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Installation and IMR on a subsea production system

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Subsea Technology
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Preface

This master‘s thesis was written during spring 2017, and is the closing part of our 2-year Master‘s Degree Programme in Subsea Technology, at the Norwegian University of Science and Technology. The project was conducted at the Department of Geoscience and Petroleum, and is a part of a SUBPRO project involving development of a new concept called "Subsea Gate Box". SUBPRO is a combined research center between NTNU and industry partners.

Our supervisor, Professor Tor Berge Gjersvik, gave the idea of this project and we would like to thank him for guidance throughout the semester. Also a thank you to our co-supervisor Postdoctoral Fellow Mariana J.C. Diaz Arias for guidance and input.

Trondheim, June 11, 2017

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Summary

In recent years, the focus on increased production and reducing operating costs has become an important goal for the oil and gas industry. This trend is likely to be even more important in the future. Installation and maintenance of underwater production and processing facilities is expensive, complicated and can cause problems. Solutions that facilitate easier maintenance operations, are an essential factor that reduces operating costs over time.

SUBPRO is a combined research program between the Norwegian University of Science and Technology and industry partners, that are developing a concept to mitigate these problems. This concept is called "Subsea Gate Box", where one of the goals is to increase production from individual wells within the same well network. To achieve this, each well will be prepared for further processing, before they are commingled in a common manifold. Thereby, each well is to a higher degree accommodated with its own processing equipment.

This thesis addresses modular architecture, and investigates solutions that can contribute to achieve a versatile process facility, as well as facilitating for an efficient installation, inspection, maintenance, and repair of the Gate Box system. In order to identify important factors that are related to these subjects, and than be able to come with some suggestions, relevant theory and "state of the art"-solutions for existing systems have been investigated. Based on this, a number of requirements and specifications have been stated. Furthermore, these requirements and specifications are the basis for the solutions presented in two different cases, which contain various module architecture and connection systems. The two cases were evaluated according to the given specifications in order to identify which one of them fits the requirements best. Important factors that were considered includes; modular interfaces, system redundancy, access to equipment, and possibility for easy replacement of equipment modules. The survey shows that both cases have their advantages and disadvantages, but the layout that allows fast disconnection and replacement of modules, appears to be the best solution.

Sammendrag

De siste årene har økt produksjon og en reduksjon av driftskostnadene blitt viktige mål for olje og gass industrien. Disse målene vil trolig bli enda viktigere i fremtiden. Installasjon og utførelse av vedlikehold på undervanns produksjon- og prosesseringsanlegg er både kostbart og komplisert. Løsninger som kan tilrettelegge for enklere vedlikeholdsopperasjoner er en esensiell faktor som kan bidra til redusere driftskostnadene på sikt.

SUBPRO er et kombinert forskningsprogram mellom Norges Teknisk Naturvitenskaplige Universitet og en rekke industripartnere, hvor målet er å utvikle et konsept for å redusere problemene knyttet til økt produksjon og driftskostnader. Konseptet kalles "Subsea Gate Box" og har som målsetning å blant annet øke produksjonen fra individuelle brønner innenfor samme brønnnettverk. For å oppnå dette vil hver brønn være klargjort for videre prosessering, før de omsider blir samlet i en felles manifold. Et slikt system vil dermed i større grad være avhengig av hver enkelt brønn har sitt egne prosesseringsutstyr.

Denne oppgaven tar for seg modularkitektur og undersøker løsninger som kan bidra til et allsidig prosessanlegg, og samtidig tilrettelegge for effektiv installasjon, inspeksjon, vedlikehold og reparasjon av Gate Box-systemet. For å identifisere viktige faktorer som er relatert til disse områdene og igjen kunne foreslå løsninger, har relevant teori og "state of the art"-løsninger for eksisterende systemer blitt undersøkt. Ut i fra dette, har en rekke krav og spesifikasjoner blitt identifisert. Disse kravene og spesifikasjonene dannet videre grunnlaget for løsningene som er presentert i de forskjellige casene med ulik modularkitektur og koblingssystem. Casene ble til slutt vurdert i henhold til de gitte spesifikasjonene for å identifisere hvilken av dem som tilfredsstiller kravene best.

Viktige faktorer som blant annet har blitt vurdert er: standardisering av modulgrensesnitt, grad av redundans for systemet, tilkomst til utstyr og muligheten for enkel utskiftning av utstyrsmoduler. Undersøkelsen viser at begge casene har sine fordeler og ulemper, men oppsettet som tillater raskest avkobling og utskiftning av moduler ser ut til å være den beste løsningen.

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Abbreviations

AUV = Autonomous Underwater Vehicle
CBM = Condition Based Maintenance
DP = Dynamic Positioning
HSE = Health, Safety, Environment
IMR = Inspection, Maintenance, Repair
IPB = Integrated Production Bundle
IPU = Integrated Production Umbilical
JIP = Joint Industry Project
KPI = Key Performance Indicator
MHS = Module Handling System
MHT = Module Handling Tower
MNOK = Million Norwegian Kroner
MOC = Milti Quick Connector
MRU = Motion Reference Unit
MTTF = Mean Time To Failure
NCS = Norwegian Continental Shelf
NDT = Non Destructive Testing
RFO = Ready For Operation
ROV = Remotely Operated Vehicle
SCM = Subsea Control Module
SHS = Special Handling System
SSBI = Subsea Separation, Boosting, and Injection
TCI = Technical Condition Index
UTA = Umbilical Termination Assembly
WoW = Waiting on Weather

Chapter 1

Introduction

1.1 Background

Wells within the same field have different capacity and performance. Usually, they are commingled in a common manifold and then led towards further transportation or processing. As a result, the well with lowest productivity are setting the pace, which in turn means that the stronger wells need to be constrained. Hence, the overall productivity of the field is lower than its potential.

The Subsea Gatebox concept wants to increase the productivity of the system, by decoupling the production before it is commingled to the manifold. It can consist of a variety of multi-functional modules or distributed structures that includes appropriate process equipment for the individual wells. The content of the functional modules may change depending on the demand from each well. Equipment such as chokes, multiphase flow meters, boosters and separators are some examples.

This concept aims to increase system flexibility for the production and at the same time allow optimization of equipment, which in term can be utilized over the life cycle of the field. Each production train can be designed to receive production fluids from individual wells or a group of wells, and then prepare the flow for further processing. The module assembly could be designed as a single structure adjacent to the well heads, or as a central structure containing several production trains [1].

This thesis addresses alternative solutions that can increase the efficiency of installation, maintenance and repair (IMR) operations on a subsea production system. In order to develop a versatile system that quickly can be readjusted, installed and maintained, it is important to have knowledge about "state of the art" solutions from recent subsea processing systems. From already existing systems one can bring the benefits while highlighting and mitigating drawbacks for designing a best possible system. Different solutions should be considered and compared to investigate which possible solution has the most benefits in order to meet the desired requirements for the system.

1.2 Objectives

In order to propose possible solutions for the stated challenges, this Master's Thesis contains the following objectives:

1. Perform a survey on connection systems and their potential to enhance the efficiency of installation and retrieval operations.
2. Present a study on existing subsea processing system with information about maintenance operations that is conducted.
3. Highlight important factors to consider in the design phase of modules, that can optimize installation and IMR operations.
4. Present architectural solutions for the Subsea Gatebox concept with different module setups and connection systems, and investigate possible benefits by integrating both control and production lines into the same intermodular connector.
5. Give recommendations on which solutions that may be beneficial for the Subsea Gate Box.

1.3 Limitations

The presented proposals for the Subsea Gatebox only consider a three phase flow. Problems related to sand handling and flow assurance is not accounted for in this thesis. Furthermore, this thesis does not include the processing itself. The proposed setups only shows how the modules and configurations can be put in relation to each other.

This thesis is based on literature gathered from bibliographic databases provided by the university, and occasional correspondence with the industry. With this in mind, the literature and solutions presented are limited to the information these sources can provide.

1.4 Approach

A stepwise approach as illustrated in Figure 1.1, are carried out for this thesis. First, a problem formulation was established in collaboration with supervisors. Secondly, a literature study should be conducted on relevant topics. Third, essential information are extracted, and is the basis for developing the two presented cases. As a part of the case development, the software AutoCad Plant 3D, and Inkscape 0.92 are used to create process flow diagrams, and illustrations for architecture. As a closing part, a discussion on relevant findings which should lead to a conclusion, is performed.

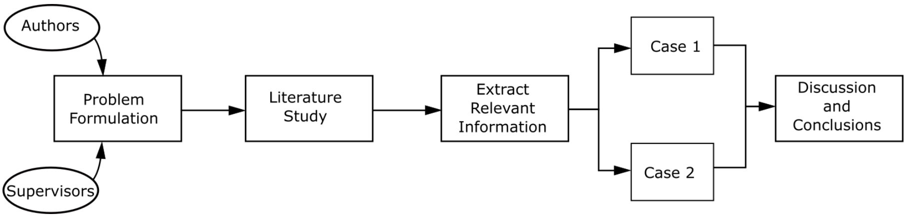


Figure 1.1: Stepwise approach for this thesis.

1.5 Structure of the Thesis

This heading presents the structure of the thesis and content of each of the listed chapters:

- Chapter 2 presents basic theory regarding subsea production systems, connector systems and equipment related to this. Further, it presents marine operations related to installation, maintenance and repair (IMR) for subsea production systems.
- Chapter 3 presents important features for obtaining a system design that facilitates for efficient installation and IMR operations.
- Chapter 4 concerns a design study of the Subsea Gate Box with proposals of two cases with different architecture and connection system.
- Chapter 5 discusses the design suggestions given in the previous chapter.
- Chapter 6 presents suggestions for further work and gives a conclusion on the considered cases.

Chapter 2

Theoretical Background

The activity level in the oil and gas industry on the Norwegian Continental Shelf (NCS) has been high for the past two decades. Figure 2.1 shows the change in production of oil, gas, condensate, and NGL, from 1970, and a production forecast to 2020. The period from around 2000 led to a growth in investment and operating costs. This trend has been a result of a high demand for petroleum, together with relatively high prices for oil and gas, which again has made it desirable to invest in the industry. In the past few years, the oil price has decreased, and significant cuts had to be made. The oil- and supply companies are both searching for more cost-efficient ways to develop and operate fields. The goal is to make them profitable even at low oil and gas prices.

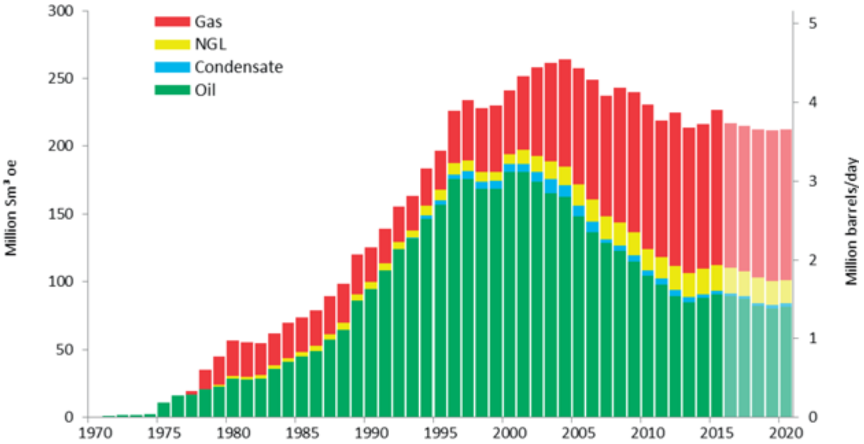


Figure 2.1: Actual sale of petroleum from 1971-2015 and a forecast forward to 2020 [2].

In 2015 there were 82 fields producing on the NCS and the total operational costs that year was approximately 60 billion NOK [2]. Figure 2.2 illustrates the operational cost by different field status. Oil companies have an ongoing struggle to cut these costs, but from Figure 2.2 it seems to increase. This is because new fields will be put into production, and contribute to keep the it at a stable high level in the future.

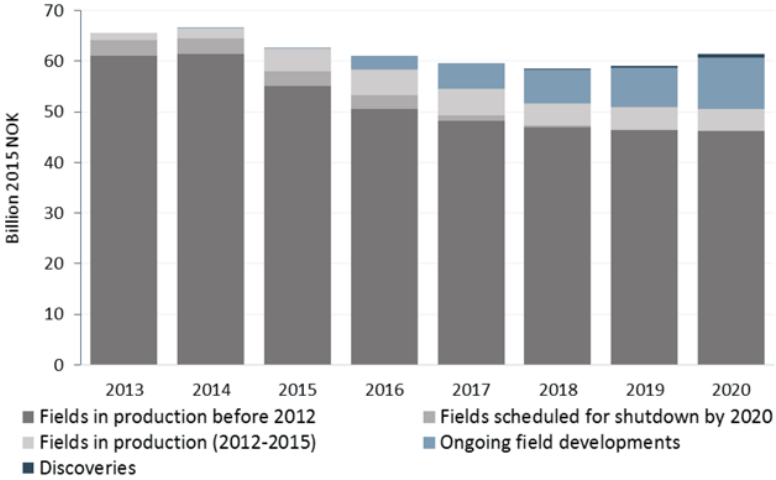


Figure 2.2: Forecast for operational costs from 2013-2020 and costs distributed on field status [2].

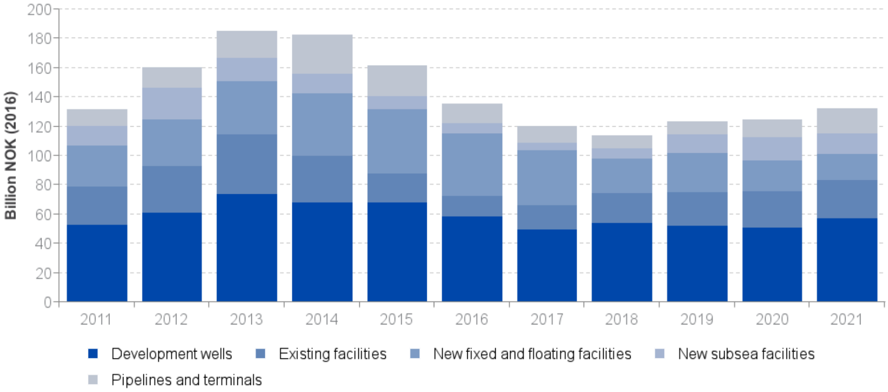


Figure 2.3: Historical investment on different categories and forecast for 2011-2021 [2].

A large part of the operational costs is due to inspection, maintenance and repair (IMR), which is necessary to maintain the production. Figure 2.3 illustrates a historical overview, and a forecast of the investment in development wells, existing wells, new fixed and floating facilities, new subsea facilities, pipelines, and terminals, on the NCS. It shows that investments in new subsea facilities, and floating and fixed facilities has been relatively high from 2011 to present. The reasons for this is due to ongoing developments, such as Johan Sverdrup [2]. The forecast show that investments in floating and fixed facilities will decrease, and that new subsea developments will increase until 2021.

When oil companies develop new fields, there are economical reasons to develop more accessible shallow fields first. However, such fields are more or less already developed, and the search for oil and gas is moving towards deeper and more hostile environments, such as the Arctic. This can be an indication for a further increase in developments of subsea facilities in the future. The need for better and cheaper ways to operate and maintain production systems on the seabed arises, and new technology and ideas needs to be developed. In this chapter, basic theory regarding subsea processing systems, connection systems, and installation and IMR procedures will be presented.

2.1 Subsea Production and Processing Systems

In 1961, the first subsea well was put into production, and in the early 80s, Norway's first subsea project Frigg was developed. Later, Statoil started the development of Gullfaks, where it was decided to invest in a subsea solution. Additionally, development of Tommeliten Gamma started in 1988, which was the first field using a subsea template structure serving several wells. In the early 90s, engineers understood and acknowledged the potential of moving production equipment down to the seabed. The goal was to connect the subsea systems to the already existing infrastructure, and avoid building new topside facilities. This made it economically feasible to develop smaller fields with tieback to a nearby host. Ever since, Norway has been in the forefront in the development of subsea production systems where larger and more complex systems have been put into production.

Some of the main drivers for moving production facilities to the seabed, can be summarized as follows [3]:

- Increased recovery of hydrocarbons through enhanced oil recovery and accelerated production.
- Possibility to produce from marginal fields.
- Better energy efficiency due to facilities located closer to the well.
- Increased production on already existing wells.
- Reduced topside equipment.

