damages are not as critical when comparing CO2 to HC's. This leads to the idea that there might not be a necessity to utilize identical wellbore casings as traditional wells. By reducing the size of the wellbore, it will also reduce the size of wellheads and needed BOPs. Consequently, this approach promises to significantly reduce the overall costs associated with installation, drilling and cementing during wellbore development.

This concept idea has by discussion with project supervisors been regarded as something to investigate in the future, not as a focus point in this project. Simply a preliminary examination of each casing system has been conducted to enhance understanding for future endeavors.

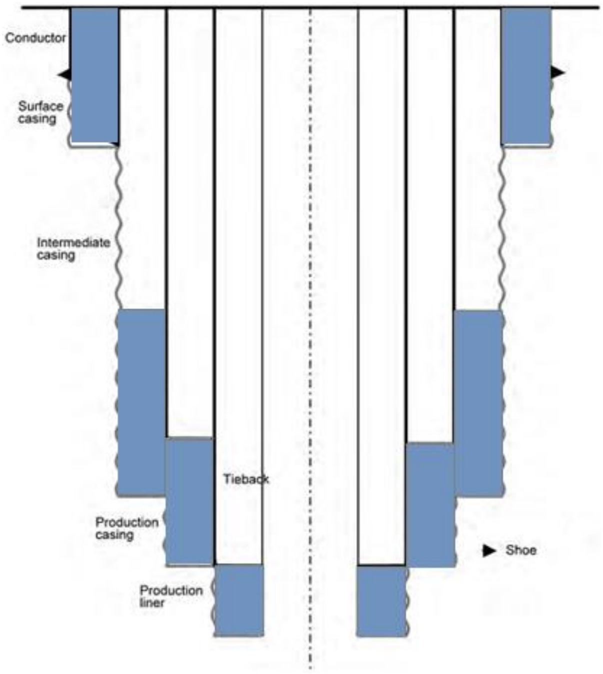


Figure 16: Casings in Wellbore [33]

5.3.1 Conductor Casing

The initial casing installed in a well, known as the conductor casing, serves to isolate unconsolidated formations and water sands, providing protection against shallow gas. Typically, the conductor string is where the casing head is attached, and the casing itself is always cemented to the surface at a depth of approximately 20 meters.

5.3.2 Surface Casing

The surface casing string needs to be positioned at a sufficient depth to safeguard against freshwater contamination and prevent issues related to drilling fluid circulation. Consequently, it is consistently cemented to the surface at depths ranging from 300 to 900 meters.

5.3.3 Intermediate Casing

Intermediate casings are installed to isolate unstable hole-sections, zones with lost circulation, low-pressure areas, and production zones. Some wells may require multiple intermediate strings, while others may not need them at all.

5.3.4 Production Casing

The primary role of the production casing is to isolate production zones and contain formation pressure. This casing may also be subjected to injection pressure during activities such as fracture jobs, gas lifts, or water injection operations.

5.3.5 Liner

A liner casing string doesn't extend all the way to the wellhead; instead, it is suspended from another casing string. This approach reduces costs, enhances hydraulic performance during deep drilling, allows for the use of larger tubing above the liner top, and doesn't impose a tension limitation on the rig. Liners are typically cemented along their entire length.

5.3.6 Tieback String

Tieback string casing ensures additional pressure integrity from the liner top to the wellhead. Tiebacks can either be partially cemented or not cemented at all. [33]

6. Concept Analysis

This chapter will concentrate on the structural and loading modifications associated with the newly introduced concepts. It aims to establish a revised baseline for the design criteria for each concept, taking into account structural adjustments. The calculations will employ various approaches derived from previous studies, offering a preliminary estimation. More advanced techniques will then be applied in the master theses during the final design phase. This process will set the groundwork for subsequent discussions on the challenges and advantages for each concept.

6.1 Template Structure

A subsea template structure installed at the seabed encounters diverse loading conditions depending on its phase during operation or installation. The main scenarios will include the following loads:

- Installation loads tied to lift off and environmental loads in the splash zone.
- Static loads from installed equipment.
- Oscillation loads tied to rise connection during drilling or intervention.
- Loads during production.
- Dropped objects.
- Trawling loads.

For a safe installation and operational functionality of the template structure it must meet predefined requirements established for each of the specified load scenarios. As this report focuses on introducing new concepts, only basic calculations will be conducted to assess potential advantages and disadvantages.

6.1.1 Single Centered Suction Anchor

Opting for a single centered suction anchor will need the installation of a notably larger anchor compared to the four-anchor configuration. The augmented size of the anchor will impact both the production and installation phases. To illustrate this distinction, two examples are presented. The first example will highlight the necessary increase in size for the single suction anchor compared to the configuration using for the Northern Lights project. The second example will estimate the extent of drift experienced by the two configurations during installation in a current.

6.1.1.1 Penetration Depth

To determine the size difference of the suction anchors, a calculate is caried out to establish the penetration depth of the Northern Lights configuration. This involves estimating typical soil conditions, as outlined in table 4. Once the penetration depth of the Northern Lights anchors is determined, it serves as a baseline for evaluating the required increased diameter of a single anchor to achieve equivalent penetration resistance.

Table 4: Penetration Depth - Undrained Shear Strength

Penetration Depth [m]	Undrained Shear Strength [kPa]
0	5
1	5
2	7
3	6
4	8
5	10
6	11
7	11
8	12
9	11
10	14
11	15
12	17
13	22
14	20
15	20
16	24
17	25
18	25

The template structure and anchors must be designed for the maximum weight experienced during operational use. For this example, the drilling operation will be disregarded, and the maximum installed weight will be from the X-Mas tree. The weight of the tree is set to 45 tons, representing a typical tree design. An overview of the known weights, dimensions and needed parameters is listed in Table 5 below.

Table 5: Component Specifications

Structures	Unit	Value
Weight of NL template	[kg]	103 000
Weight of X-Mas tree	[kg]	45 000
Suction anchor diameter	[m]	4
Suction anchor thickness	[m]	0.022
Wate density	[kg/m^3]	1025
Steel density	[kg/m^3]	7850
Design factor	[-]	1.15
Bearing capacity factor, N_c	[-]	8
Friction factor, α	[-]	0.3

The first thing needed is the wet weight of the complete system. To calculate this a bouncy factor is needed. Assuming the entire system is made of steel:

$$BF = (7850 - 1025) / 7850$$
$$BF = 0.869$$

Equation 5: Buoyancy Factor

The total force from the weight for each suction anchor then becomes:

$$103000 + 45000 = 148000t$$
$$148000 * 0.869 = 128612t$$
$$128612 * 0.00980665 = 1261.3kN$$
$$1261.3 / 4 = 315.3kN$$

Going further an estimated penetration depth must be established as a baseline. Considering the results from this, the difference between the total resisting penetration forces, Q_{tot}, and total wet weight, W_{wet}, will be compared. The penetration depth is then adjusted until equilibrium is achieved. The first predicament for the penetration depth is 8 meters.

$$A_{top} = (\pi / 4) * (ø - 2t)^2$$
$$A_{top} = (\pi / 4) * (4 - 2 * 0.022)^2$$
$$A_{top} = 12.3 m^2$$

Equation 6: Area of top Section

$$A_{tip} = (\pi / 4) * (ø^2 - (ø - 2t)^2)$$
$$A_{tip} = (\pi / 4) * (4^2 - (4 - 2 * 0.022)^2)$$
$$A_{tip} = 0.28 m^2$$

Equation 7: Area of tip Section

$$A_W = \pi * ø * (L + 1)$$
$$A_W = \pi * 4 * (8 + 1)$$
$$A_W = 113.1 m^2$$

Equation 8: Area Outside Cylinder Wall

$$A_{Wall} = 2\pi * (ø - t) * L$$
$$A_{Wall} = 2\pi * (4 - 0.022) * 8$$
$$A_{Wall} = 200 m^2$$

Equation 9: Area both Walls

$$W_{wet} = (A_{top} + A_w) * t * \rho * BF * g$$
$$W_{wet} = (12.3 + 113.1) * 0.022 * 7850 * 0.869 * 9.81$$
$$W_{wet} = 184.6 kN$$

Equation 10: Wet Weight of Suction Anchor [15]

$$S_u^{av} = (5 + 5 + 7 + 6 + 8 + 10 + 11 + 11 + 12) / 9$$
$$S_u^{av} = 8.3 kPa$$

Equation 11: Undrained Shear Strength

Using the input obtained, W_{tot} and Q_{tot} can be found:

$$W_{tot} = (315.3 + 184.6)kN * 1.15$$
$$W_{tot} = 574.9kN$$

Equation 12: Total Wet Weight

$$Q_{tot} = (N_c * S_u^{av} * A_{tip}) + (\alpha * S_u^{av} * A_{wall})$$
$$Q_{tot} = (8 * 8.3 * 0.28) + (0.3 * 8.3 * 200)$$
$$Q_{tot} = 516.6kN$$

Equation 13: Total Penetration Resisting Force [15]

The results indicate that the weight surpasses the resisting penetration force. Since the difference is relatively small, the next step is to test at a depth of 9 meters. If Q_{tot} is higher than W_{tot} at this depth, the exact value can be determined by plotting the results on the same graph. The results are shown in Table 6 below, where the same approach as above is done for the depth of 9 meters.

Table 6: Penetration Depth Results, 8-9 meters

Depth [m]	W_{tot} [kN]	Q_{tot} [kN]
8	574.9	516.6
9	596.3	599.8

As seen from the results, W_{tot} is almost the same as Q_{tot}. The means the needed penetration depth can be estimated to 9 meters.

6.1.1.2 Dimensions of Single Suction Anchor

When utilizing only one suction anchor it must carry the total weight of the template and equipment. For this example, the stability of the structure is not considered, and the calculation will only estimate the needed size of the anchor to support the total weight. The same wall thickness of 0.022 meters is used, along with the BF of 0.869. The first predicament is a diameter and length of 10 meters and 11 meters, respectively. Using the same approach as in section 6.1.1.1 we get the results shown in Table 7 below.

Table 7: Penetration Depth Results, 11-12 meters

Depth [m]	W_{tot} [kN]	Q_{tot} [kN]
11	2220.7	2039.0
12	2273.9	2358.3

Considering the results above the needed penetration depth is in between 11-12 meters. From the plotting the results in Figure 17 the estimated depth can be read as 11.7 meters for a diameter of 10 meters.

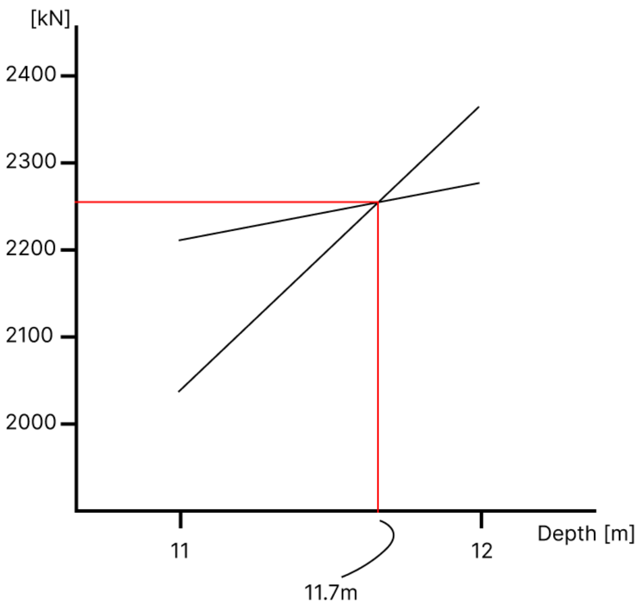


Figure 17: Estimated Penetration Depth

Using linear interpolation, the wet weight of the suction anchor can be found for a length of 11.7 meters:

$$\frac{11-11.7}{11.7-12}=\frac{669.7-x}{x-716.0}$$

$$x=701.5kN=71.5t$$

Equation 14: Linear Interpolation

The combined weight of the four suction anchors in section 6.1.1.1 totals 82.8 tons, showcasing an estimated weight reduction of 11.3 tons. The weight of the anchor could be decreased further by implementing a smaller diameter and increasing its length. For this example, the thickness of the anchor walls is assumed to be constant for the two configurations. It is likely that this must be increased for a larger anchor, thereby reducing the overall weight saved. The larger diameter will also represent a difficulty regarding the production process.

To make the single anchor approach more appealing, it should be complemented by a more compact template for enhanced stability and reduced weight. The diameter of the anchor should be designed with large enough footprint that the anchor will provide a sufficient stability during the various loads experienced for the template.

6.1.1.3 Drag Force and Drift During Installation

During installation it is expected to experience a drift of the template when it is wired down from the crane vessel. This drift occurs due to ocean currents at typical offshore installation sites. The current will result in drag forces on both the template and wire. This drag force will cause the template to drift horizontally during lowering. This must be calculated beforehand, ensuring the template hits the intended spot at the seabed.

For this example, only the drag force for the suction anchors and wireline will be considered, meaning the frame of the template structure is neglected. The complex structure of the template will require the use of computational fluid dynamic (CFD) simulations. The example will show the expected difference considering the amount of drift for the two template configuration discussed earlier with one or 4 suction anchors. The needed parameters are listed in Table 8 below. Water depth is taken from the Northern Lights installation site and is set to 300 meters. The current is set to 2.0 m/s for this example.