- Enables production from remote fields like the Arctic and deep waters.
- Improved flow assurance which allows longer tiebacks.

2.1.1 Subsea Factory

In recent years, subsea production systems include more features such as separation, boosting, injection, etc. Such developments are often referred to as subsea factories where production and processing technology are combined. In 2012, Statoil launched their concept Statoil Subsea Factory™at the Underwater Technology Conference in Bergen. Figure 2.4 illustrates an example of Statoil's subsea factory concept, with the different production and process equipment.

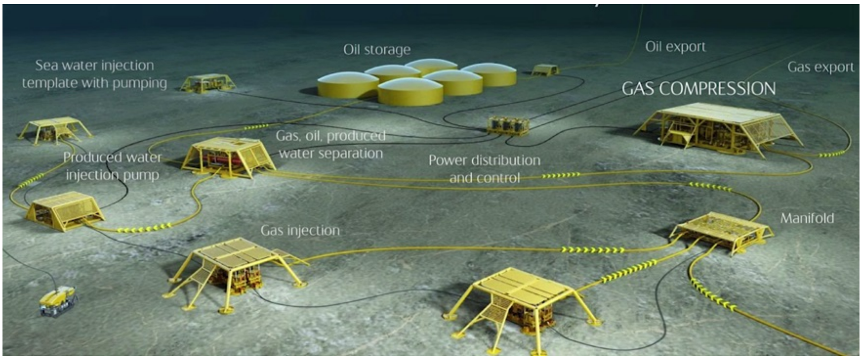


Figure 2.4: Statoil Subsea Factory™[4].

The objective is to combine and use the subsea production and processing technologies that was already installed and under construction. However, there is no single solution for a subsea factory that can be implemented at all fields, but rather several solutions that is specialized for wells in different production phases. Statoil's solutions where adapted to three cases, which where categorize into [3]:

- Brown Field Factory
- Green Field Subsea Factory to host
- Subsea Factory to Marked

Brown Field Factory

The Brown Field Factory is a first-generation approach to a subsea factory, which focuses on enhancing production for already existing wells. On the NCS, many fields have passed the plateau production and are on decline. To maintain the production, artificial lift is required. Additionally, fields that is routed to existing topside facilities often have long tieback distances. This requires systems that can prepare the well stream, and ensure flow assurance to manage the long transport distances. Examples of this, are implementation of separation equipment that removes water and sand from the well stream to avoid hydrate formation and erosion problems. Another common problem, is wax formation where equipment for chemical injection are required to stop accumulation along the pipe walls. Some of these problems usually increases at greater water depths and long tieback distances due to thermal complications, which is a result of low water temperatures at such depths. An additional problem arises with the large hydrostatic head, where the fluid is to be transported from the seabed to the surface. As a result, the subsea factory would require a powerful boosting station.

Green Field Subsea Factory to Host

The Green Field Subsea Factory to Host includes development of new subsea fields with tiebacks to existing facilities. These fields may be located in challenging areas that require long transport in deep and cold conditions. New oil fields typically produce at plateau-rate for 6 to 8 years [3]. By developing several fields and routing the production to a centralized process facility, the plateau can be extended, and the production capacity can be maintained for a longer period. Due to space and weight restrictions on existing topside facilities, the demand for moving subsea equipment to the seabed increases. For the green field factory, the main feature may include a subsea to host factory to avoid bottlenecking, an extended reach factory to allow long tiebacks, a deep water factory, a heavy oil factory, and an arctic factory. For these cases, the flow assurance aspects is of great importance, and one of the key drivers for the developments.

Subsea Factory to Marked

The Subsea Factory to Marked is the ultimate system that processes the well stream for direct transport, either to an offloading buoy, or a land facility in a ready for sale state. This concept is still a goal for the future and requires further technology developments.

All subsea factory approaches requires a greater number of components than earlier production and processing facilities. Being able to operate and maintain such systems in a cost-efficient manner, retrivability, inspectablity, interchangebility, and re-configurability should be some of the key factors in the design and architecture [5]. These factors will be highlighted further in this thesis.

2.2 Connection Systems

There are several types of connector systems in use within the oil and gas industry. They play a vital role for interconnecting equipment, so production fluids, hydraulics, chemicals, electrical power, and electrical signals, can be transported and distributed between the components in a subsea production and processing system. Connector systems designed for subsea equipment usually requires a higher degree of durability compared to the ones used topside. This is mainly due to harsh conditions and remote locations on the seabed. Further in this section, fundamental information regarding subsea connectors and tie-in technologies are presented. The purpose is to provide insight how the connection systems work, and furthermore be able to suggest a reliable and flexible connection system that can be used in a subsea system.

2.2.1 Installation and Connection Procedures

Lack of direct access to subsea equipment results in a connection procedure that rely on assistance from a Remotely Operated Vehicle (ROV). Functions of an ROV will be elaborated in Section 2.6.5. In general, this makes the connectors more complex than the commonly used for topside applications. There are mainly two types of mating configurations; vertical- and horizontal connection.

Vertical Connection system

Figure 2.5 illustrates a vertical connection system used between an X-mas tree and a manifold, where 2.5a shows a close-up view of the connector assembly, and 2.5b an overview of the pipe spool with vertical connector hubs on each end. The vertical tie-in system is normally characterized by an inverted U-shaped rigid spool as illustrated in Figure 2.5b. The actuating half of the connector is attached to the retrievable jumper, while the mating hub is installed at the subsea equipment. Connection of the spool is performed directly onto the upward facing hub in one operation. In this case a stroking operation is not required, which contributes to a simple and time efficient procedure. Stretching to align the connectors and fastening them, are performed by the connector assembly, or with help from an ROV equipped with special purpose tools.

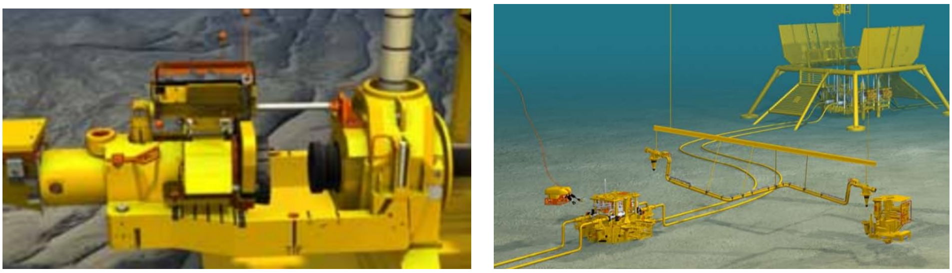
(a) Vertical connection assembly [6].

(b) Installation overview of a vertical connection system [7].

Figure 2.5: Vertical connection configuration.

Horizontal Connection System

Figure 2.6 illustrates a horizontal connector. Illustration 2.6a shows the mating operation that is performed by a stroking mechanism on the assembly, which extends the pipe hub towards the opposite hub on the production and processing equipment. Illustration 2.6b on the right, shows the connectors mounted on the rigid jumper spool.



(a) Horizontal connection assembly for tie-in [8].

(b) Overview of an installation of a horizontal connection system [8].

Figure 2.6: Horizontal connector configuration.

Installation and connection procedures may differ, as the mechanical design of connector assemblies usually are unique for the various suppliers. A typical installation procedure for a rigid pipe spool with a horizontal connection configuration is illustrated in Figure 2.7. With this approach, one of the connector assemblies is first landed, which in this case is on the manifold porch. Secondly, the connector head is lowered on to the X-mas tree guide base. This makes it easier guiding the spool into correct position, where it only needs to align one end at a time. After both spool ends are landed onto the manifold and X-mas tree, the ROV uses several tools to prepare and perform the connection operation. The used tools are illustrated on the bottom of Figure 2.7. First, the ROV deploys a cleaning tool to clean the mating interfaces on the hubs. This is to remove dirt or organic matter that might cover the sealing surfaces. Further, the ROV deploys a stroking tool that pulls the termination assembly towards the mating hub on the manifold and tree. Now the connections can be fastened by deploying a torque tool, which closes the clamp mechanism as described in Section 2.2.2. When this is completed on both ends of the spool, the ROV performs a sealing test by applying hydraulic pressure to the connectors. If the test results are satisfactory, the isolation boxes or "Dog Houses" are placed and sealed around the connector assemblies to prevent heat transfer from the well stream to the surroundings [9].

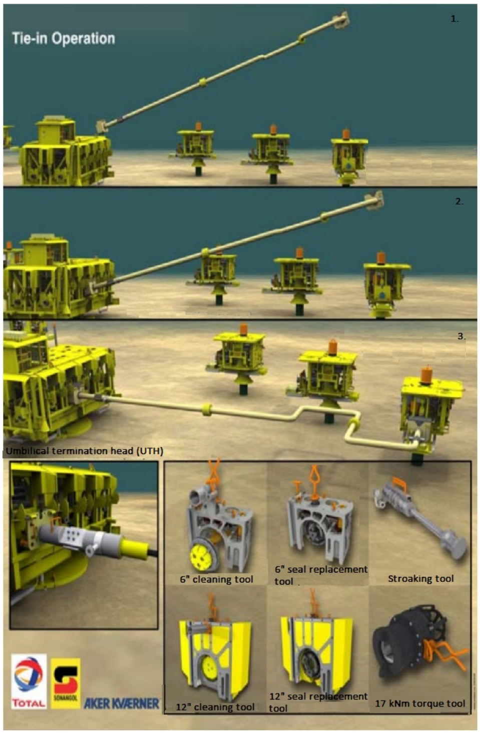


Figure 2.7: Tie-in operation between manifold an X-mas tree [9].

Comparison Between Horizontal- and a Vertical Connection Setup

Both the horizontal- and vertical configuration are widely used for production spools connecting X-mas trees and manifolds, with both rigid steel pipes and flexible pipes. The connection systems consists of a connector assembly, often a clamp connector or a collet connector, which is described in Section 2.2.2. Connection and installation procedures on the horizontal and vertical configurations, are slightly different.

Both systems have advantages and disadvantages. Table 2.1 compares the two configurations in a tie-in situation on several evaluation issues. From the table, the main advantages with the horizontal connection system is that it only require a relatively simple clamp connection mechanism, has lower weight, lower chance of snagging by anchors and trawl gear, lower requirement on installation vessel, simple seal change, and low dependency on weather. The latter is because the mating procedure is not dependent on crane support, but rather a higher degree of ROV assistance.

Table 2.1: Comparison between horizontal and vertical tie-in [10].

Evaluation Issue	Horizontal Connection	Vertical Connection
Equipment Requirement	Complex	Simple
Duration	Long	Short
Complexity and size	Simple	Complex
Fabrication requirements	Medium	High
Possibility of Snagging	Low	High
Vessel requirements	Low	High
Seal change	Simple	Medium
Weather dependence	Low	High

In a situation with a connection between retrievable modules in a production- or processing system, the horizontal connection system might have an advantage over the vertical system. This is due to the integrated stroking feature, which allows disconnection of equipment without removing the connector head. Hence, removal of a module can be conducted without retrieving the adjacent modules, which is a great advantage regarding maintenance. A similar feature is also possible with the vertical configuration, where the connectors are placed at the bottom of the modules, instead of the sides.

The main drawbacks with the horizontal configuration is that the mating operation is more complex and more time consuming. A vertical configuration has a relatively simple deployment, low reliance on ROV assistance and require less deployment of equipment. However, the complexity of the vertical connector is relatively high. During landing, a soft-landing mechanism is needed. This mechanism prevents uncontrolled movements generated by waves at the surface, which may damage the metal seals. Such mechanisms contributes to increase the weight of the connector assemblies, which again affects the versatility of the connectors. Additionally, the vertical setup has a higher profile, which makes it more exposed for snagging. Consequently, it may require a larger protection frame. On the other hand, this will mainly be an issue in areas with trawl activity in relatively shallow waters [10].

2.2.2 Connectors for Production Fluids

Figure 2.8 shows a bolted flange connector, while Figure 2.9 shows a bolted clamp connector. These connector types are typically used topside, or for pipes connections within retrievable modules for subsea production and processing systems.

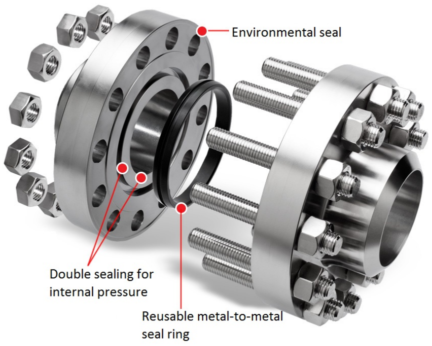


Figure 2.8: Bolted flange connector [11].

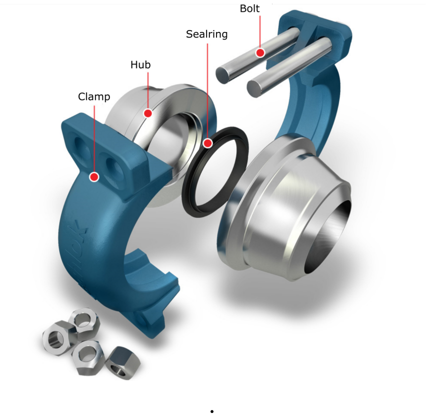


Figure 2.9: Bolted clamp connector [12].

The bolted flange connector creates a tight seal by forcing the two hubs together. This is achieved by tightening them with a metal seal in between. A drawback for the bolted flange connector, is the difficulty of achieving a uniform sealing force for the two flanges. To accomplish this, the bolts must be tightened in a fixed sequence with correct torque. This is a relatively simple procedure onshore, or on topside facilities, but time consuming and more complicated subsea.

ROV Operated Clamp Connectors

As illustrated on Figure 2.10, the clamp connector achieves a tight seal by forcing the two pipe ends together with a clamping device that surrounds the circumference of the hubs. The clamp has a chamfered surface on each side. By forcing it down onto the chamfered surfaces, the clamping force is transferred to a uniform axial force along the pipe length, which again pushes the flanges together against the metal seal.

Due to the more challenging fastening mechanism for the bolted option, it is not convenient to deploy them at the seabed. On this basis, they are mainly used for pipe-connections that are performed topside. For connections on subsea applications, ROV operated connectors

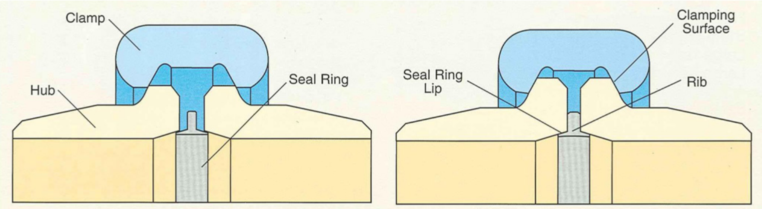


Figure 2.10: Cross sectional view of the interface between the hubs and clamp [13].

are required. Figure 2.11 shows the coupling mechanism for an ROV operated clamp connector, that is widely used for production pipes subsea. This type of clamp connector has the same sealing mechanism as the bolted clamp connector, but the bolts are replaced by either a torque mechanism, or a hydraulic mechanism that provides the clamp force. The clamp connector showed in Figure 2.11, is a torque operated connector, where an ROV must deploy a torque tool that can rotate a connector screw, which tightens or detaches the connection. For a hydraulic configuration, the clamping force is achieved by forcing hydraulic fluid provided by the ROV into a cylinder that again squeezes the clamp around the pipe hubs.

Figure 2.11: ROV operated clamp connector [14].

ROV Operated Collet Connectors

Collet connectors are also widely used for subsea applications such as flow line tie-ins, connecting wellheads and umbilicals. Figure 2.12 illustrates a hydraulic wellhead collet connector. The locking mechanism principle is the same for pipe and umbilical connectors, except that the umbilical connector often requires an additional rotational alignment mechanism, which will be further explained in Section 2.2.3.

The connection mechanism for a collet connector, is illustrated in Figure 2.12. To lock the connector, hydraulic fluid is fed through a supply line and into the annuls over the actuator piston head. This forces the actuator piston downwards, and subsequently forces the locking segments on to the hub. The locking segments works like fingers, which grips on to the mating hub, and pulls them together against the seal. To open the connector, hydraulic supply is fed through the supply line that corresponds to the opening mechanism, where it fills up the annulus over the secondary unlocking piston. This forces the actuator piston up, and the locking segment away from the hub.