Table 8: Parameters

Description	Symbol	Unit	Value
Wireline diameter	$D_{wireline}$	[m]	0.1
4 configuration anchor diameter	$D_{4\text{-anchor}}$	[m]	4
1 configuration anchor	$D_{1\text{-anchor}}$	[m]	10
Currant velocity	U	[m/s]	2.0
Hight of crane tip	h	[m]	20
Water depth	L	[m]	300
Water density	ρ	[kg/m^3]	1025
Gravity	g	[m/s^2]	9.81
Kinematic viscosity	ν	[m^2/s]	$1*10^{-6}$

The drag force can be calculated using the following equation:

$$F_D = \frac{1}{2}\rho U^2 C_D A_P$$

Equation 15: Drag Force from Constant Current [34]

The drag coefficient is dependent on the Reynolds number:

$$R_n = \frac{UD}{\nu}$$

Equation 16: Reynolds Number [34]

Using equation 16 the Reynolds number is given in the table below for the wireline and two anchor configurations.

Table 9: Listed Reynolds Number for each Component.

Description	Raynolds number
Wireline	150 000
4-anchor	600 000
1-anchor	1 500 000

With the Reynolds numbers established the drag coefficients for each part can be read for the table below when the surface is considered a smooth circular cylinder.

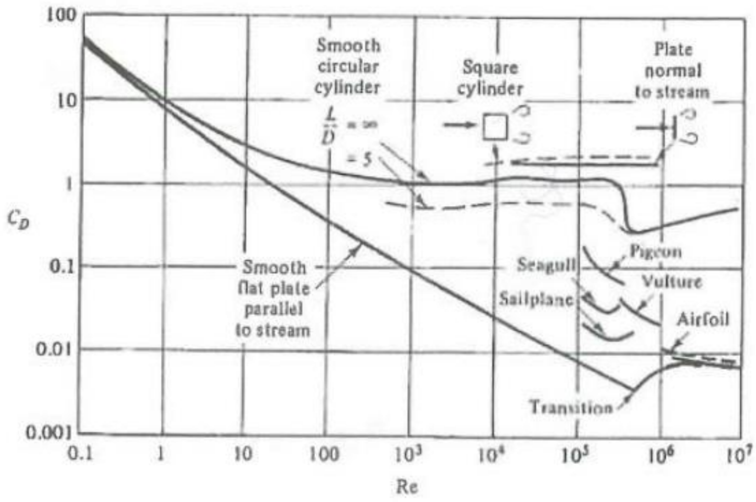


Figure 18: Drag Coefficient Plotted Against Reynolds Number [34].

Table 10: Drag Coefficients for each Component.

Description	**Drag coefficient (C_D)**
Wireline	1
4-anchor	0.5
1-anchor	0.6

Drag force can then be calculated with equation 14. This is only shown for the one anchor configuration, but the same is done for the wireline and 4-anchor configuration. For the latter it is assumed that the template is directly facing the current, and that only the two anchors in front will result in a significant drag force.

$$F_{D-1} = \frac{1}{2}\rho U^2 C_D A_P$$
$$F_{D-1} = \frac{1}{2} * 1025 \frac{kg}{m^3} * (2m/s)^2 * 0.6 * 10m * 11.7m$$
$$F_{D-1} = 143.9kN$$

Equation 17: Drag Force for Single Anchor.

To establish the horizontal drift length an equilibrium equation is set up for the crane tip for a complete system illustrated in Figure 19.

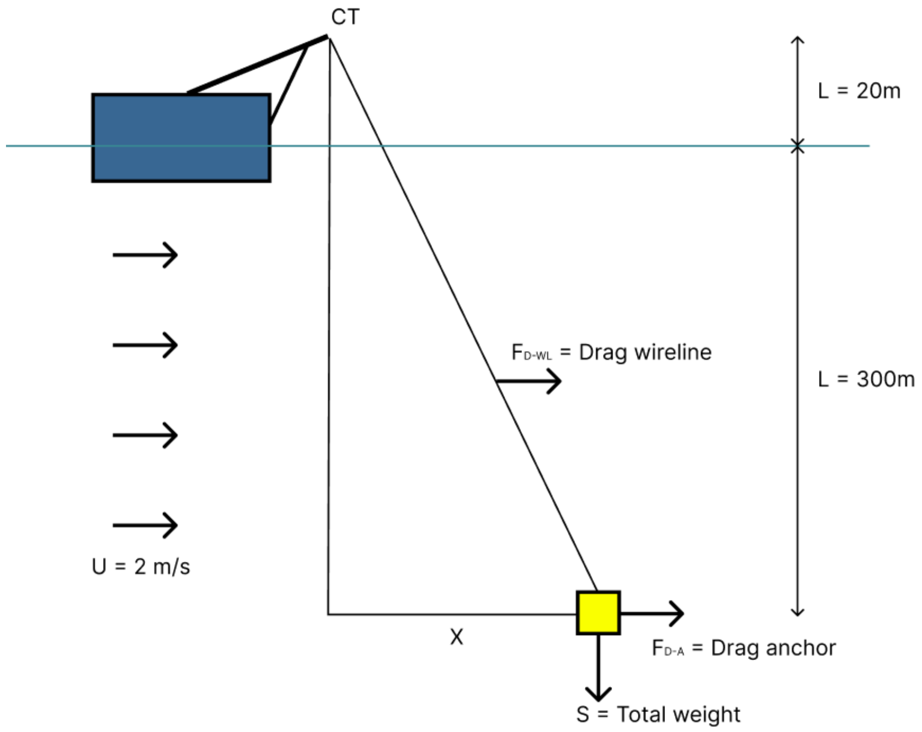


Figure 19: Forces in System during Installation

$$M_{CT} = 0 \Rightarrow$$

$$F_{D-WL} * (20 + 150)m + F_{D-1} * (20 + 300)m = S * x$$

$$(61.5kN * 170m) + (143.9kN * 320m) = (1261.3 + 701.5)kN * x$$

$$56503kNm = 1962.8kN * x$$

$$x = 28.8m$$

By doing the same for the 4 anchor configuration results in a drift of:

$$M_{CT} = 0 \Rightarrow$$

$$F_{D-WL} * (20 + 150)m + F_{D-4} * (20 + 300)m = S * x$$

$$(61.5kN * 170m) + (73.8kN * 320m) = (1261.3 + 203.2 * 4)kN * x$$

$$34071kNm = 2074.1kN * x$$

$$x = 16.4m$$

It is important to note that this represent an estimated length that neglects the frame of the template. Regardless, the results show a significantly increased drift length of 12.4 meters for the one anchor configuration. This representation will also indicate an increased impact from wave forces during lowering through the “splash zone” due to the increased exposed surface area.

6.1.2 Compact Frame Structure

Reducing the size of the installed equipment on the template presents an opportunity to create a more compact frame structure. This will enhance the possibility of employing a single centered suction anchor considering the gained stiffness and stability of the frame. The stability of the structure will be most compromised for horizontal loads when utilizing one suction anchor compared to a four-anchor configuration. This is illustrated by Figure 20, where the spacing of the reaction forces from a horizontal unit load, P, is shown.

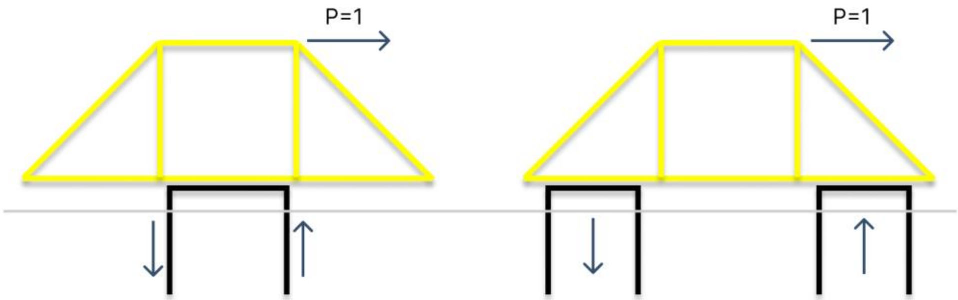


Figure 20: Stability of Frames for two Different Configurations.

To assess the frames capability an example is carried out, examining the stiffness and loads of two frame configurations. The first mirrors the size similar to that installed in the Northern Lights project. This is then contrasted with a frame scaled down by 30%, offering insights into the potential gains achievable through size reduction. Table 11 below shows the compared dimensions of the two templates.

Table 11: Dimensions of Northern Lights frame (1) & Frame with a Reduced Size of 30% (2) [14]

Dimension	Unit	Frame 1	Frame 2
Width	[m]	18	12.6
length	[m]	11.8	8.3
Height	[m]	11.1	7.8

The calculations will be caried out by using the direct approach to establish the stiffness relation in Equation 18, before solving for the displacement vector **r**. To simplify only bending stiffness will be considered, meaning axial and shear deformation is neglected.

Looking at the bottom of the frame as infinitely stiff compared to the top frame the structure can be modeled with clamped ends at point A and D as shown in Figure 21. The frame is also modelled using vertical beams for simplicity. As only bending stiffness is considered, the frame can be represented with only 3 degrees of freedom (dofs) with rotation of point B and C and horizontal translation of point C, respectively.

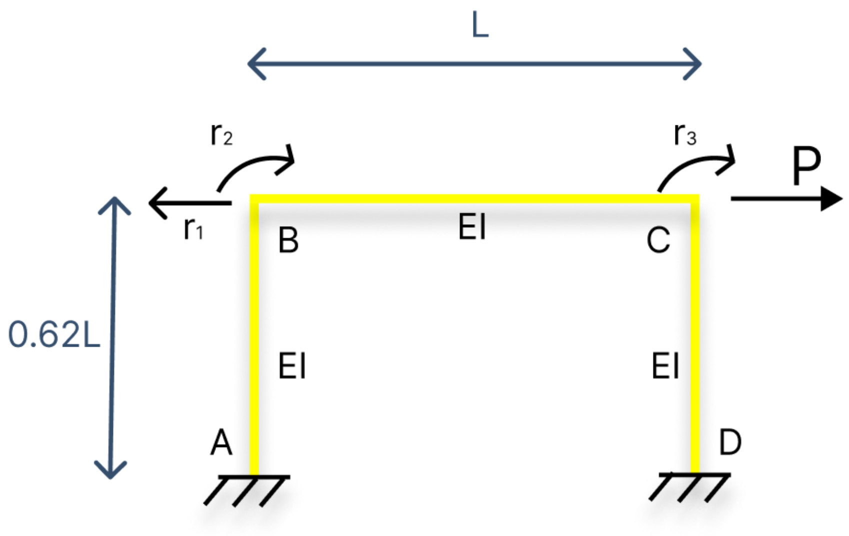
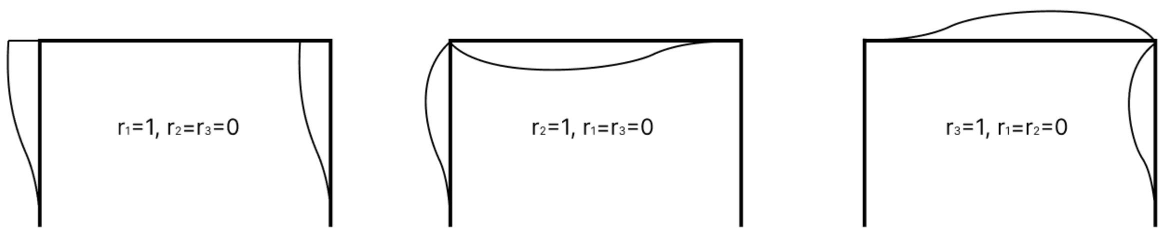


Figure 21: Simplified Representation of Frame

$$\mathbf{Kr} = \mathbf{R}$$

Equation 18: Stiffness Relationship [35]

The stiffness matrix, **K**, can then be found by setting each dof equal to 1 and looking at the corresponding stiffness terms from the beam collection. [36]



Resulting in the stiffness matrix **K**:

$$\mathbf{K} = \frac{EI}{L^3}\begin{bmatrix} 100.8 & 15.6L & 15.6L \\ 15.6L & 10.5L^2 & 2L^2 \\ 15.6L & 2L^2 & 10.5L^2 \end{bmatrix}$$

The Load vector **R** can be directly computed as:

$$\mathbf{R} = \begin{bmatrix} -P \\ 0 \\ 0 \end{bmatrix}$$

Using the inverse of **K**, the displacement vector **r** can be expressed as:

$$\mathbf{r} = \mathbf{K}^{-1}\mathbf{R}$$

Equation 19: Displacement Vector

$$\mathbf{K}^{-1} = \frac{L}{EI}\begin{bmatrix} 0.0162L^2 & -0.0202L & -0.0202L \\ -0.0202L & 0.1240 & 0.0064 \\ -0.0202L & 0.0064 & 0.1240 \end{bmatrix} \Rightarrow$$

$$\mathbf{r} = \frac{L}{EI}\begin{bmatrix} 0.0162L^2 & -0.0202L & -0.0202L \\ -0.0202L & 0.1240 & 0.0064 \\ -0.0202L & 0.0064 & 0.1240 \end{bmatrix} * \begin{bmatrix} -P \\ 0 \\ 0 \end{bmatrix}$$

$$\mathbf{r} = \frac{PL^2}{EI}\begin{bmatrix} -0.0162L \\ 0.0202 \\ 0.0202 \end{bmatrix}$$

The end moments and shear forces can then be calculated using the following equation:

$$\mathbf{S} = \mathbf{kv} + \mathbf{S}^0$$

Equation 20: End Beam Forces

$$\mathbf{S}_{AB} = \begin{bmatrix} S_{Z1} \\ S_{\theta 1} \\ S_{Z2} \\ S_{\theta 2} \end{bmatrix} = \frac{2EI}{(0.62L)^3} \begin{bmatrix} 6 & -3(0.62L) & -6 & -3(0.62L) \\ -3(0.62L) & 2(0.62L)^2 & 3(0.62L) & (0.62L)^2 \\ -6 & 3(0.62L) & 6 & 3(0.62L) \\ -3(0.62L) & (0.62L)^2 & 3(0.62L) & 2(0.62L)^2 \end{bmatrix} * \frac{PL^2}{EI} \begin{bmatrix} 0 \\ 0 \\ -0.0162L \\ 0.0202 \end{bmatrix}$$

$$\mathbf{S}_{AB} = P \begin{bmatrix} 0.5 \\ -0.188L \\ -0.5 \\ -0.123L \end{bmatrix}$$

The same procedure is done for beam BC and CD. Results for the end forces are shown in Table 12 below.