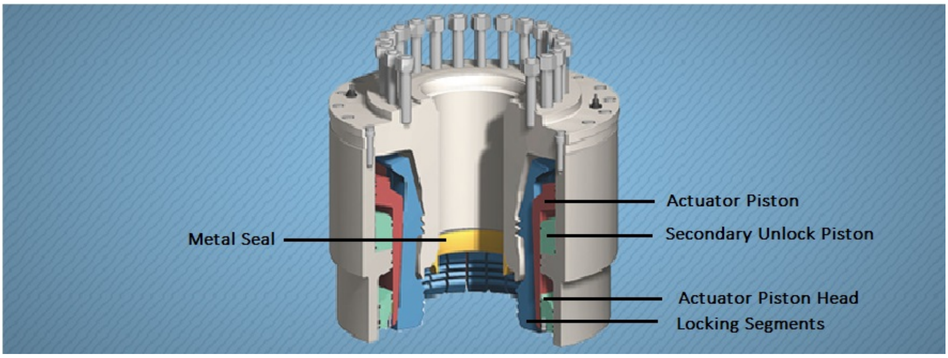


Figure 2.12: Cross sectional view of the connector mechanism on a wellhead collet connector [15].

2.2.3 Multibore Connection Systems

Multibore connectors are more or less a common term used for connectors that can connect multiple lines within one connector assembly. There are several names for this setup within the industry, such as multiple passageway connectors and umbilical connector. However, their latching principal is the same. Multibore connection-hubs are mostly used to connecting umbilical cables that supplies electric power, hydraulics, chemicals and control signals. All these features are supplied through separate lines that are wound together in a helical formation, with plastic fillers in between. Figure 2.13 shows a cross section of a typical umbilical.

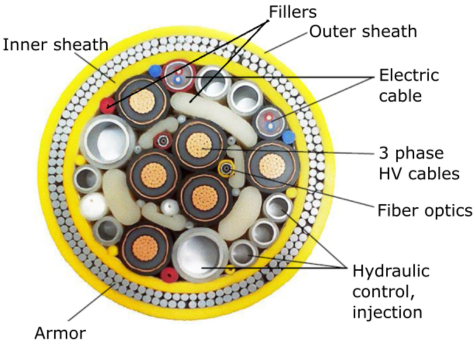


Figure 2.13: Cross sectional view of an umbilical [16].

The multipurpose solution that umbilicals provides, contributes to reduce the number of pipes and connections required in a system. Additionally, this also affects the number of installation operations, which has a direct impact on the overall installation costs. However, when various supply and production features are combined in one cable or pipe, the complexity of the connector system also increases. For control umbilicals, the cable is often fitted with a Umbilical Termination Assembly (UTA). The UTA, as shown on Figure 2.14, is already attached to the umbilical end, which again is rolled onto a reel. Under installation, the umbilical with the UTA attached, is lowered to the seabed. Here it functions as a distribution center, where the different supply lines can be routed to several locations.

Figure 2.14: Umbilical Termination Assembly (UTA) [17].

Figure 2.14 shows a UTA for a multiplexed electro-hydraulic control system, that enables distribution of hydraulics and electric power to several Subsea Control Modules (SCM). Distribution is achieved by fitting several connection points around the UTA, where flying leads can be connected. Figure 2.15 shows a flying lead Multi-Quick Connector (MQC) stab plate for hydraulic supply, which can provide connection from an UTA to the individual X-mas trees. In general, there are two configurations of connector interfaces; concentric and non-concentric. These will be explained later in this section.

Electrical connectors that can be connected subsea, so called wet mate connectors, requires a special mating technology. In general terms, this technology relies on achieving an electrical connection, where the two electrical lines are connected without having any trapped seawater between the interfaces. To achieve this, a flushing mechanism must be integrated into the connector.

Figure 2.15: Flying lead for hydraulic supply [18].

In addition to the umbilicals that provides control and chemical injection features, it is also possible to include a production line. Such arrangement is often referred to as an Integrated Production Umbilical (IPU), or an Integrated Production Bundle (IPB). Figure 2.16 shows the cross section of an IPU that consists of a steel pipe in the middle with electrical, control and injection lines coiled around. To keep the lines and cables in place, a PVC matrix is fitted in between. This matrix also works as a thermal insulation layer for the production fluids.

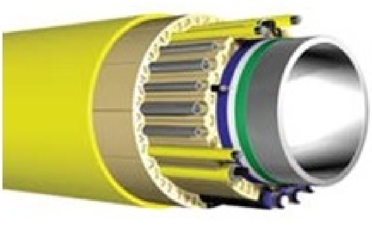


Figure 2.16: Cross section of an Integrated Production Umbilical (IPU) [16].

In a production system that consists of several wells which produces to a common manifold, one can skip the UTA solution. Instead, the control umbilical can directly be connected onto the manifold. Further, from the manifold to the X-mas trees, both control and production can be routed through IPB spools. This solution will require an integrated control distribution system in the manifold.

Figure 2.17 illustrates an example of rigid well jumpers between a manifold and X-mas trees on Moho-Bilondo production wells outside the coast of Congo. The jumpers are an IPB configuration that contains a 6" insulated flow line, 2" gas injection line, 2" methanol line, in addition to hydraulic and chemical small bore pipes [19]. All these lines are connected through horizontal multibore connectors.

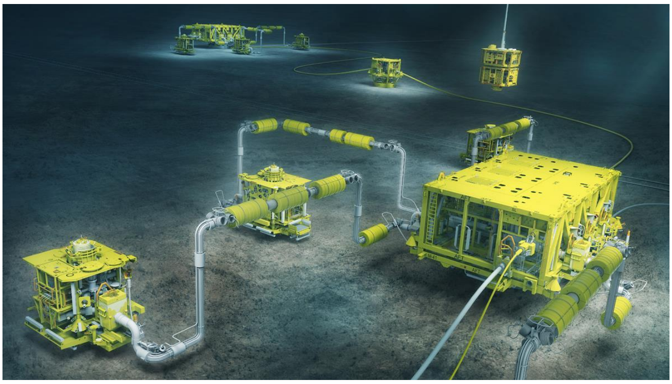


Figure 2.17: Integrated production bundle jumper between manifold and X-mas tree [20].

Connector Interfaces

Figure 2.18 illustrates a pipe configuration with two rigid steel pipes bundled together with a connector assembly at the end. This assembly consists of internal piping, that guides each pipe or cable from the bundle, to the correct location on the connector interface.

Figure 2.18: Non-oriented multiple passageway flow line connector [21].

The connector interface on this connector, is a concentric configuration as illustrated in Figure 2.19. It is designed in such way that all the annuli has a common center. This means there is no need for rotational alignment of the connector interface during the mating procedure.

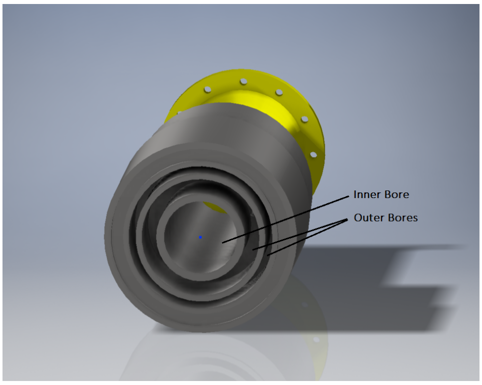


Figure 2.19: Concentric multibore connector interface.

Figure 2.20 shows a connector interface with bores oriented in a non-concentric pattern. This configuration has no common center for the different bores, as they are placed around a bore in the middle. To make sure that the right bores on the two connector assemblies align, an alignment mechanism must be included in the connection system. Such a mechanism may contribute to increase the overall weight of the assembly. This configuration is still the most commonly used in the industry. A potential benefit is that the interface can contain more connection points, while for the concentric setup, a great number of supply lines could be complicated, and result in a large and heavy connector assembly.

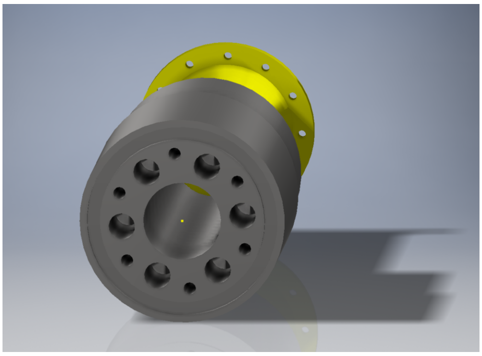


Figure 2.20: Non-concentric multibore connector interface.

There are both advantages and disadvantages with the multibore configurations. One of the drawbacks is the added complexity, where the different annuli or bores will require an individual seal. This issue are explained in more detail under the next heading. Another drawback is, if a failure occurs in one of the lines and replacement is needed. Then the entire bundle must be retrieved, which in term means disconnection of all the lines. This may result in shutdown of several systems, unless some form of redundancy is available. However, the potential of reducing the number of connectors needed, might affect the future operational costs. This will be further assessed in Section 3.3.3.

2.2.4 Seals and Gaskets

Metal seals are commonly used for subsea applications. Usually, they are plated with an outer layer of a more ductile material, often silver, that fills the microscopic micro structure of the harder metal surface on the connector interface. This plated layer provides the plastic deformation that is needed, and with a harder metal in the core, some elasticity is also added. The combination of plasticity and elasticity, is crucial to ensure a tight seal even under small cyclic decompression loads, which often occurs in a connection due to thermal expansion and contraction.

A metal seal performs well at high temperatures, and they have high durability due to their good mechanical properties. However, the ductility and elasticity of metal seals are a limiting factor compared to the non-metallic seals, such as soft compressible elastomers, which provides good sealing performance, but lack in high temperature performance [22].

The mating force that is transferred from the connector, must be sufficient to achieve a proper seal. A ductile metal layer on the surface contributes to a reduction of the force needed to achieve a plastic deformation. If too little force is applied, the soft metal may not fill the micro structure of the mating hub, and leakage may occur. Too much force however might damage the seal.

2.3 Subsea Control Systems

Valves and chokes in a subsea system must have the ability to be actuated from topside. In addition, diagnostic information gathered by monitoring devices, such as vibration monitoring, sand monitoring, leakage detection, etc. is sent through a control system. There are mainly five types of control systems:

- Direct hydraulic
- Piloted hydraulic
- Sequenced hydraulic

- Multiplexed electrohydraulic
- All-electric

Direct control systems relies on hydraulic supply from topside, as a result, it performs weakly on long distances due to the lack of response time.

Piloted hydraulic systems works by hydraulic supply from topside, with an additional accumulator at the SCM that boosts hydraulic supply, and decreases the actuation time. This system is typically used for single satellite wells, with short and medium distances from the host facility.

Sequenced hydraulic control systems is similar to the pilot hydraulic system, but it consists of several sequence valves and accumulators. This system also has limited range, but can be used for more complex control operations.

Multiplexed control systems has much faster response time, and are usually used on deep-water installations. While the control systems mentioned above only relies on hydraulic supply form topside, the multiplexed system is a combination between electrical and hydraulic supply.

All-electric control systems rely only on electrical supply. This reduces the umbilical cost and decreases the actuation time significantly. An all-electrical system is typically used in complex, marginal, long distance, high pressure and high temperature fields [23]. This type of system is not put in extensive use yet, but can be expected in the future.

2.4 Subsea Valves

Valves are essential in the production of oil and gas, as they control the flow and are an important barrier that contribute to the integrity of a system. Operating the valves is mostly done by remotely controlled actuators. The actuators is operated by an energy source, which can be hydraulic pressure, pneumatic pressure or electric current. Some valves can both be operated hydraulically and mechanically by an ROV.

The most common subsea valves are gate- and ball valves. Figure 2.21 and 2.22 shows a typical subsea gate valve and a ball valve, with a fail-safe-close actuator and ROV actuation feature. Gate valves are kept either fully open or fully closed and are mostly used in pipelines containing liquids. They have been used in BOP stacks, trees and manifolds for a long time, and are considered to be reliable due to an extensive development of the valve actuators over the years. The ROV bucket on the top of the gate valve and on the front side of the ball valve, is an additional safety measure to ensure redundancy in the system. Ball valves are mainly suited for gas pipelines, and can accommodate larger pipe dimensions with low pressure, while the gate valves are better suited for high pressure [24].

Figure 2.21: Gate valve with fail-safe-close function and ROV actuation feature [25].

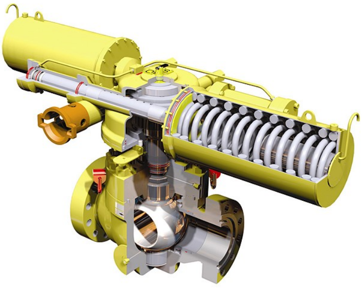


Figure 2.22: Ball valve with fail-safe-close function and ROV actuation feature [26].

Choke Valve

A choke valve is used to control the flow by adjusting the valve-opening, thereby, a reduction of downstream pressure is achieved. This is especially important for both production and injection manifolds, to allow commingling of flows. For subsea manifolds hydraulic actuated variable chokes are commonly used. Chokes are exposed to wear and tear, and are therefore often modularized to enable an efficient change-out. Figure 2.23 illustrates a retrievable choke module manufactured by FMC Technologies.

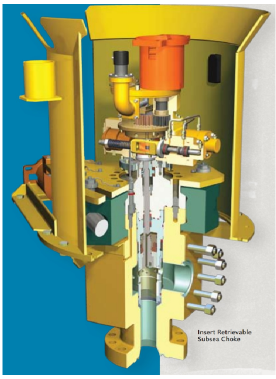


Figure 2.23: Retrievable choke module with ROV actuated clamp connector [27].

2.5 Subsea Inspection, Maintenance and Repair

Inspection, Maintenance and Repair (IMR) is a collective term for intervention operations subsea. NORSOK U-007 [28], addresses subsea intervention and states that the primary objective for an invention system is to facilitate safe and cost efficient intervention on subsea installations.

For the subsea industry, the term IMR is impossible to avoid. Subsea equipment is exposed to various degrading factors, such as corrosion, stress, erosion and wear. The outside environment together with “inside” factors from the reservoir, such as pressure and temperature is also contributing to degradation of the equipment. Identifying, monitoring and analyzing all these factors are important to be able to anticipate potential degrading factors for the production system.

For deployment and retrieval of heavy structures as large templates, separators etc., large lifting vessels are required. This have a big impact on the cost of the operation. Therefore, they are usually only used when there is no other way around.

IMR support vessels are intended to perform operations that is a level below the heavier operations mentioned above. Lighter IMR vessels are cheaper to have on contract, and can be mobilized faster. The most important features for a IMR support vessel, is the ROVs that can perform light activities around the subsea system. Further, the vessels have special heave compensated cranes, and a module handling system that is intended to guide the modules through the splash zone. All these features will be explained in more detail later in this chapter.

The oil and gas industry operates under strict requirements related to Health, Safety and Environment (HSE), and not least, operators own demands for maximum profits and availability for the equipment. Another important aspect for the industry, is the way towards the subsea factory. This makes operations previously considered as relatively simple, more complex.

2.5.1 Categorizing of IMR-operations

The IMR activities can be divided up by its complexity. The industry classifies the activities under the headings; I-type, M-type and R-type:

I-type (Inspection)

Classified as scheduled condition monitoring such as structural inspection, pipeline inspection, or corrosion monitoring, are usually performed by an ROV. Inspections may reveal a need for more extensive jobs as maintenance or repair.

M-type (Maintenance)

These tasks arise from earlier condition monitoring, or a decreased performance reported by the operator. Typical maintenance tasks would be replacement of modules (chokes, pumps, control modules etc.), jumpers, seals, or removal of objects, like fishnets.

R-type (Repair)

According to NORSOK Z-008 [29], repair is considered as more complex operations on structures, such as repair of caisson or conductor pipe, repair of template hatches, locks and hinges. Maintenance activities use standardized procedures and running tools, while repair activities often require customized solutions to perform the job [30].

2.5.2 Preventive and Corrective Maintenance

NORSOK Z-008 [29], defines maintenance as: *"combination of all technical, administrative and managerial actions, including supervision actions, during the life cycle of an item inended to retain it in, or restore it to, a state in which it can perform the required function"*.

In the most simplistic way, one can divide maintenance in two categories; preventive and corrective:

Preventive maintenance is performed before the equipment has failed. This type of maintenance is often performed after a certain time interval determined on the basis of criticality and experience (calendar based maintenance). On the other hand, corrective maintenance is performed after a fail occurs (run to failure). This type of maintenance is not scheduled if otherwise not stated. There are exceptions. If a component that is not critical, or a component with redundancy fails, the maintenance might be scheduled and carried out together with already scheduled jobs. This must of course be consistent with the stated guidelines for equipment given by operators and authorities.