Table 12: Results for Frame Analysis

Point	**Shear force [P]**	**Moment [PL]**
A for beam AB	0.5	-0.188
B for beam AB	-0.5	0.123
B for beam BC	-0.242	-0.123
C for beam BC	0.242	0.123
C for beam CD	0.5	-0.123
D for beam CD	-0.5	-0.188

The moment, shear, and axial force diagram is shown below where the concentrated load P is equal to 1 N in this specific example. Notably, the shear force remains independent of the length parameter L, while the moment experiences a proportional decrease equivalent to the percentage reduction in size. This behavior aligns with the expectations for a point load.

In contrast, when dealing with a distributed load, the length parameter L is squared. Consequently, the moment undergoes exponential reduction, highlighting the greater significance of size reduction in such scenarios. For the example below, the length parameter L is set to 18 meters for frame 1 and 12.6 meters for frame 2.

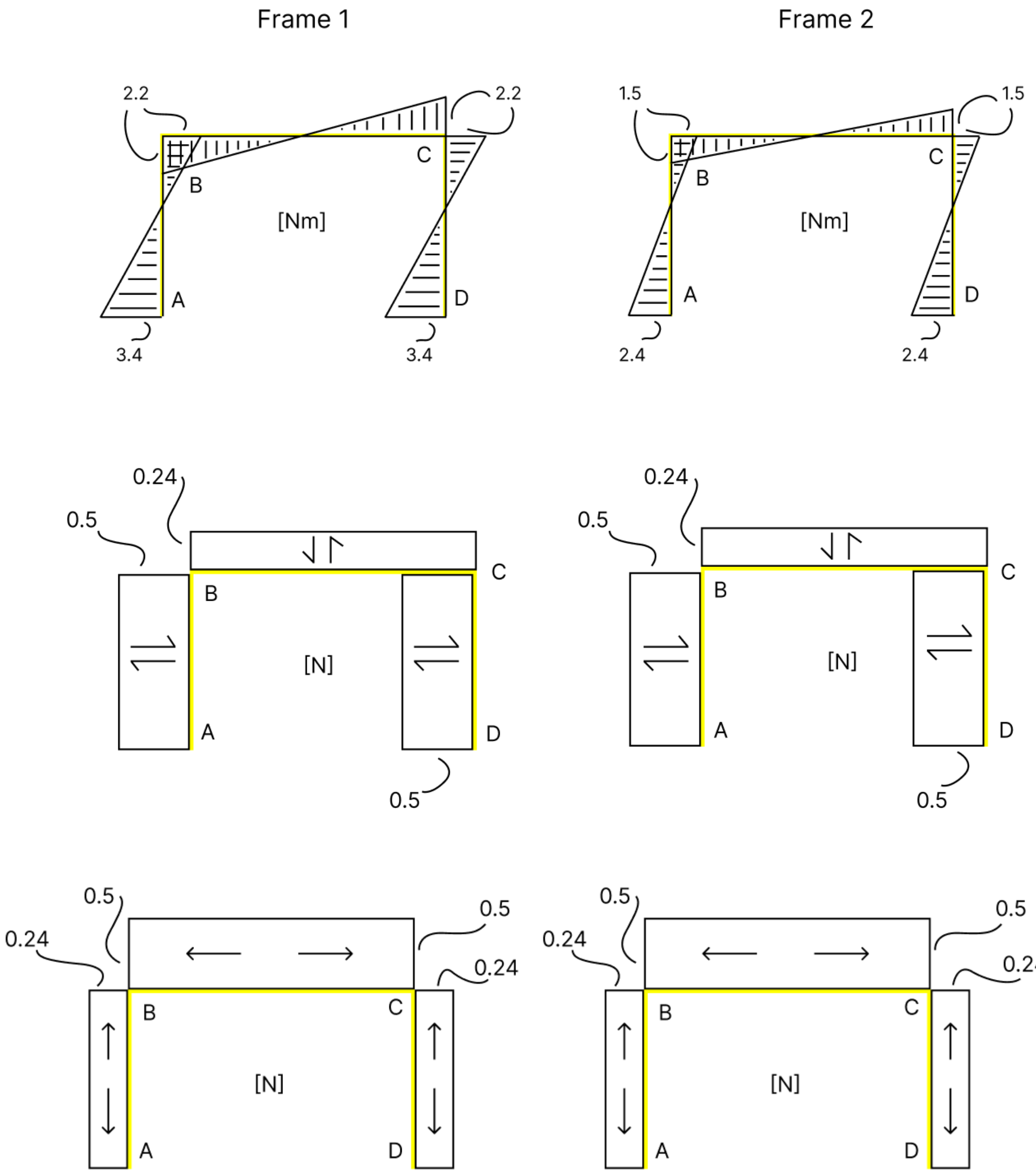


Figure 22: Momen-, Shear-, and Axial Diagrams

This example highlights the advantages of designing a smaller, more compact frame structure. Applying this approach with realistic loads will also help estimating the required cross-section for the primary beams during the initial design phase. As the project progresses, transitioning to the finite element method (FEM) becomes essential for obtaining more precise values for complex structures. Employing the FE method enables the simulation of complex load scenarios as accidental loads. In such cases, a non-linear analysis can be carried out to account for geometrical, material, and contact non-linearities. This analysis will be conducted in later stages once a detailed model of the primary load-bearing beams of the template is established.

6.2 X-Mas Tree

The conceptual X-Mas Tree introduced a complete design change regarding both configuration and size. The configuration is now set at making the X-Mas Tree in separate modular configurations, making for easier and more accessible installation. The concept also considers what valves and components are an absolute necessity for an injection tree, where the magnitude of environmental strain within the wellbore will be far less than for traditional HC wells.

6.2.1 Size Reduction

The introduction of a modular conceptual idea promises a significant reduction in both size and weight for the X-Mas Tree. This innovation aims to address the inherent challenges associated with traditional trees, which face large forces during installation. The current installation processes for standard X-Mas trees carry substantial risk factors, attributed to their considerable size, weight, and potential for disastrous outcomes.

The proposed concepts offer a solution by mitigating or eliminating many of the dangers associated with these installations. Through the adoption of a smaller modular system and a configuration that enables step-by-step installation of individual modules, the overall installation process becomes more manageable and safer. This approach reduces the financial risks and operational costs associated with traditional installations, where component failure, accidents, or technical issues could lead to significant equipment losses.

The reduced weight of each module allows for the utilization of smaller vessels during installation, contributing to overall cost savings. From a structural perspective, the modular configuration facilitates spreading across the seafloor, minimizing the contact area exposed to ocean currents and other environmental forces. This design helps reduce stress on the wellhead and the system, enhancing their resilience to external forces and make for a more reliable system with lower chance of any fatigue conditions. A simple illustration of how the cycling current-load will affect the system is shown in Figure 23. A detailed analysis is to be performed within a master thesis to evaluate more exact values based on actual size differences.

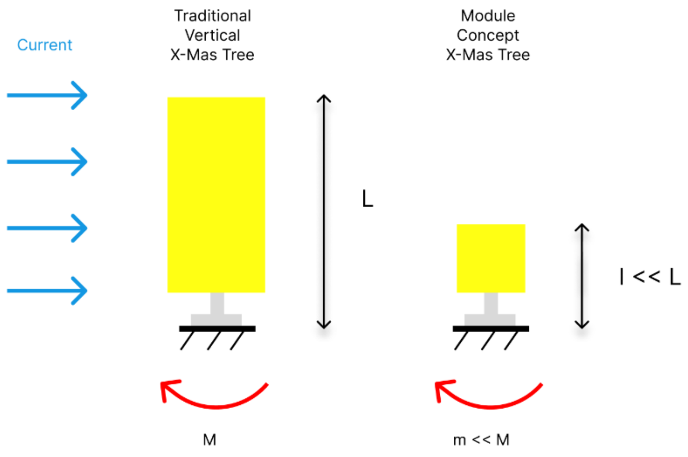


Figure 23: Current Loads on X-Mas Tree & Resulting Moment

While concerns may arise regarding the fragility of the modular system due to its smaller size, a viable solution involves introducing support structures that utilize the seafloor as stable connection points. This approach ensures a rigid connection for modules positioned directly above the wellhead, the component most exposed to oscillating, static, and environmental loads. Such implementation will be a cheap solution for redundancy ensuring in overall safety and a more reliable system.

6.3 BOP

Analyzing the bending moment on a wellhead stack when connected to a drill string demands an extensive and thorough examination. Such calculations have not been performed for this project. Instead, an initial study within this type of analysis have been conducted to get an understanding for future work, where such analysis could be performed. This section will discuss some of the analytical parts that are to take place for such simulations.

6.3.1 Loads and Fatigue

In such scenarios, the direct forces acting on the wellhead can be disregarded. Instead, the emphasis in fatigue calculations shifts to the movement of the riser and drilling platform induced by dynamic forces. The platform's motion generates stress on the wellhead and connected components, introducing potential fatigue risks.

6.3.2 Soil Strength

The soil integrity significantly influences fatigue accumulation along the conductor and surface casing. For a comprehensive analysis specific soil data at the installation site is needed to integrate into the analysis software for modeling different types of soil strengths. Subsequently, the soil stiffness is modeled using p-y curves following standards as: ISO 19901:4 [37], ISO 19902 [38], and API RP2A [39] depending on what soil is present at the geographical site [40]. This will provide properties for non-linear soil springs, as illustrated in Figure 24.

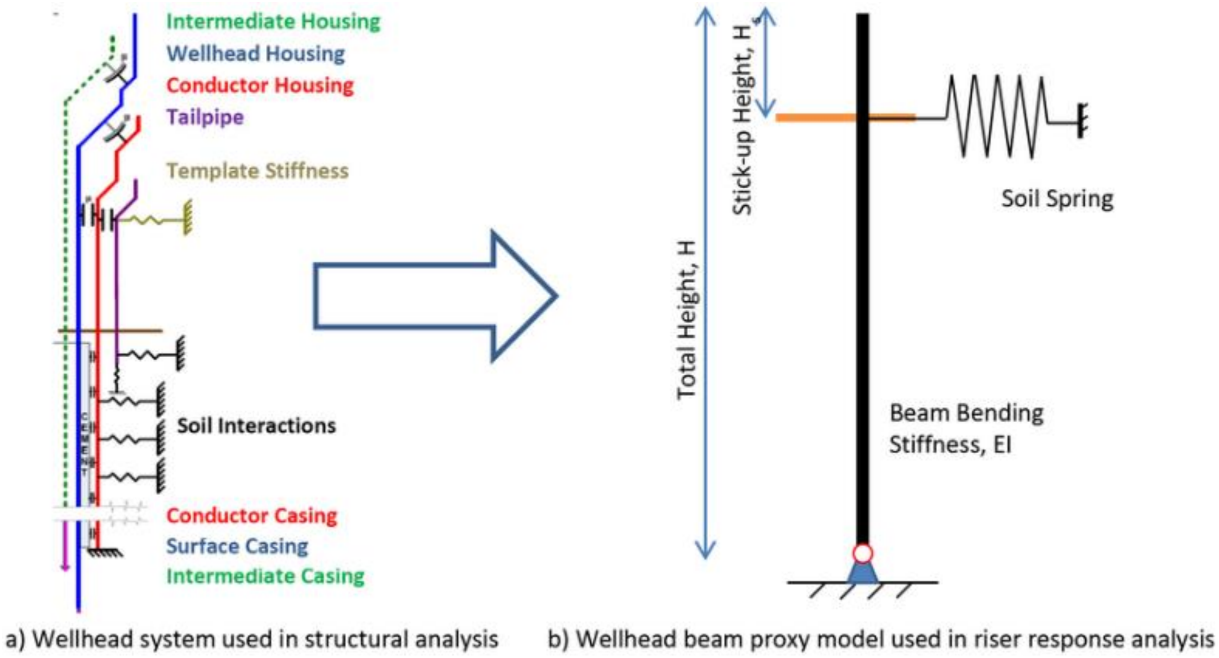


Figure 24: Illustration of Well Model w/Soil Springs [41]

6.3.3 Wellhead and BOP

As the BOP stack and components are connected to the wellhead the weight and size of the instruments can induce and worsen the fatigue criterion along the wellhead and subsurface casings. The weight and height of the component stack introduce an increase in bending moments by being influenced by current forces acting on the riser. This can contribute to Vortex Induced Vibrations (VIV) effects potentially increasing risk of fatigue.

6.3.4 Static Analysis:

A static analysis must be conducted to determine the equilibrium state of the system when stationary on the seafloor. These calculations serve as the foundation for the subsequent dynamic simulation, where the static equilibrium meets with the dynamic motions, contributing to stresses on the fixed system. An illustration of such system is provided in Figure 25.