As mentioned this is only the most simplistic way to explain the different types of maintenance operations. However, the truth is that the operations are more complicated. The oil and gas industry used advanced methods, sophisticated tools, and strategies, to achieve their goals. Relevant methods and strategies for improving the safety and availability for subsea production systems are described more in detail in Section 3.1.2.

2.6 Marine Operations Related to IMR

Subsea equipment is built at yards onshore, and must be transported and installed in a safe and efficient manner at its intended location. This is often associated with challenges and complex operations, including weather conditions, positioning and heavy lifting. At a later stage in the life cycle, the equipment must be inspected, maintained or repaired. This chapter explains features that are associated with installation and IMR operations on subsea equipment.

2.6.1 Vessels

Various types of vessels may be used for transportation and installation of subsea structures and equipment. Planning helps to choose the most appropriate alternative. Common vessels that are used for various installations, are listed below [31]:

- Transportation barges and tug boats
- Pipe-Laying vessel
- Umbilical-Laying vessel
- Heavy lift vessels
- Light IMR vessels

For installation of typical subsea equipment, such as modules, a medium- or light vessel with on board crane or Module Handling System (MHS), is used. MHS is further described in Section 2.6.4. The lifting operation takes place through the moonpool or over the side of the vessel. Figure 2.24 shows the vessel "Seven Viking", which is state of the art regarding IMR operations.

Figure 2.24: Offshore construction and IMR vessel Seven Viking [32].

Vessel Requirements

Vessel requirements highly depend on the scope of the operation. Size and weight of the structure that is to be lifted, are a key factor. In general, the owner of the equipment wants to use the smallest vessel possible to keep the costs down. However, there are functional requirements that should followed. Some important requirements for intervention vessels are listed below:

1. Main crane capacity:

   Operations often require lifting activities, such as moving equipment, placement of equipment in the launch system, and lowering of equipment to the seabed. The capacity of the crane or MHS, is determined by maximum lifting capacity and lowering reach. Heavy construction vessels may have a lifting capacity up to several thousand metric tons. However, these vessels are very expensive to hire. Consequently, they are not suited for subsea light intervention operations.

2. Deck area:

   Operations offshore often require various equipment that may occupy a significant area of the deck space. The deck is also used to store modules or other equipment that is retrieved from the seabed, or equipment to be replaced. Because of this, a spacious deck area is beneficial. It can also avoid the need for frequent trips back and forth to ports, which again reduces costs.

3. Remotely Operated Vehicle (ROV):

   Vessels should accommodate a ROV system. The use of ROVs are common in most IMR operations these days.

4. Module Handling System (MHS):

   MHS is a custom-made lifting and handling system for subsea modules. It is most common to have a MHS tower over the moonpool. Installation through the moonpool is beneficial because of better stability and tolerance due to weather conditions. This features is more thoroughly explained in Section 2.6.4.

5. Ready For Operation (RFO):

   RFO are used to verify the integrity and functionality of the installed equipment.

2.6.2 Installation Capability

The installation complexity increases with the water depth. The depth challenges may be a constraint due to the lowering, load control and positioning system.

Steel wires are durable and well proven, but they have their weaknesses at ultra-deep waters. For a steel wire with a diameter of 5 inches (0,13 meters) at depth of 3000 meters, the weight of the wire itself is about 170 metric tons. As the depth increases the payload increases with it. At 6000 meters, the weight of the wire is so high that it will not be able to carry any equipment [24].

Another challenge is the resonance from the natural period of the load on the wire and with surface vessel excitation, this can result in large dynamic loads. It can also be challenging to estimate the added load created by hydrodynamic drag, especially for complex geometries. An alternative to steel wires is fiber rope. The fiber rope has benefits such as lower self-weight, allows small bend radius, lower stiffness, good ability for absorbing heave from surface waves, and the ability to be repaired. However, fiber ropes unfortunately also have shortcomings, such as creep, stretch related problems and relatively low melting point [24].

Heave, positioning, and stability is a challenge when lowering a structure. During lowering of heavy structures, large dynamic forces are present. Excitation caused by motions from the vessel, can be amplified with large oscillations and high dynamic loads in the lifting wire. A structure load can be many times bigger than its own weight in air, due to the water trapped both inside and around it. Therefore, the shape of the structure to be installed or retrieved is an important factor that determines the added mass. The added mass can be crucial to the dynamic response, and to the installation capability. When installing a structure in deep water there will almost always be a depth at which resonant response will occur. This resonant region must be passed through as quickly as possible, and not to occur at final depth where complete control is required for a smooth placement on the seabed [24].

When installing structures at deep water, the heave motions must be compensated. Active and passive motion compensation systems are frequently used for the installation operation. A further explanation on heave compensation systems is provided in Section 2.6.4.

2.6.3 Subsea Lifting Operations

Different installation methods, with their own advantages and disadvantages, exists. In this thesis, the traditional installation method is explained. A subsea installation can be divided into the following categories [33]:

Installation positioning

The vessel must keep its position with great accuracy to perform the installation in an efficient manner. A well-known solution for this, is Dynamic Positioning (DP), which allows the vessel to keep its position with help from thrusters and satellite positioning.

Lifting from the deck

At installation site, the structure can be prepared for lowering. The crane operation should be as simple as possible to avoid unnecessary risks. Test-lift inshore is recommended. Once the structure is airborne, pendulum forces, and stability motion of the vessel must be considered. A situation where the structure accidentally is dropped, also needs to be analyzed.

Lowering through the wave zone

Entering the splash-zone reduces the pendulum effect, but the challenges are not over. This is where one get introduced to the most violent dynamics. Relative motion between structure and sea, and acceleration due to wave motion, slamming of waves, and motions due to crane tip movement is present. Rolling motion of the vessel will also contribute to the lowering speed of the structure. All this makes transportation through the splash zone problematic, thus it is critical to perform it correct. As mentioned, MHS systems for guiding the equipment through this critical zone, is described in Section 2.6.4.

Further lowering down to seabed

The pendulum motion of the wire is not a concern a this point. When submerged, the wave impact will disappear. The dynamics is then dependent on the crane tip motion.

Positioning and landing

It is important to perform a controlled and soft landing to protect the structure from damages due to the impact. Guiding is often used to control the landing, and to make sure that the structure meets its desired point. Figure 2.25 summarize all the phases in a lifting operation.

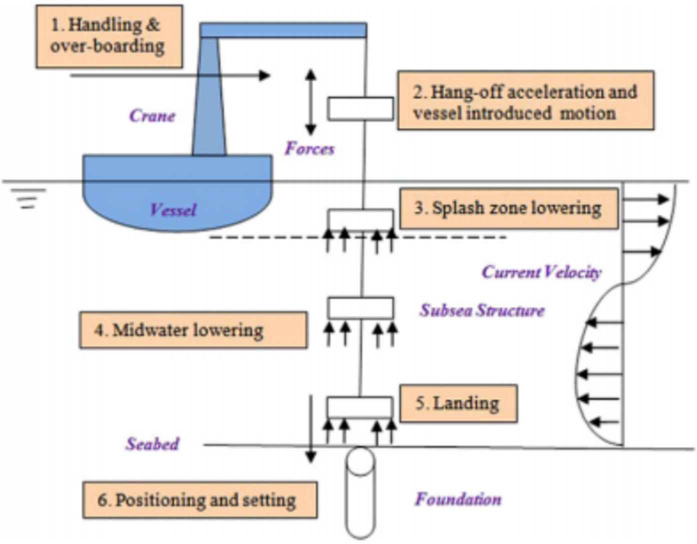


Figure 2.25: Steps of a subsea lifting operation [24].

2.6.4 Heave Compensating and Module Handling

As explained, offshore lifting operations are performed by vessels that are in constant motion. These motions cause large load variations on the object that are lifted, lowered, or installed. To compensate for, and reduce these motions, heave compensation systems are used. They can be either, passive, semi-active, or active:

Passive Heave Compensation

In passive heave compensating systems, pneumatic pressure is used. The motions are compensated by gas filled cylinders that either is compressed or expanded.

Semi-active Heave Compensation

The semi-active system is a combination system where a passive system absorbs most of the motions, and an additional active system absorbs the remaining motions.

Active Heave Compensation

With active heave compensation, the energy is supplied to the system as function of the heave measurements performed from an Motion Reference Unit (MRU). Based on data from an accelerometer, the unit calculates the required compensation force that is required to stabilize the load. The supplied energy can come from hydraulic or electric powered cylinders.

These heave compensating systems can be mounted with the vessel crane, or in connection with module handling systems.

Module Handling Systems

The most common use of MHS is by a Module Handling Tower (MHT) installed over the vessels moonpool. The moonpool is an opening in the ship hull, which extends through the air-water interface. This is beneficial as it provides a protected environment when lowering the module, and the critical splash zone is avoided. The module is skidded into the MHT with help from a pallet-base that is attached to skidding rails. Figure 2.26 shows the system setup. Besides the tower and skidding system, the system consists of hatches, guiding system, guide wires, and cursor frame. The cursor frames main objective is to enable a controlled and safe launch and recovery of the lifted module [34].

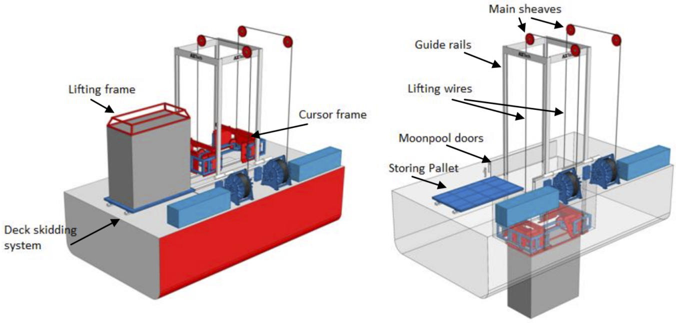


Figure 2.26: Module Handling System [35].

The moonpool is usually placed as close to the vessel roll and pitch axis as possible, to reduce the affects from vessel angular motions. If the vessel is designed in a proper way, the motions in the moonpool should be smaller than from lowering the module from the vessel side. Below some advantages and disadvantages are listed [34]:

Advantages:

- Protection of equipment from environmental forces.
- Skidding system eliminates the need to lift equipment on deck.
- Minimized affect from the vessels angular motions during lifting operations, due to moonpool close to vessel roll and pitch axis.

Disadvantages:

- Water plugs within moonpool may cause flooding of vessel deck and large loads on equipment in moonpool.
- Risk of equipment slamming into cursor frame or get stuck when entering the moonpool.
- Size limitations of equipment.

Special Handling System (SHS)

The Special Handling System, is a concept developed by AxTech for launch and recovery of heavy subsea modules under extreme environment and sea states. The special designed lifting system, has a safe work load of 420 tones at a sea state as high as 4,5 meters significant wave height [36].

The Special Handling System consists of a tower structure with the ability to rotate around the tower axis. The module is lowered by a railing system and the cursor frame is attached to the module, and then guide through the splash zone. Figure 2.27 shows a module that is lowered through the splash zone. After leaving the splash zone, the module is released from the skidding rails for further lowering. Final installation is often performed with help from guide wires [37].

Figure 2.27: Module lowered through the splash zone [37].

2.6.5 Remotely Operated Vehicles

There are many different types of ROVs. The most common types used in the subsea industry, are inspection and working ROVs. Inspection ROVs are vehicles equipped with cameras to give visuals of the structure. It usually has the capability to perform Non Destructive Testing tasks (NDT). A work ROV is shown in Figure 2.28. This is a much bigger vehicle that normally is equipped with two manipulators. A manipulator is a remotely controlled arm that is intended to execute required work tasks. The ROV must meet the interface requirements from the different intervention tasks. The most common tools are listed below [38]:

- Cleaning tools - Various types, mainly used for cleaning of connectors, seal surfaces and removal of marine growth.
- Cutting tools - Mainly used for cutting ropes in connection to decommissioning or other intervention tasks.
- Intervention tools - Various types, such as alignment framing for docking on interface, change out of gaskets, etc.
- Camera/Lightning/Displays - Used for observations and assisting other tasks.
- Override tools - Mainly used for actuation of different types of valves.
- Measurement tools - Used for data collection.
- Skids - Framing structure mounted to the ROV, used for fluid intervention such as injection of hydraulic fluid or methanol.
- Hot Stabs - Used for powering hydraulic tools, transfer fluid, perform chemical injections, and to monitor pressure.
- Torque tools - Used for operating of docking interfaces.

Figure 2.28: Oceaneering Millennium Plus work class ROV [38].

The Millennium Plus ROV, shown in Figure 2.28, is a typical work ROV that is used for various operations subsea. Total weight of the ROV is 4 metric tons, and the dimensions is 3.3 x 1.7 x 1.9 meters. It is equipped with two hydraulic power units of 110hp, that controls the manipulator arms. Further, the ROV have a thrust power of 900 kilograms [38].

Future Trend: Autonomous Underwater Vehicles (AUV)

Nowadays comprehensive development of new types of underwater vehicles for subsea applications, are ongoing. Compared to traditional ROVs, the AUV operates without an umbilical, which again removes the need for complex umbilical handling systems and gives better maneuverability and accessibility. The AUVs are intended to perform cost-efficient inspections and light repair operations. It is desired to dock the AUVs subsea in a docking station for charging and storage when not used. This feature enable shorter reaction time, and makes the operations independent from weather conditions.

The AUV shown in Figure 2.29 is a snake robot developed by Elumee, which is a spin-off company from NTNU. This development is one example of many, which is aiming to revamp future IMR-operations [39].

Figure 2.29: Elumee snake AUV [39].

Chapter Summary

The subjects that were presented in this chapter was included to give an understanding of the fundamental knowledge required in the next chapters. The main subjects that was presented, are listed below:

- A brief introduction of the history and future of subsea production and processing systems.
- Information on different types of subsea connection systems.
- An insight into main aspects of inspection, maintenance and repair on subsea applications.
- General information on marine operations related to IMR on subsea systems.

Next chapter highlights important design factors that can affect the ability to perform installation and IMR on subsea production and processing systems.

Chapter 3

System Design for Efficient IMR Operations

Development of subsea systems is a stepwise process. After over 30 years of development almost all processing can be performed subsea. The main drivers for a subsea system design is to achieve a high availability and quality. These drivers are obtained through:

- High quality on the selected equipment.
- Some degree of redundancy and fault tolerance on a system level.
- Efficient design for IMR operations for replacing failed or degraded equipment.

This chapter presents important methodology for subsea production and processing developments that has its main focus on easy installation, inspection, maintenance, and repair. Important factors will be pointed out by studying already existing subsea production and processing developments. For instance, the architecture of a subsea production system should provide a degree of redundancy for some of the equipment. As it is not feasible to have a redundant component for every part of the system, the parts must be closely monitored instead, so that failure or lack of performance on equipment can be detected in an early phase. The final and most important factor in term of this thesis, is the modularization of the system. Efficient replacement of failing equipment is essential to achieve the desired availability. Solutions as redundancy, rerouting, and monitoring of performances, is only temporary solutions, while the replacement operation is the final solution for bringing the system back to optimal condition.

The system design must also compile with given rules and regulations given by standards, operators and authorities in the relevant area. Figure 3.1 shows the hierarchy of the design, which must be followed when developing a new concept.

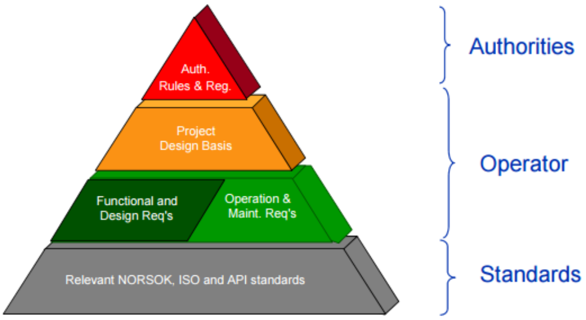


Figure 3.1: Design Basis Hierarchy [40].

3.1 Minimizing the Need for Intervention

The ultimate goal is intervention-free systems. However, with today‘s technology this is not possible. Instead, the focus must be aimed towards facilitating for a system that can be maintained in an efficient manner. An intervention friendly design, and smart solutions, contributes to achieve this.