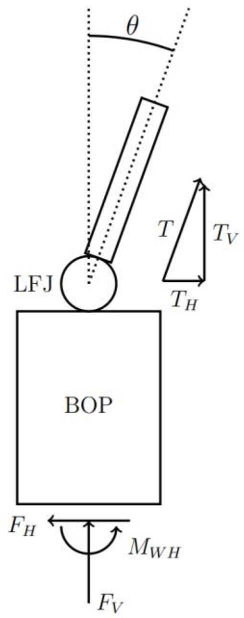


Figure 25: Illustration of BOP and Riser Connection [42]

6.3.5 Dynamic Analysis:

Dynamic analysis is conducted to replicate the motion of the model across a specified time interval. This involves the introduction of the dynamic equation of motion, Equation 21, which is solved through a numerical approximation. The solution is achieved through the application of numerical integration methods.

$$Q(t) = M\ddot{u}(t) + C\dot{u}(t) + Ku(t)$$

Equation 21: Equation of Motion [34]

Where M is the systems mass matrix, C is the damping matrix, K is the stiffness matrix, Q is the external load vector, $\ddot{u}$, $\dot{u}$, and u are acceleration, velocity and displacement vector respectively and t represent the time step.

While initial values for acceleration, velocity, and displacements are known, new values are recalculated at each time step. The precision of the results relies on assumptions regarding acceleration variation. Larger time step intervals may introduce inaccuracies in these assumptions, consequently resulting in inaccurate results. [34]

6.3.6 Loads

The model is exposed to different loads simulating the reality as accurate as possible. These loads could include environmental, functional, and accidental loads and needs to be specified within the simulation.

6.3.6.1 Waves

Wave considerations is significant to the analysis, necessitating specific implementations tailored to the geographical location of the rig and subsea system. This ensures that wave forces accurately simulate the real conditions anticipated. Wave simulations are usually integrated within the simulation software, where random waves are generated within a specified amplitude range and adjusted according to geographical environmental data of where the real-life model is to be placed.

6.3.6.2 Hydrodynamic Loads

The hydrodynamic loads on slender circular structures such as drill strings can be calculated using Morison's equation. [34]

$$dF = \rho \frac{\pi D^2}{4} C_M a_x dz + \frac{1}{2} \rho C_D u \,|\, u \,|\, dz$$

Equation 22: Morison's Equation [34]

Where ρ is the density of water, a_x and u is horizontal particle acceleration and velocity calculated from the velocity potential for incoming waves, D is the diameter of considered model, C_M represents mass coefficient and C_D is the drag coefficient.

6.3.6.3 Current

Consideration must be given to the existing forces acting on the topside rig and riser. These currents have the potential to induce Vortex-Induced Vibrations (VIV) on the risers, propagating along the structure and ultimately contributing to bending moments and stresses on the wellhead and subsea components. An implementation within the analysis software can be done by either utilizing precisely measured current data from geographical area or a statistically determined current profile from DNV.

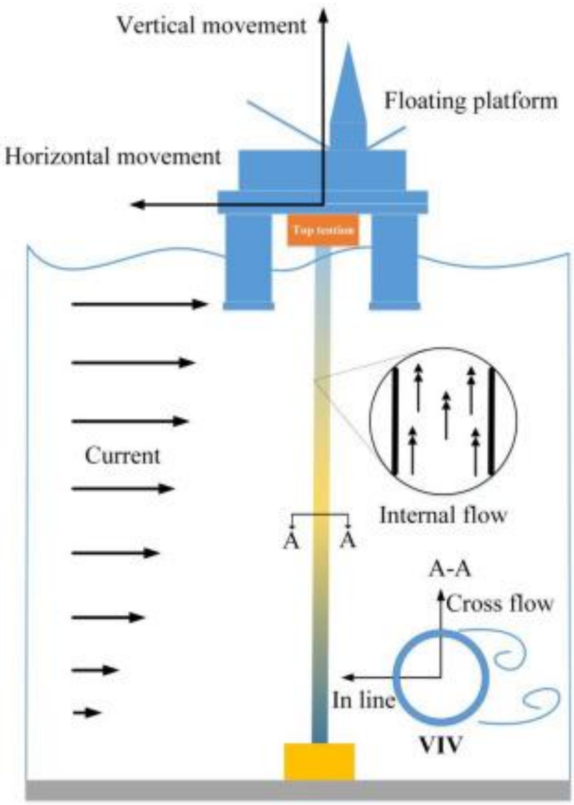


Figure 26: Vortex Induced Vibrations on Riser [43]

6.3.7 Simulation

Once all relevant parameters and design dimensions are established, the model is computed based on predetermined load criteria for simulation following the DNV standard for Wellhead and Fatigue Analysis Method (DNV-RP-E104). [44] Multiple analyses are to be conducted, each exploring different load conditions and operational scenarios. While results may vary from real-life situations, these simulations serve as indicators of potential risks such as fatigue or other failures, prompting consideration for design changes or component replacements.

In the context of this project, such an analysis would determine whether a reduction in the blowout Preventers (BOP) size can endure the stress during well intervention operations. By following the operational loads from NORSOK U-001 the goal is to ultimately challenge the criterions for BOP size within a complete injection system [45]. A simplified illustration has been provided to showcase the potential behavior of the entire system under environmental loads.

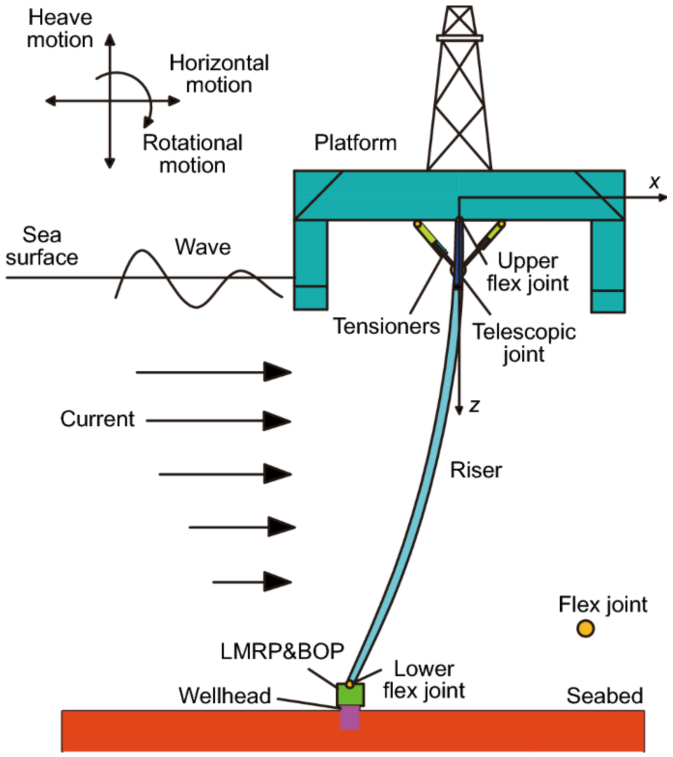


Figure 27: Illustration of Riser & Platform Movement due to Current Forces [46]

7. Discussion

This chapter will discuss the various design philosophies introduced in Chapters 5 and 6. The collective research has provided a deepened understanding of a complete subsea systems, with a particular emphasis on an injection systems. Given the different solutions presented, it is necessary to summarize and refine the projects scope. This will involve an assessment of the core values, specifically focusing on cost reduction and effectiveness for each concept. The goal is to think new to enable the industry to see the financial gain in utilizing components beyond what is today looked at as the standard. Ultimately, a final solution will be selected to advance the project. This final solution may combine different ideas presented to create a well-rounded and streamlined subsea injection system with the desired qualities.