3.1.1 Maximizing the Availability for the System

The availability expresses the time a system is capable to perform its intended function under given conditions. It is affected by reliability and maintainability. Reliability is the probability for a component to survive a given period of time under given operational conditions. It does not account for the downtime of a component. Maintainability says something about how easily and quick a failed component can be brought back to life [41]. Table 3.1 shows the relationship between these parameters.

Table 3.1: Relationship between reliability, maintainability and availability [42].

Reliability	Maintainability	Availability
Constant	Decreases	Decreases
Constant	Increases	Increases
Increases	Constant	Increases
Decreases	Constant	Decreases

By studying the relationships between the factors, one can seen that the availability will increase if the system is designed in a manner that facilitate for efficient maintenance.

3.1.2 Condition/Performance Monitoring and Condition Based Maintenance

As described in Section 2.5 about IMR, subsea equipment will sooner or later be in need for intervention in terms of maintenance. However, the problem is to know exactly when the need arises. This is where predictive maintenance, by implementation of condition and performance monitoring comes into play.

Condition monitoring while systems are operating, is relatively new. The application of these systems is most advanced within military, industrial, and consumer sectors, where safety and reliability are highly valued. The space, aviation, and automotive sectors started off with these systems - and are still in the forefront of developing and using advanced monitoring systems [43].

On the other hand, the subsea industry is some steps behind regarding utilization of this technology, and the "run equipment until it fails" philosophy have been more accepted. However, the subsea industry is gradually developing and implementing condition monitoring systems. An example of this implementation is presented in Section 3.1.3.

By implementing a condition based maintenance strategy for subsea equipment, efficiency of the intervention operations, and decrease of the operation costs, can be achieved at the same time.

Implementation of Condition Monitoring for a Subsea Pump

Further, an example of implementing condition based maintenance will be presented. The example addresses the maintenance strategy for a subsea pump. Such pumps, is typically predicted to have a Mean Time To Failure (MTTF) of 5-10 years. Typical maintenance strategies for this pump might be:

1. Run to failure
2. Replace after a certain time (calendar/time based)
3. Replace when performance is reduced (condition based)

The run to failure strategy uses the "if it works, don´t touch it" philosophy. By using this approach, the time between each intervention operation is maximized. However, an unexpected fail will result in longer downtime due to mobilization time for new equipment, vessel, crew, etc. This time could range from days up to months, depending on the circumstances.

If the time based strategy is applied, the highest numbers of intervention operations are expected. Change-out of equipment is only dependent of time/usage. (e.g an oil filter for a car is changed every 12 months, or when reached 15000 kilometers). Another drawback with this strategy, is that one may end up replacing completely intact equipment. Also worth mentioning, is that the intervention operation itself is not risk free, as other equipment in the system may be damaged during a scheduled intervention operation.

The last strategy, where equipment is changed on basis of the condition is the most optimal solution with respect to intervention intervals and costs. To achieve this strategy a combination of run to failure and time based are used together with condition monitoring tools.

Table 3.2 compares the yearly costs for a subsea pump module with the different maintenance strategies applied. These numbers are derived from simple assumptions and calculations, and they are only meant for showing the potential difference in costs by making use of the different maintenance approaches. Assumptions and calculations can be seen in Appendix A.

Table 3.2: Intervention strategies and their yearly costs.

Strategy	Yearly costs (MNOK)
Run-to-failure	25.6
Time based	6
Condition Based	2.4

This simple example shows that by implementing condition monitoring and predictive maintenance in form of condition based maintenance, both costs and the intervals of intervention are optimized [44].

The concept of Condition Based Maintenance (CBM), is to get an indication of the system status, and most desirable a warning in good time before a failure occurs. By achieving this, the maintenance can be performed by the "just in time" philosophy before a fail occurs or when the performance is reduced. Further, scheduling of change-out of well-functioning equipment is avoided. However, it is not possible to avoid all failures. Sudden breakdowns will always at some point occur, so there is also necessary to have a strategy for changing already failed equipment.

The terms Condition Monitoring and Condition Based Maintenance is in a way overlapping. A definition of the terms might be [44]:

- Condition Monitoring: measuring and monitoring the state of the equipment (historic and current data).
- Condition Based Maintenance: using obtained information to perform “just in time” maintenance operations (extrapolate to future fails and schedule maintenance on the basis of this).

Figure 3.2 shows a simplified flowchart of a condition based maintenance system. The basis for the system that is used are sensors, they measure and monitors the performance of the relevant equipment. These measurements are captured and stored in a data storage system for further processing. The processed data is analyzed, and KPIs (Key Performance Indicators) are calculated for comparing the actual performance with the predicted performances for the equipment. Finally, the prediction of remaining life can be confirmed, and further actions may be scheduled [44]. A detailed condition monitoring flowchart can be found in "ISO17359 - Condition monitoring and diagnostics of machines – General guidelines"

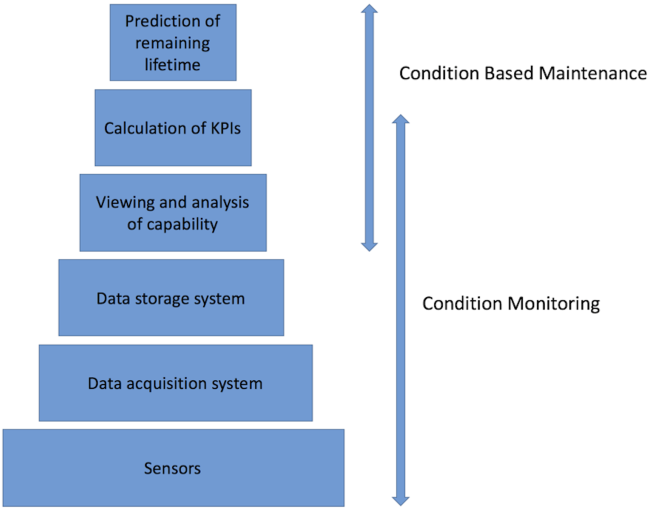


Figure 3.2: Overview of a typical CM/CBM system [44].

Sensors for subsea condition monitoring can be used for [43]:

- Subsea pressure/temperature/flow

- Control pod pressure/temperature
- Downhole pressure/temperature/flow
- Subsea processing pressure/temperature/flow
- Pipe wall thickness/erosion/corrosion
- Stress/strain
- Acceleration/vibration
- Voltage/amperage/resistance/impedance
- Leak detection/video

3.1.3 Condition and Performance Monitoring at the Gjøa Oil and Gas Field

The Gjøa Field is a successful example of the benefits obtained by implementing a condition and performance monitoring system. The CPM system is developed by TechnipFMC (previously FMC Technologies), on behalf of Engie E&P Norge (previously GdF Suez) which operate the field. The purpose of the system is to maximize production uptime and asset availability.

As previously described in section 3.1.2, this kind of systems collect, store, and processes data in real time. It uses integrity monitoring beyond traditional KPIs by taking a holistic approach, and utilizing all available data and information, where design parameters, criticality, system experience and operating philosophy is modeled and built into what is defined as Technical Condition Index (TCI) [45].

It takes maximum ten minutes for the operator to get total overview of the system TCI status, and it gives the possibility to detect faults in real time.

In less than one year following cases are solved with help from the CPM system

- Detected leak in subsea router module early. Change-out facilitated before failure.
- Erosion damage to choke. Detected before serious degradation. Component changed.
- The CPM system detected abnormally high pressure drop over oil filter in control system.

The initial investments in the CPM system was paid back in less than two months, due to properly planning of the IMR-operations [45].

3.2 Cost Related to Installation- and Maintenance Operations

This section will provide an insight of costs related to maintenance operations of modules on a subsea processing system. Costs for installation and IMR operations subsea is a big variable. As indicated, all subsea field developments are unique, with different processes and equipment. Because of this, it is difficult to compare one field to another. However, it is possible to compare similar equipment. Most subsea process equipment is module based, and the procedures for retrieving or installing a module is quite similar.

The costs related to installation and IMR operations are usually, frame contracts with contractors executing the operations, planning of operations, personnel, overhaul of equipment, new equipment, and logistics. Repair operations often requires extensive planning and customized solutions, which may involve special vessels, additional personnel, and special equipment. This is much more expensive compared to standard operations.

Section 3.2.1 addresses replacement of two different modules on the Tordis Subsea Separation Boosting and Injection station. Both replacements are considered as standard operations. Hence, as explained in Section 2.5.1, they are regarded as maintenance operations.

3.2.1 Case Study: Change-out of Modules on the Tordis Subsea Separation Boosting and Injection (SSBI) Project

The Tordis field is located in the Tampen area in the North Sea. Production from the field started in 1994, and the field is developed as a subsea tieback to the Gullfaks C facility. The Tordis SSBI is a further development of the Troll pilot separation, and was installed in 2007. The system is the world's first commercial subsea separation, boosting, and injection facility. Originally, it was supposed to separate water and sand from the oil and gas, and then re-injects the water through a 12-inch injection well to Utsira, a non-hydrocarbon reservoir. However, this feature is no longer operational, and the water and sand is treated topside.

The separator itself is 17 meters long, has a diameter of 2.1 meters and a weight of 250 metric tons. The footprint of the entire system is 40 x 25 x 19 meters, and the total weight is approximately 1130 metric tons [46]. Table 3.3 lists the main building blocks for the SSBI system that all are independently retrievable:

Table 3.3: Main modules for the Tordis SSBI [46].

Module	Weight [metric tons]
Manifold including SCM	230
Desander Module	60
Multiphase Pump Module	20
Water Injection Module	20
Water Flow Module	15
Multiphase Meter Module	16

As part of the case study related to costs and duration of the intervention operation, change-out of two different modules on the Tordis SSBI system are presented. The information in this example is provided by Statoil through personal communication (N. Lazarevic, personal communication, May 16, 2017). Following modules where replaced first quarter in 2016:

- Desander module
- Multiphase pump (MP) module

For replacement of the two modules, the IMR-vessels Seven Viking and Normand Ocean where used. Seven Viking replaced the desander, and Normand Ocean replaced the multiphase pump. Table 3.4 shows the key features of the selected vessels [47], [48]. According to AxTech (R. Myhre, personal communication, May 31, 2017), which deliver module handling systems to various vessels, these dimensions are a standard based on Statoil's specifications that is required to handle existing modules.

Table 3.4: Key features for selected vessels [47] [48].

Feature	Normand Ocean	Seven Viking
Working Deck Space [m2]	1020	600
AHC Crane Capacity [metric tons]	150	135
MHS Capacity [metric tons]	40	70
Work ROV (no.)	2	2
Moonpool Size [meters]	7.2 x 7.2	7.2 x 7.2
Significant Wave Height [meters]	5.0	5.0
Accommodation (no. of persons)	90	90

Approach for the two different modules:

For the desander module, operations involved the following activities:

- Operation preparation, where the desander was emptied and flushed with MEG.
- Valve operation and verification of the barriers.
- Electrical disconnection.
- Retrieval of the desander module.
- Installation of the new desander module.
- Commissioning, including electrical connections.

The duration of the intervention was approximately 4 days, excluding Waiting on Weather (WoW). Costs of the operation was approximately 13 MNOK, excluding overhaul of the old module.

For the multiphase pump, the operation involved the following activities:

- Preparation and verification of the barriers (the production had to go to a bypass over the SSBI).
- Electrical disconnection.
- Retrieval of the multiphase pump module.
- Disconnection of the HV- (High Voltage) Jumper.
- Installation of new HV-jumper.
- Installation and commissioning of pump (including electrical connections).
- Start up and function testing.

The Multiphase pump module is connected to the manifold with Destec process clamps. The duration of the intervention operation was just under 2 days, excluding WoW. Costs of the operation was approximately 8 MNOK, excluding overhaul of the old module.

Table 3.5: Summary of the change-out operations for Tordis SSBI.

Module	Weight[tons]	Vessel	Duration[days]	Cost[MNOK]
Desander	60	Seven Viking	4	13
MPP	20	Normand Ocean	2	8

As seen in Table 3.5, the installation operations are performed by two different vessels. The reason is that Normand Ocean do not have sufficient MHS lifting capacity. Seven Viking have greater capacity, so it had to perform the job. It is also seen that change-out of the larger desander module is more time consuming, which naturally leads to higher costs. Both vessels are on a long-term frame contract with Statoil.

3.3 Retrievable Modules

Subsea production and processing systems are usually divided into several separate modules in which the equipment are installed. Within the industry, all equipment that makes up the processing system, is often referred to as a process train. The process trains, with associated modules, are placed inside a framing structure, which is supposed to protect the equipment from e.g. trawling activity or dropped objects. In addition, the frame should work as a foundation, and carry the load of the process trains. One of the reasons for a modularization setup is because subsea production equipment in some cases is too large and heavy to be lifted in one operation. Consequently, the base structure and the separate modules, are occasionally installed separately.

Another reason addresses maintenance operations, where it is desirable that the equipment has a high availability through high maintainability. The idea is to be able to retrieve only the relevant equipment in a separate operation, without removing the entire system. This provides versatility, in which maintenance and repair can be performed throughout the entire life cycle. There are several variables involved for achieving easy installation and retrieval. Installation vessels, operational planning, module design and module architecture are some of them. To keep the installation and intervention costs as low as possible throughout the life cycle, the time it takes to install and retrieve a module is a relevant factor during the design phase. Further in this section, some important factors to take into account in the module design regarding installation and IMR, will be presented.

3.3.1 Strategical Placement of Modules

In general, the components that have the highest probability of failure are placed in such a way that they are easy to access, easy to retrieve and, and easy to install. Some examples of typical "vulnerable" components are pumps, compressors, chokes, SCM, and multiphase meters. Modularization of subsea equipment must be balanced in a optimal way to facilitate for easy IMR operations. These components are likely to require frequent intervention, thus, they should be placed in a strategical position to ensure an efficient change-out operation [49].

Providing easy access to components, is an important part to achieve a module configuration that facilitates for easy IMR. This can include factors like sufficient space between components, so that the ROV and crane can reach the relevant equipment. Preferably, the need for ROV intervention should be kept at a minimal level. However, when the need arises and ROV assistance is necessary, the design must facilitate for this. Placement of modules must be clearly arranged and with clearances so that the ROV mounted tools can reach the desired point. Interfaces on the modules should be standardized for common ROV tooling. Choke and valve operations that is not hydraulic, or operated electrically must be in reach for an ROV. Further the structures must be designed for easy inspection and monitoring. However, there are some important consequences to take into account. Increased space between the components might result in an increase in the module size, and weight for the system.

To put this into perspective, a simplified subsea structure with one, two, and three process trains is illustrated. The presented figures below are meant to show the exterior of the system and not the equipment inside. The main focus will be on the accessibility and installation capabilities of the different configurations.

One Process Train in One Base frame

The first and most simplistic setup has only one process train accommodated in the frame. Figure 3.3 illustrates a simple sketch of a base frame on the bottom with one additional frame on top that shall contain the process train. In this case, accessibility is high from all levels. Further, the total weight and foot print of the system will be relatively low. Hence, the installation of the structure will be fairly simple.

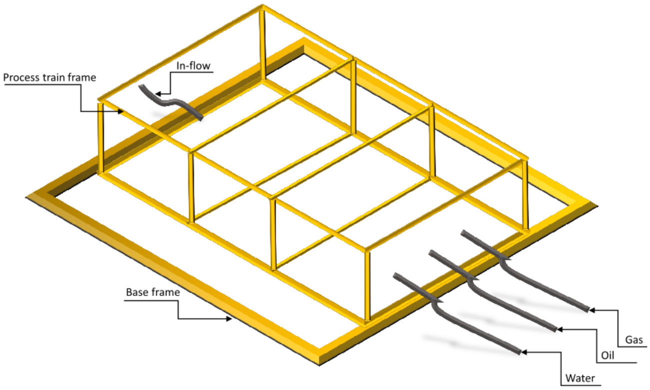


Figure 3.3: Base frame with one process train.

Two Process Trains in One Base frame

The second option is to have two process trains in parallel. Naturally, the weight of the system is increased. As shown on Figure 3.4, the affect of having two process trains in parallel, can affect the accessibility between the process trains.

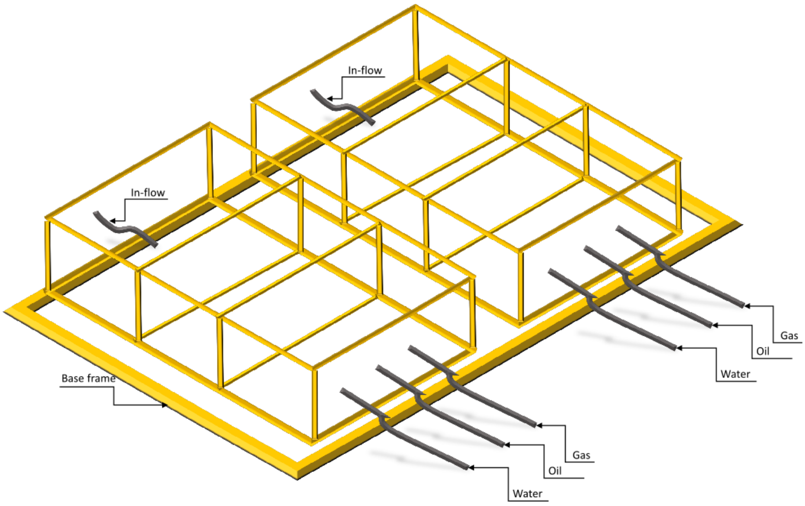


Figure 3.4: Base frame with two process trains.

Three Process Trains in One Base frame

Finally, the third option suggests to have three process trains placed in parallel on the frame. The weight is further increased compared to the other suggestions. As seen on Figure 3.5, the accessibility for the two process trains in the outer edge is the same as the former option, while the middle train can only be accessed from above, or from the two shortest sides.

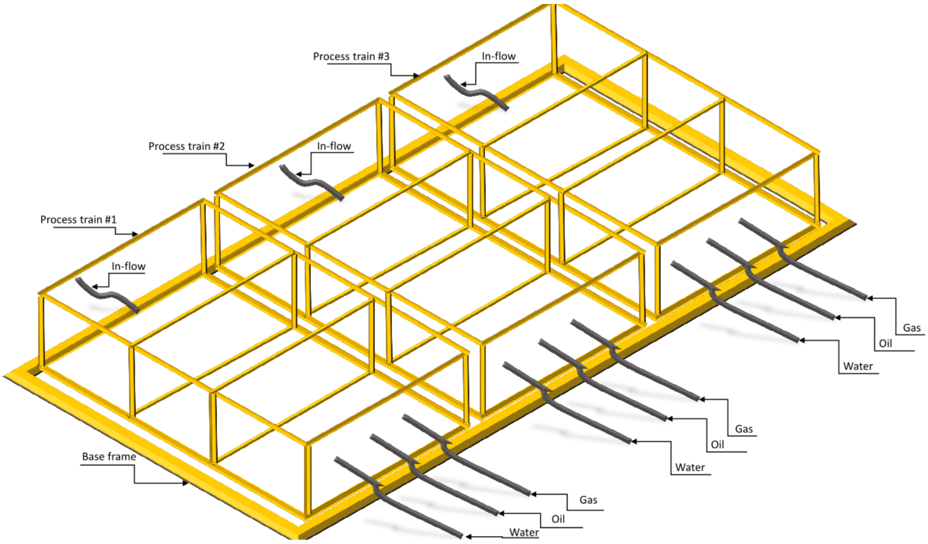


Figure 3.5: Base frame with three process trains.

3.3.2 Size and Weight

Size and weight of the functional modules depends on the contained equipment. For instance, a separator module and a manifold module is usually quite large. Thereby, they are more challenging to handle, and require a vessel with larger lifting capacity. As pointed out earlier, this can become costly. However, it is important to mention that their failure rate is low compared to more vulnerable equipment, and retrieval are thereby rarely necessary.

The functional modules in a subsea system has varying size and weight. This variation results in different demands for choosing an appropriate lifting vessels. As explained in Section 2.6.1, operators desires to use small intervention vessels to reduce costs. With this in mind, size and weight of the modules should be kept as low as possible to assure a compact solution that can be installed and retrieved with a light intervention vessel.

However, if the size is reduced, the amount of equipment that can be placed within them decreases. Further, the number of separate module-frames increases to be able to accommodate all necessary equipment, which also affects the number of connectors required in the system. An additional consequence may result in less accessibility, and performing IMR may become more challenging.

It is apparent that there are some challenges and trade-offs involved in choosing the best configuration. This will be further elaborated in Section 3.3.5.

3.3.3 Intermodular Connections

Between modules in a subsea processing system, supply of either hydraulic, electrical power, control signals, production flow, or all of the above, are required. These sources rely on intermodular connectors to achieve their intended function. These connections are crucial to functionality of the system. A failure in any of them, may lead to reduced production or even shutdown. Further in this section, two different intermodular connection approaches will be explained.

Connector system

Connector systems that are used between the modules, varies depending on the supplier and the equipment that is to be connected. Every supplier have to some degree their own connector design that differs from other competitors. To generalize, subsea connectors for tie-in of production fluids, as described in Section 2.2.2, usually include a clamp- or collet system. Both solutions can be used for either a horizontal or a vertical configuration. Figure 3.6 shows a simple sketch of a subsea processing facility, with production piping routed though the base structure, also called flow base. Connections between the modules are made through vertical connectors mounted on the top of the base structure, while the piping that is to be routed to the next module, are fitted with a mating hub at the bottom of the module-frame. During installation, modules are guided down towards the connector hub on the production base, and then onto a soft-landing mechanism, as described in Section 2.2.1. At this point, the connector hubs are aligned, and an ROV can operate the connection mechanism from a panel located somewhere with easy access.

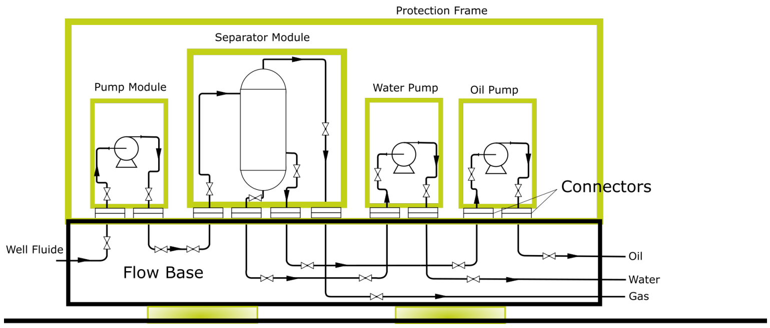


Figure 3.6: Processing system with vertical connectors in the flow base.

Figure 3.7 shows the module setup of Pazflor subsea separation station, which consists of a separator module on the right, two pump modules to the left, and a manifold between the separator and pumps. Additionally, the production fluids goes through an inlet module as seen in the front on the figure. In this setup, there is no flow base as in the former example. All the modules are placed on an intermediate frame, which again is placed on the foundation base structure. The manifold is integrated into the intermediate frame, and cannot be retrieved separately. Installation of the system was divided into four operations. First, the foundation base structure, then intermediate frame with manifold, then separator, and finally the pump modules. Connection system for the intermodular connections, is a horizontal configuration. Tie-in of the connectors on the separator module, pumps, and inlet module was performed accordingly [50]:

- After landing the separator module on to the intermediate frame, tie-in to the manifold was achieved by sliding the separator module on low friction pads 800 millimeters towards the connector hubs on the manifold. Connector interface between the separator and manifold, includes three connector hubs being mated together. The separator module has a submerged weight of 283 metric tons, and was pushed by high pressure cylinders operated by an ROV. Duration of the operation was 1.28 days.

- The tie-in of pump modules was performed in the same way as the separator module. In this case, there where two sets of connector hubs, both inboard and outboard for each pump, with one monobore and one multibore hub. The tie-in of one module was 0.6 days.

- Tie-in of the inlet manifold to the separator module was achieved by skiding it 600 millimeters towards the connector hubs on the separator module. Then a connector actuator tool is lowered down to make the connections. Duration of the tie-in was 0.9 days.

Figure 3.7: Pazflor subsea separation system [51].

Connector systems that connects piping for production fluids between the modules are more or less the same as the ones used for tie-ins described in Section 2.2.1. It can be some differences regarding the procedure connector hubs are joined together, and from where actuation of the locking mechanism is controlled. In some cases, there are not enough space between the modules to allow an actuator tool to reach the connectors. This results in the need for alternative mating methods, where actuation must be performed away from the connector assembly. This is usually done as explained in the first example, where the connector is operated from a panel located away from the assembly. This panel allows an ROV to apply hydraulic power to the latching mechanism, for instance, a clamp or collet mechanism.

Multibore Connectors for Intermodular Connections

A problem regarding connectors between pipes or cables, is that the overall pipe integrity is decreased around the connection points. A leakage is in general more likely to occur at a connection than other parts of the pipe or cable. With this in mind, a reduction of connections can affect the availability of the system. Therefore, it will be beneficial to keep the number as low as possible. An additional factor is the time consumption of installing and operate connectors. A reduction of these operations can contribute to reduce the overall time it takes to retrieve, and install modules. As a result, the operational costs can be reduced in the long run.

As described in Section 2.2.3, the electrical and control supply are transported through umbilicals from topside, to a distribution system which is either integrated, or placed along side the subsea structure. From here, the electrical and hydraulic control usually are distributed to the equipment with flying leads. The connection interface of these connectors are often a multibore configuration, as shown on Figure 2.15. In a subsea processing facility that consists of several retrievable modules, in which all need some kind of control and power supply, the number of connection points in the system gets quite high. Although multibore flying leads can reduce this number, an IPB, as described in Section 2.2.3, can potentially decreases the overall number even more.

Tolerance management

As described above, the different modules are connected with intermodular connectors. The location in which they are placed on the module interface, depends on several factors. Figure 3.8 illustrates a module with a vertical vessel that is to be placed on a base frame. Deformation in the frame either caused by the weight of the module, or a weaknesses in fabrication, can result in deviations on the connection interfaces between the modules. As illustrated on the right part of the figure, the deviation (Dx) increases by the position in which the connector is placed along the y-axis and the angle ($\alpha°$) along the x-axis. In the case of tall modules, for instance a vertical separator module, these deviations is sensitive to small deformations at the bottom. This can influence alignment of the connectors from the adjacent modules. A result may be that the two hubs deviates in such way that the connection can not be completed. Another case may be that the misalignment is within the limits for the connection to be made, but that the stress applied on the pipes because of it, could be too high. This problem, as described above, was a challenge faced in the design of the Åsgard Subsea Compression Station. Especially regarding the tall modules, such as the scrubber. The large amount of retrievable modules, where each have several dimensions that was critical to ensure good interchangeability in the system, resulted in both a theoretically challenging and time consuming task [52]. As one can see, the tolerances required in a modular interchangeable system is quite high, and a thoroughly study on this issue may be an important factor to consider when designing the modules and the interfaces.

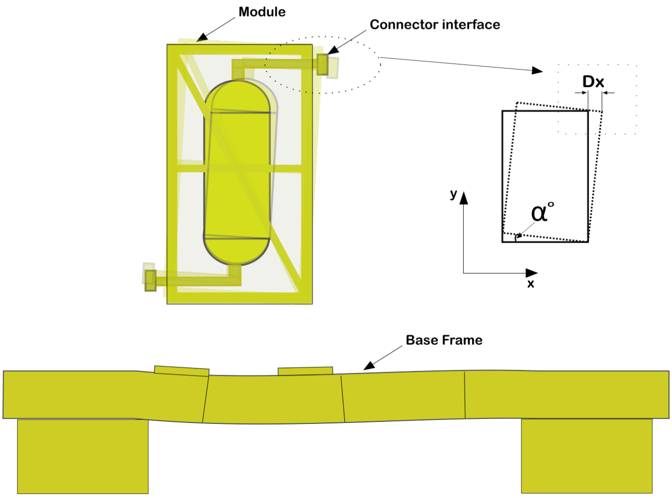


Figure 3.8: Alignment deviations on modular connector interfaces.

3.3.4 Standardized Interfaces

For subsea production and processing facilities that are based on a modular design, standardization of modular interfaces can contribute to ensure the availability of spare parts in the future, as the operator is not dependent on one supplier throughout the life cycle of the system. An additional advantage, is that the duration for engineering and manufacturing of equipment, is reduced due to standardization. The equipment can thereby be delivered faster and with lower costs.

However, it is important to acknowledge that standardization not just involves modular interfaces and material specifications, but also the process in which the projects are delivered and handed over to the operator. Another important thing to address, is that standardization should not come in the way of further innovation. After all, the main goal is to remove operations that does not contribute to either quality or functionality. An example of this is the lack of standardization for supplying of materials. As a result, the equipment suppliers are more hesitant to order materials, due to own risk and cost prior to have a contract with the costumer ready. This can typically add 7-12 months delivery time for forgings [49].

A Joint Industry Project (JIP) was started by DNV GL together with the industry partners FMC, OneSubsea, Petrobras, Shell, Statoil, and Woodside, to standardize subsea pumping. The objective of the JIP, is to "*reduce costs in a lifetime perspective by giving a guideline for subsea processing modules and interfaces that are efficient, reliable and within limits for effective installation and retrieval*" [49]. A higher degree of standardization benefits both the oil companies and the suppliers. Table 3.6 presents some of the benefits.

Table 3.6: Advantages of standardization for oil companies and the suppliers [49].

Oil Companies	Suppliers
Reduction in costs.	Increased volumes.
Less uncertainty for production start up.	Predictable requirements from operators.
Short delivery time.	Shorter project execution time.
Less uncertainty in cost estimation.	Less uncertainty in cost estimation.
Increased production (higher reliability).	Reduced documentation requirements.
More flexible in contract stages.	Optimization of testing.
Improved quality.	Improved quality.
Reuse of qualification.	Reuse of qualification.

During times with low oil prices, the desire for standardization in the industry increases, due to higher necessity to reduce costs and increase efficiency. To achieve the goal of an industry standard for modules and interfaces, the competing companies must to some extent be willing to share knowledge with each other, so that the best solutions can emerge. There are some conceptual projects going on within the industry that are based on the standardized interface approach. Below, two such examples are presented.

Statoil's Standardization Program

Statoils next-generation Cap-X subsea production technology, claims to be cheaper both to produce and install than other existing systems. The concept builds on putting already proven technology together in new ways. The most notable impact is that the footprints are reduced by around 75%. The footprints of today's templates are in many cases greater than 20 x 20 meters, while the Cap-X concept will have an average of 10 x 10 meters. The significant reduction in size helps to enable more of the operations to be performed by light weight IMR-vessels, instead of special installation vessels.

The concept is also suggested to improve the profitability, by standardizing all subsea structures. According to Statoil, this concept will reduce the time spent on IMR-operation due to the light weight, reduced sizes, and standardized building blocks. Further, the ability to drill single wells enables for higher flexibility in terms of positioning for optimal reservoir drainage.

Statoil claims that by enabling "plug-and-play" solutions for the subsea production equipment, the overall cots may be reduced up to 30% compared to traditional subsea installations [53].

The key features of the Cap-X concept is summarized below [54]:

- Standardized foundation and protection.

- Standardized equipment envelopes.
- Snag free design.
- Full access when the hatches are open.
- Small design enables optimal placement relative to the reservoir.
- Flexibility to change and reuse equipment.
- Improved IMR-operations.

The improvement of IMR-operations are of special interest for this thesis. The reduced sizes enable for smaller IMR vessels to perform operations in harsher weather. Further this leads to an reduced mobilization and transit time. The standardized design will also enable for the usage of one standardized module handeling system.

Open Source Architecture Development

A project started by Sonsub (Saipem brand name) involves developing a "open source architecture" Subsea Factory with standard building blocks and standardized interfaces [5]. A part of this project is integrating a system that is independent of any proprietary equipment and exclusive interfaces, called SUBSEA BUS. This system is a module based structure that makes it possible to use the same building blocks in different subsea architectures. It contains the distribution system for process, chemicals, service fluids and control. In addition, manifold functions with inlet and outlet facilities are integrated. The SUBSEA BUS system contributes to a reduction of modular interfaces and consequently number of flow-line connections. Figure 3.9 shows the SUBSEA BUS concept applied in the seawater treatment plant called SPRINGS developed by Saipem. In this case the SUBSEA BUS is placed in the middle, while the other equipment modules are placed and connected alongside.

The key driver of the Subsea Factory is creating a system based on changeability, robustness, and sustainability [5]. Changeability implies the possibility of expansion or reconfiguration in situations where the performance requirements change over time. This is mainly obtained by modularization of the different components involved in the processing facility. Robustness involves building the system so that it can maintain the production up time. This is achieved by applying high redundancy to the system and make sure that IMR operations easily can be performed on the installed equipment. Sustainability implies that it should be possible to keep the life cycle cost low by allowing future development through standardization of the modular interfaces.