7.1 Template Structure

The different concepts presented for the template structures offer distinct approaches of achieving a reduced cost, improved operability, and a lower environmental footprint. Section 5.1.1 shows a new configuration of the template utilizing one centered suction anchor. This design contributes to a reduction in both weight and overall footprint, as shown in section 6.1.1. This configuration is especially desirable when achieving an overall more compact injection system, enhancing the stability and stiffness of the structure.

The module-based design presented in section 5.1.2 offers a solution that opens for reuse of specific components. The design of the joints between the different modules will have to be developed in a later stage, combining it with a detailed understating of the framework of the entire structure. This kind of incorporation will also open for the opportunity discussed in section 5.1.3, with utilizing alternative materials for certain modules of the template. The module base design will then provide the opportunity to exchange specific parts of the template that may requiring more frequent maintenance related to the material choice or external interferences.

From assessing the discussed concepts, it's clear that a combination of the different concepts can provide an altogether better performing structure with well-rounded qualities. The combination of the concepts will enhance the functionality of each, resulting in a system that provide an economically viable alternative compared to the implementations typically used today.

7.2 Subsea Christmas Tree

The concepts for different configurations of the X-Mas tree mainly revolve around two ideas: simplifying with a minimalistic design or increasing flexibility for interventions and maintenance. The construction today is designed for extreme operational factors and corresponding risks, which are absent in the intended operational environments that the concepts are based upon. The different philosophies will represent unique ways of achieving a more cost efficient and safe design tailored to a pure injection system.

The first concept in Section 5.2.1 is the most minimalistic, involving fewer integrated valves. This design is particularly advantageous because it reduces the number of valves that need potential replacement or interventional work. Splitting the main structure of the tree also allows for easy retrieval of the PWV implemented in module 2, using and inspection, maintenance and repair vessel (IMR). To make this concept effective during well interventions, the connection point between module 1 and 2 must be designed to ensure a secure connection during normal operation as well as a riser connection after removal of module 2.

Concept 2 presented in Section 5.2.2 takes a more traditional approach, where the main structure of the X-Mas tree is treated as one segment. This eliminates the ability to replace the Production Wing Valve (PWV) independently and introduces the need for a traditional swab valve or tree cap at the top of the main tree structure for vertical access. However, this configuration challenges industry standards by eliminating the Downhole Safety Valve (DHSV) and incorporates a minimalistic implementation of control valves. It still maintains two main barrier valves for the injection line, ensuring the same well integrity as Concept 1.

Section 5.2.3 presents a familiar approach of deploying the subsea tree in a buried silo as opposed to a traditional template structure. This method can be particularly advantageous when considering the module-based designs discussed earlier, allowing for a more compact tree with reduced height. This makes the economic aspect of burying the silo more viable. Additionally, it offers increased protection to modules outside the main structure of the tree. The buried equipment will be shielded from external factors, such as currents, dropped or dragging objects such as ship anchors or icebergs.

Choosing between concepts 1 and 2 will require further investigation into the expected lifespan of each component in the tree, as this will be the main deciding factor. Both options represent a solid solution showing promising aspects. The design of the template structure or silo will also influence the desired choice, as the implementation of the equipment on the template require a tailored solution for both concepts.

7.3 BOP

In Section 5.3, we explore the conceptual framework of optimizing traditional well dimensions to align with the environmental strain within an injection system. Recognizing the significant environmental stress on HC wells, attributed to pressures exceeding typical injection systems, a concept of the reduction of well dimensions is proposed. This adjustment, involving potential changes in casing size, also opens the possibility of employing smaller Blowout Preventers (BOPs). These modifications offer substantial benefits in achieving the outlined goals, with a notable impact on the industry's financial landscape. Key cost savings include:

- Cementing costs: Reduction through the use of smaller/fewer casings.

- Installation costs: Easier accessibility, smaller installation vessels are to be utilized.

This prompts an exploration of the feasibility of reducing casings and BOP size, a topic addressed in Section 6.3. The section details a study on fatigue analysis conducted on the wellhead and associated components, including the BOP. Additional research needs to delve into the wellbore and reservoir dynamics to determine the safety of employing a smaller-sized BOP. This investigation aims to assess its ability to withstand not only environmental fatigue above the mudline but also the pressure and internal forces within the wellbore and reservoir, mitigating the risk of a potential blowout.

Emphasizing the critical importance of such an analysis, it serves as a foundational step to determine the viability of restructuring today’s standards. This potential modification presents an opportunity to develop a complete subsea injection system, as discussed throughout this report, contributing significantly to the overall financial benefit of such implementations.

7.4 Future Work

The main goal for future work is to design and plan a complete subsea injection system which utilizes the idees that build upon each other to establish a well-rounded solution. The structures and equipment must be modelled in a detailed way showcasing the selling point of the system as a whole package. This will mean detailed drawings which will help estimate the cost and implementation of the system. This also opens the possibility to do more simulation work regarding both hydrodynamic and structural challenges that must be addressed. It is important to note that such a project not only have to consider the specific components involved, but also represent a viable infrastructure built around the concept. All this represent a huge amount of work for further development within different segments and specializations.

8. Conclusion

The primary objective of this study has been to present new conceptual ideas aimed at minimizing costs associated with a subsea injection system. Concurrently, the focus has extended to enhancing the system's operability and streamlining both the production and installation phases. The presented ideas introduce unique approaches to achieve these goals, with their effectiveness indicated through calculations. This demonstration has shown promising outcomes for the initial design phase where the following remarks can be concluded:

- Utilizing equipment and regulations for a production well will be excessive for a pure injection well.
- The different design criterion for pure CO_2 injection show distinct opportunities for designing a complete streamlined subsea injection system.
- Achieving a more compact X-Mas tree show a significant advantage for the template structure, allowing for new design philosophies resulting in a reduction of overall cost, emissions and footprint of the structure.
- Employing a module-based design for the X-Mas tree will allow for easier retrieval of specific parts for maintenance or repair.
- Reducing the size of the WH and BOP is a viable option considering the varying operational criterion and associated hazards for pure injection, and will result in a substantial weight reduction.
- A more detailed analysis of specific components and cases must be done by narrowing down the scope of the study for further work.

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