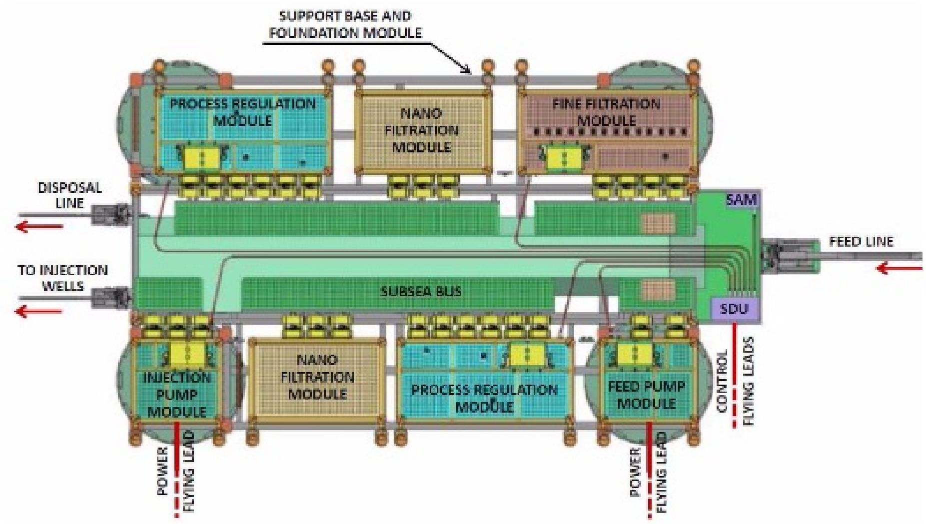


Figure 3.9: SUBSEA BUS system implemented in SPRINGS subsea station [5].

3.3.5 Modularization Challenges

Besides all the positive features that a modular design presents, there are some aspects to take into consideration. In addition to an increase in the equipment maintainability, modularization also increases the complexity, weight and building cost. Due to the option to remove the equipment, the amount of flow-, electrical- and hydraulic connections increases. This results in a higher possibility of leakage and electrical failure, and will affect the overall availability of the system.

Future subsea developments will probably contain an even larger number of components, with more advanced technology than today, and a modular approach to the design will be inevitable to ensure a long operational life. The modularization concept always involves a carefully considered trade-off between reliability and maintainability. This of course depends on several factors, where the operator and the supplier must decide which of the components that should be included in each module.

Chapter Summary

The main subjects in this chapter includes:

- Factors that can minimize the the need for intervention.
- Costs related to installation and maintenance operations.
- Important factors to consider in the module design of a subsea production and processing system.

The upcoming chapter will contain suggestions for solutions, and point out important factors that should be considered for the Subsea Gate Box concept.

Chapter 4

Design Study of the Subsea Gate Box

This chapter addresses important factors regarding structural and functional requirements for the Subsea Gate Box concept. The factors presented are supposed to contribute to efficient installation and IMR operations, as well as providing a versatile system, that allows further enhancement and replacement of equipment throughout the life cycle of the field. There are several factors that play a role to achieve this. Two cases with different system architecture, and connection systems, will be presented later in this chapter. Regarding the functional requirements, factors that can affect time and cost of installation and IMR operations, will be highlighted. Suggestions for structural and architectural solutions will focus on the following parts:

- Module architecture
- Module interfaces
- Inter-modular connections
- Redundancy and rerouting options

All suggestions and recommendations presented are based on literature described in the previous chapters. This includes literature about fundamental principles for installation and IMR operations on subsea equipment, as well as information about structural solutions gathered from already existing subsea processing developments. Additionally, relevant factors from other concept developments will be considered.

4.1 The Subsea Gate Box Concept

As described in Section 1.1, some wells will produce more than others, although they produce from the same field. In a situation where the production from several wells, are commingled into a common manifold, a strong interdependence between flow rates and the production pressures from the different wells arises. Based on this, the Subsea Gate Box concept‘s objective, is to accommodate each well separately, which will remove the interdependence between wells and increase the productivity.

Figure 4.1 shows a simple overview of a conventional setup and the Subsea Gate box setup, for a subsea boosting configuration. The setup to the left is the conventional architecture, where all four wells are commingled into a manifold and then boosted. The right side of the figure, illustrates the Subsea Gate Box setup where each well is boosted separately before they are commingled into the manifold.

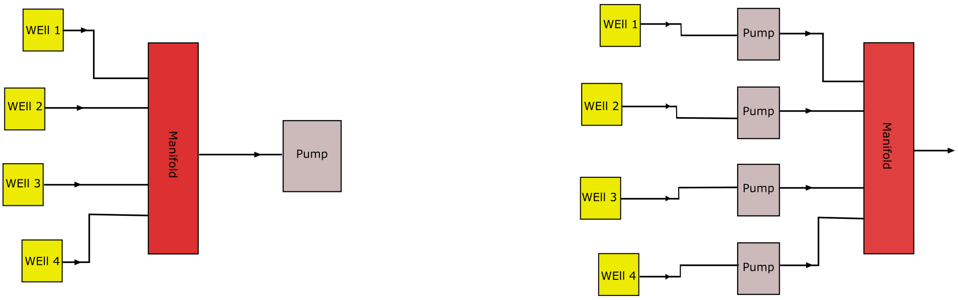


Figure 4.1: Conventional setup of a boosting station on the left, and the Subsea Gate Box setup on the right.

The Subsea Gate Box concept mainly focuses on developing a modular and multi-functional subsea assembly that shall prepare the production fluid for transport to further processing on a host facility, either on a platform or on the seabed. To achieve this, the structure should contain appropriate equipment to accommodate each well. Additionally, it shall be possible to change the components for facilitating for changes in well performance over time. The module assembly can either be designed as a single central template structure that receives production from several wells, or as individual structures that is located adjacent to the wellheads.

4.2 Structural and Functional Requirements

To obtain a system design that provides versatility, with focus on efficient installation and replacement of equipment and modules, important requirements should be examined and considered. This section will highlight some of the most important requirements, based on literature presented in the former chapters.

4.2.1 Standardized Module Interfaces

To ensure that installation and IMR operations for the functional modules in the Subsea Gate Box is as cost efficient as possible, the modular interfaces should be standardized. Ideally, subsea production and processing systems should contain as much standardized parts as possible, to reduce development costs and to obtain interchangeability. Unfortunately, this is not straight forward. No reservoirs are equal, hence different production and processing developments to some extent requires their own unique solution. However, the framework used for accommodating the equipment, such as retrievable modules and base structure, has potential to be further standardized. Considering retrievable modules, connector points in which the modules are interconnected, should be standardized both with regard to location in which they are placed, and the connector system used. This can contribute to increase the interchangeability of the equipment, where the production lines can be routed between modules at fixed locations. The idea is to increase the versatility of the system where one can change equipment inside the retrievable modules, and keep the same intermodular connection points. As a result, one can deploy the same modules from other Gate Box systems that are in stock, without any prior adjustments.

4.2.2 Accessibility and Retrievability

As described in Section 3.3.1, the most "vulnerable" equipment in a subsea production and processing system should be located at a place where it easily can be retrieved and accessed by an ROV. The Subsea Gate Box should have an architecture and module design that facilitates for space to perform inspection and maintenance.

Additionally, a high degree of retrievability should be implemented in the system. Thereby, separate retrieval of the functional modules must be possible. The connector system that is used for production and control lines should allow fast and simple deployment and retrieval of modules. Accessibility to the actuation mechanism should be sufficient so that an ROV can easily operate them. Additionally, the number of connectors should be kept as low as possible to reduce installation and retrieval time.

4.2.3 Redundancy

During maintenance or in a situation with equipment failure, the opportunity to bypass production fluid around equipment modules should be included in the design. Either to a redundant component, or through the entire processing train. This solution contributes to mitigate production shutdowns, and retrieval of functional modules can subsequently be performed while keeping the production capacity at an acceptable level.

In a system where the Gate Box consists of several process trains that serves their own wells, the possibility to reroute the production increases, as equipment from other trains can function as a redundant component.

4.2.4 Condition and Performance Monitoring

As explained in Section 3.1.2, condition and performance monitoring can contribute to a more stable operation, and earlier detection of system degradation. This gives a better decision making basis for planning and scheduling maintenance of equipment. Some kind of condition and performance monitoring should be considered in the Subsea Gate Box design. This feature is however not included in the illustrations for the cases presented later, but rater mentioned here as a general requirement that should be considered, as it can contribute to further optimize maintenance procedures.

4.2.5 Valve and Connector Actuation

Utilizing ROVs to perform actuation of valves, connectors, and similar, can be time consuming. To reduce reliance on ROV support, the actuation components should ideally not be too dependent on this. A step towards all-electric control system, that allows remote actuation, would be beneficial. As for condition monitoring, this feature is not included in the illustrations of the cases, but only mentioned here as a general requirement that should be considered for the Gate Box concept.

A hydraulic system for actuation of connectors is in this case required. This is partly because it is by far the most used solution within the industry and in relation to the literature review, information regarding electrically operated production connectors have not been investigated.

Subsea control systems are briefly described in Section 2.3. In general, this field is not covered in detail in this thesis, but as it can potentially contribute to increase the maintainability, it is mentioned.

4.2.6 Vessel Requirements

In terms of vessel requirements, the Gate Box should be designed to allow use of already existing vessels, for both installation and IMR operations. In other words, functional modules should be designed in a such way that they fit the given module handling systems provided by the contracted vessels. Operators of the various fields already have long term contracts with IMR-vessels for performing services. Previously in Section 3.2.1, examples of module change-outs on the Tordis SSBI are presented. These modules where changed by Normand Ocean and Seven Viking, which is similar light IMR-vessels contracted by Statoil.

With great flexibility and response time due to its high equipment specifications, these vessels meet most requirements for performing IMR-operations in today's market. State of the art features, such as large moonpool, dynamic positioning system, crane capacity with heave compensation, module handling systems and accommodation for work ROVs, are the key features of these vessels.

In special cases, such as the Åsgard Gas Compression project, the vessel North Sea Giant was modified with a unique special module handling system as described in Section 2.6.4, which is capable of installing large modules up to 420 metric tons. North Sea Giant is also on long term contract for serving Åsgard. In special cases, this vessel might be available for assistance.

4.3 Suggestions for Module Architectures and Interfaces

As stated in Chapter 3, modularization of the different process equipment basically makes it possible to change individual components and not the entire system. This is one of the fundamental features regarding maintainability and versatility in a subsea processing system. Further in this section, two different cases for module architecture and connection configuration, are presented. The suggestions are based on the requirements stated above.

4.3.1 Limitations

As stated in Section 1.3, this thesis does not include the processing itself, but mainly focuses on modular design and interfaces that contribute to efficient installation and IMR operations. As described, the components within the modules of the Subsea Gate Box, can be customized for a variety of reservoir conditions. The process and equipment that are integrated in the two cases, is consequently only an example to give a more holistic overview of the retrieval possibilities of modules, and at the same time keep the production going. In reality, the equipment could be entirely different. Processing equipment that will be included are presented under the next heading.

The illustrations provided in the two cases are just simplified sketches and does not contain all necessary equipment needed to operate the system. Structural dimensions will not be stated, as the solutions presented only are supposed to show the functional principles of the concept, and not a fully functional processing station. Electric and hydraulic lines are not included, but solutions regarding their connection to the modules in the processing trains, will be elaborated in Section 4.4. Valves that are integrated in the flow paths are not specified by type, as they are only added to show the routing options for the production flow, in case of retrieval of modules for maintenance. Control lines for actuation of the connectors, are not illustrated, and only explained in words.

Regarding process flow, for simplistic reasons the gas is assumed to flow freely to the host without need for compression. To further simplify, it is assumed that there is no sand in the production fluid. Therefore, equipment for sand handling is not included. Additionally, the process trains for the two cases presented later are only assumed to accommodate one well each.

4.3.2 General Process

Based on common components required in a subsea processing facility, the Subsea Gate Box contains following equipment:

- Choke valve
- Inlet booster
- Separator
- Flow metering
- Outlet booster

Figure 4.2 shows a simplified overview of the process with the different components. First, the well stream marked in black, which is oil, water and gas, enters a choke that controls the inflow. Then it enters an inlet booster pump that can handle multiphase flow. This pump is optional, as the system can function without it. In this case, it functions as a redundant pump, where the production can be bypassed to other equipment and transported directly to a host facility. This feature is not illustrated in this sketch, but is shown in detail for the different cases in Figure 4.4, Figure 4.9, and Figure 4.10. Further, the production fluid enters a separator that separates the three phases. After the separation, the oil (green), water (blue), and gas (red), enters the flow meters. The gas is assumed to flow freely to the host without the need for compression. The oil and water on the other hand, is boosted by one pump each.

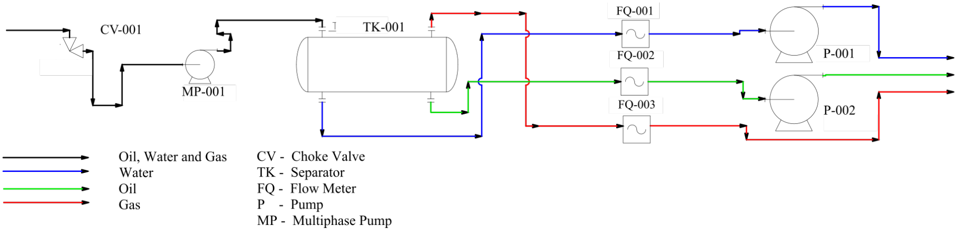


Figure 4.2: Subsea Gate Box process flow diagram.

4.3.3 Case 1

Figure 4.3 shows a simple overview of the setup that consists of a manifold and two process trains placed on each side. The two trains also contain the equipment modules, and all these components are again placed on a base frame. Equipment that is to be placed within the modules is not included in this figure, but rather given their appropriate name. According to the illustration, the functionality of the modules is only stated on train one, but it is assumed that both trains will contain the same equipment as described in Section 4.3.2.

For easy access, the clearance between the manifold and the process modules should be sufficient for an ROV to reach the connectors, and tools required to perform connection. This will also result in easier change-out of connector seals, as well as good inspection conditions within the structure.

The manifold placed between the two trains, contain connection points, in which all functional modules are connected. The connectors are based on a horizontal configuration that extends out from the side of the modules, with either a collet or clamp mechanism. This connector system would require a stroking mechanism as described in Section 2.2.1. This mechanism can extend and retract one of the connector hubs. Hence, installation and retrieval of the modules can be performed separately. The hubs containing stroking- and locking mechanism should be mounted on the retrievable modules in the process trains. This is to allow easier maintenance on connectors, as it would be easier to retrieve these modules compared to the manifold. Location of the connectors on the module interface will be, as stated in the structural requirements Section 4.2, standardized to increase the versatility, and decrease the development costs.

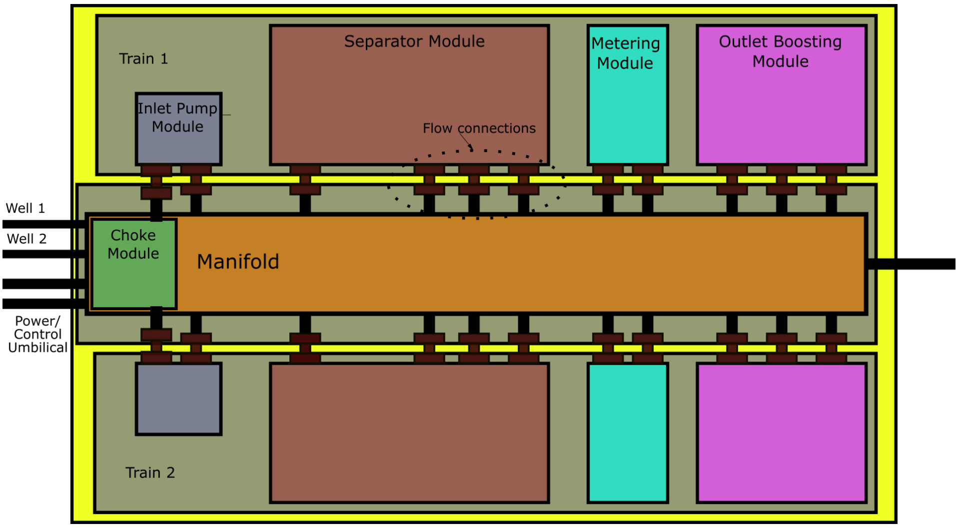


Figure 4.3: Module overview with horizontal connectors to manifold.

As shown on in Figure 4.3, the choke module is placed within the manifold. This is because the choke is relatively small compared to other modules, and it will not require its own slot in the production train. Additionally, the choke is in the first stage where the flow enters the system, so that the flow rate can be controlled before it reaches the processing facility.

Process

Figure 4.4 shows a process flow diagram for the architecture described in Figure 4.3, with equipment and flow paths for both process trains.

Distribution of fluids from the wells to the functional modules in the process trains, is provided by the manifold. In Figure 4.5, the manifold frame with fluid lines is shown in more detail. In this case, as illustrated in Figure 4.4, the manifold consists of four distribution lines, **Distribution Line 1** (black), containing all three phases, **Distribution Line 2** (green), containing oil, **Distribution Line 3** (blue), containing water, and **Distribution Line 4** (red), containing gas. Each of these distribution lines presents the opportunity to route the flow to the functional modules, in their associated process train, separately. Additionally, to add redundancy to the system, the fluids can also be rerouted between functional modules in the two trains, as well as go past modules within the individual trains. These bypass options are on Figure 4.4 labeled with two numbers that categorizes which distribution line it belongs to, and which rerouting option it is. The first bypass option for distribution line 1 is (1.1), the second (1.2), etc. For distribution line 2, the first bypass option will be (2.1), the second (2.2), and so forth. The labels are also given their appropriate color according to the fluid phase.

The first option to redirect the flow from the wells, will be before the chokes in distribution line 1, through bypass (1.1). By closing the valve before one of the chokes, and opening the valve on the bypass line, the flow can be combined with the fluid from the other process train. This makes it possible to perform maintenance on modules in one train and redirect the flow to the other. Further, the unseparated well stream in distribution line 1, from either both, or only one well, can bypass the multiphase pumps (MP-001) and (MP-002) through line (1.2) and (1.3). After the chokes and the multiphase pumps, the flow from the two wells have the option to be routed into their corresponding separators, or rerouted to the separator on the other train through (1.4). Additionally, the unseparated fluid can bypass both the separator modules (TK-001) and (TK-002) by entering the Distribution Line 2 through (1.5). Here, it can either be distributed into the metering modules and the outlet booster modules, or pass all the modules. In the latter case, the multiphase pumps can function as a redundant pump and boost the production up to the host facility for further processing.

When the production from well 1 and well 2 are directed into their corresponding separators in distribution line 1, the separated fluids oil, water and gas then enters the side of the distribution lines that is associated with their process train. The water that are separated out in (TK-001), enters distribution line 3, and can be rerouted to the other train through

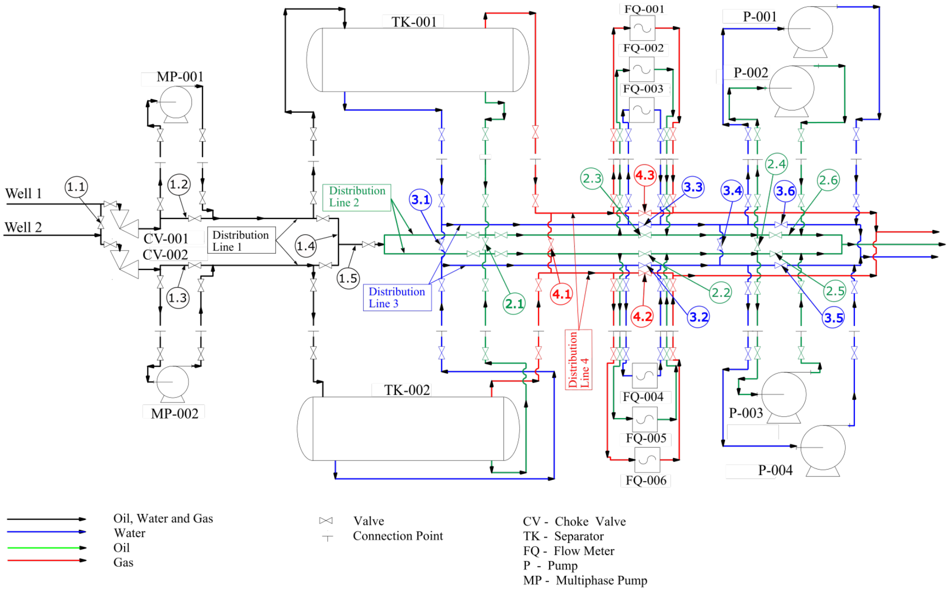


Figure 4.4: Overview of process with the rerouting options.

either (3.1) or (3.4). This depends on which module in the process train one desires to bypass. To bypass the metering module containing flow meter (FQ-001), (FQ-002) and (FQ-003), and/or the outlet booster module containing pump (P-001) and (P-002), line (3.1) will be used. If only the outlet booster module is bypassed, line (3.4) shall be used. To direct the water past the modules in the upper train on the figure, without rerouting it to the other process train, line (3.3) and (3.6) can be applied. For the train at the bottom, bypassing the modules are achieved through line (3.2) and (3.5).

The same goes for the oil and gas. After the oil has been separated, it enters distribution line 2 and can be rerouted to the other train through (2.1) and (2.4). Bypassing the functional modules in the processing train can be achieved through (2.3) and (2.6) for the upper, and (2.2) and (2.5) for the lower. After separation of the gas, it enters distribution line 4, and can only be guided to the other train through line (4.1). As the gas is assumed to flow freely up to the host facility, it skips the boosting stage. This means that the rerouting line (4.1), just exists to redirect the flow between the metering modules in the two process trains. Line (4.3) and (4.2) enables the opportunity to bypass the metering modules on either one of the trains, or both.

Architecture and Process Overview

Figure 4.5 illustrates the same module architecture in Figure 4.3, but in addition, here the equipment described is placed inside the modules to get a more overall impression of the solution.

Connectors to the metering module and the inlet connectors for the outlet booster modules on Figure 4.5 seems to contain several flow lines, both oil, water and gas. These lines are not supposed to be connected within one connector as a multibore connector, but intended to be routed through separate connectors that are placed above each other. As the illustration is an overview, these connectors will not be visible on the figure.

All modules in the process trains are separately retrievable, and as described under the former heading, the opportunity to maintain production by rerouting the flow are integrated in the system. The metering module, as seen on the illustration contains flow meters for all the three fluid phases. These components together with the outlet booster pumps and chokes, are on train one marked with dotted squares. This is to symbolize that they can be retrieved separately, and retrieved in one operation together with the module frames. The extra flow line connectors and valves that are required for this setup, are for simplistic reasons omitted in this figure.

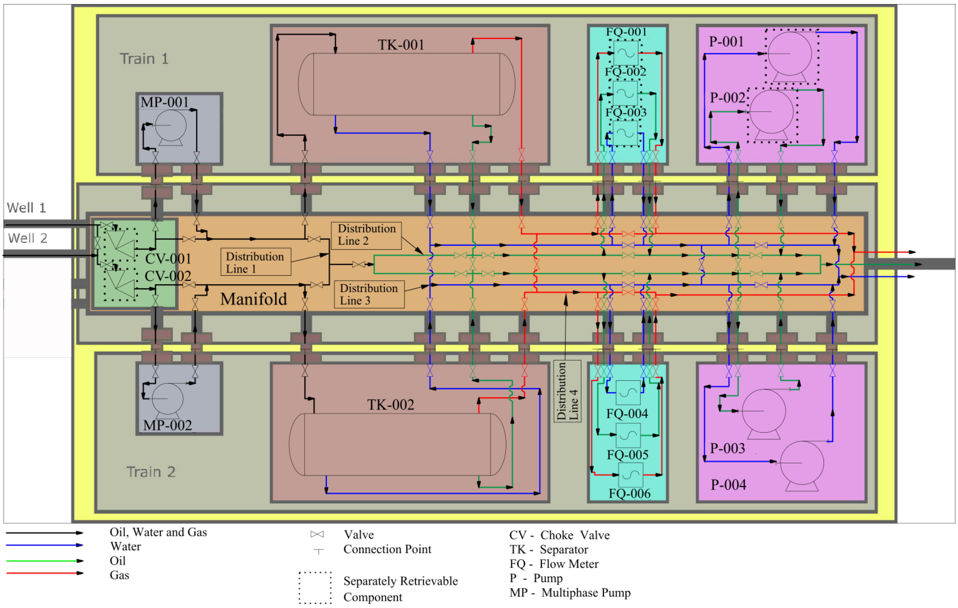


Figure 4.5: Overview of process and architecture.

4.3.4 Case 2

Figure 4.6 shows a simplified overview of the process trains and the module architecture of the setup. In this case there are three trains, each serving one well. The functional equipment modules are the same as in Case 1, but there is no manifold fitted between them, and the choke is thereby included into the process trains. A manifold is included in the system, but it is placed in the base frame below the process trains. As Case 1, electrical and hydraulic lines will not be included in the illustrations.

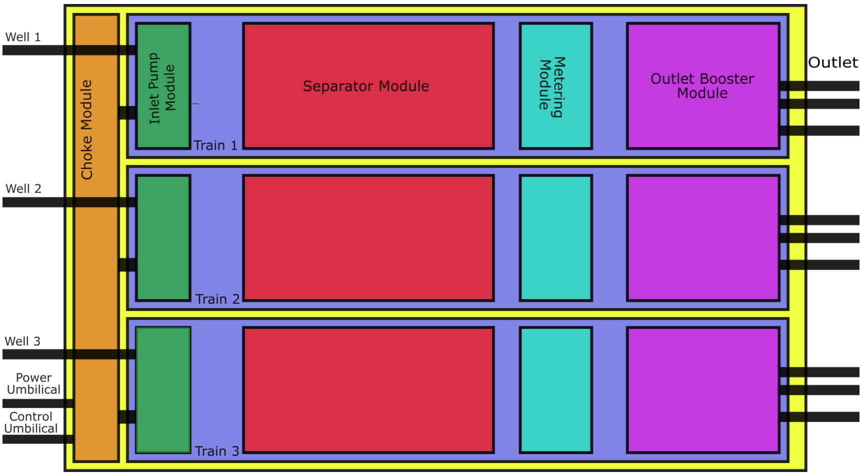


Figure 4.6: Simple overview of the module architecture with tree process trains.

Figure 4.7 shows the setup from the side. As seen from the illustration, all functional modules are placed on a base frame that contains a manifold function, which on the figure is referred to as a production base. Flow paths between modules within the system will be explained and illustrated later.

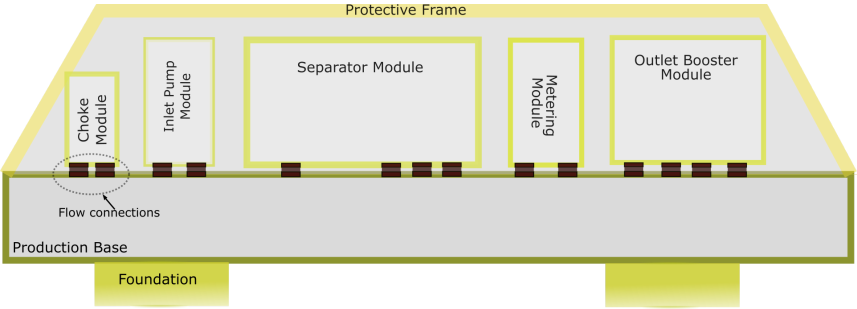


Figure 4.7: Side view of one process train with vertical connectors.

Connection between the modules is achieved by vertical connectors with a collet mechanism. The connector hubs are mounted on the bottom of the module frames. During landing of equipment to the production base, the modules are guided into position and landed on the connector hubs. A vertical connection assembly, as illustrated on Figure 2.5a has a built-in funnel on the female hub, which can do the last small alignments when it lands on the upward facing hubs on the production base.

Considering accessibility, access to connector hubs for this setup will not be sufficient for an ROV to directly control the fastening mechanism on the assembly. This function, as described in Section 3.3.3 would require a control panel located away from the connectors. From here, a ROV can control the latching mechanisms for the connectors through integrated hydraulic supply lines in the production base. As a result, it will be possible to disconnect the different modules separately. On the other hand, the production base containing the distribution lines, cannot be retrieved in a separate operation. To gain access, it would require pulling all modules from the process trains first. In this case, connector hubs that contains the hydraulic fastening mechanism, should probably be installed on the production base, and not on the modules. This is because the hydraulic supply is provided from here, and it would be an better solution. Otherwise some kind of separate hydraulic connections would be required. As in Case 1, connector interfaces will be standardized.

The access to the equipment within the models, will mainly be from the top. On Figure 4.7, a protective frame is fitted over the equipment to protect against dropped objects and trawl. This frame will have hatches that opens, so that IMR can be performed inside the structure. Additionally, it will be possible to access the equipment from the sides.

Process

Figure 4.8 shows a side view of the flow distribution between the modules in one process train. However, it would be the same setup for the other trains. Flow lines below the connection points on the figure, are part of the production base, while lines and equipment showed above, are part of the modules. This is more clearly illustrated on Figure 4.10. Regarding distribution of fluids from the wells to the equipment modules, this function is achieved through the production base. Figure 4.8 illustrates bypass opportunities within the process trains. Rerouting options between the trains, will be explained on Figure 4.9 later.

As shown on Figure 4.8, distribution lines are split up in the same way as in Case 1, according to the fluid phases. During normal operation the well stream will be guided through all the equipment modules. However, in case of maintenance, it can be rerouted. When flow from the wells enters the production base, it can either be guided up to the choke module, through vertical connectors, or guided into bypass line (1.1). Further, the fluid can enter the multiphase pump (MP-001), and go past the separator through bypass line (1.3), and into distribution line 2. Here it can either enter the equipment modules, or bypass all of them.

In a situation where the well stream has been separated in separator (TK-001), water, oil, and gas, enters their associated distribution line in the production base. Here they can be distributed to the module, or bypass them. The water can bypass the metering module through line (3.1), and the pump module through (3.2), oil through line (2.1) and (2.2), and gas through (4.1).

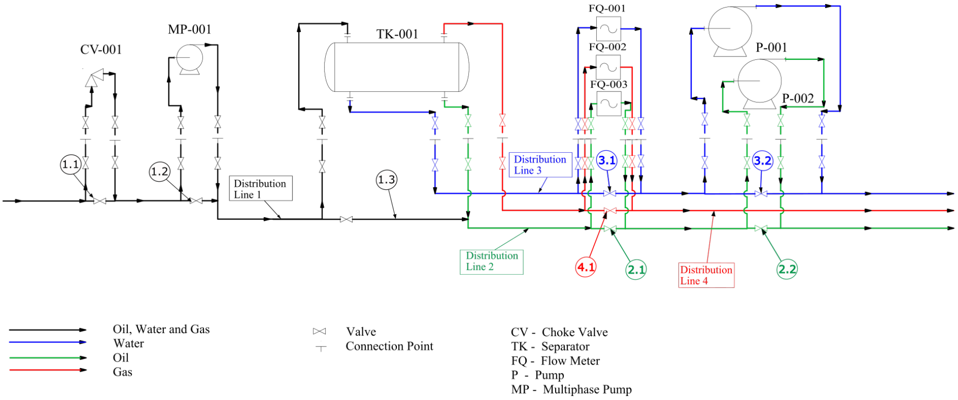


Figure 4.8: Side view of the flow distribution between the modules.

Unlike the illustration above, which only illustrated rerouting options within the separate trains, Figure 4.9 shows an overview of the process with all the processing trains and rerouting options between them. Bypass lines internally in the trains will not be part of this figure, as it would make the illustration cluttered and confusing. This feature is only illustrated in Figure 4.8.

The unseparated well stream, that enters the three trains through well 1, well 2, and well 3 in Figure 4.9, can be rerouted to the other trains through line (1.4) and (1.5). In this case, during maintenance on one of them, the two others can share the production from all the wells. After the choke, the flow can be guided to the other trains through (1.6) and (1.7). After the multiphase pumps, the flow can go through (1.8) and (1.9).

After the separator, water can be routed through line (3.3) and (3.4), and through (3.5) and (3.6) after the flow meters. The same applies for oil, which can be guided through (2.3) and (2.4), in addition to (2.5) and (2.6). Gas on the other hand can only be rerouted after the separator, through (4.2) and (4.3), as it is assumed that gas will not require any compression.

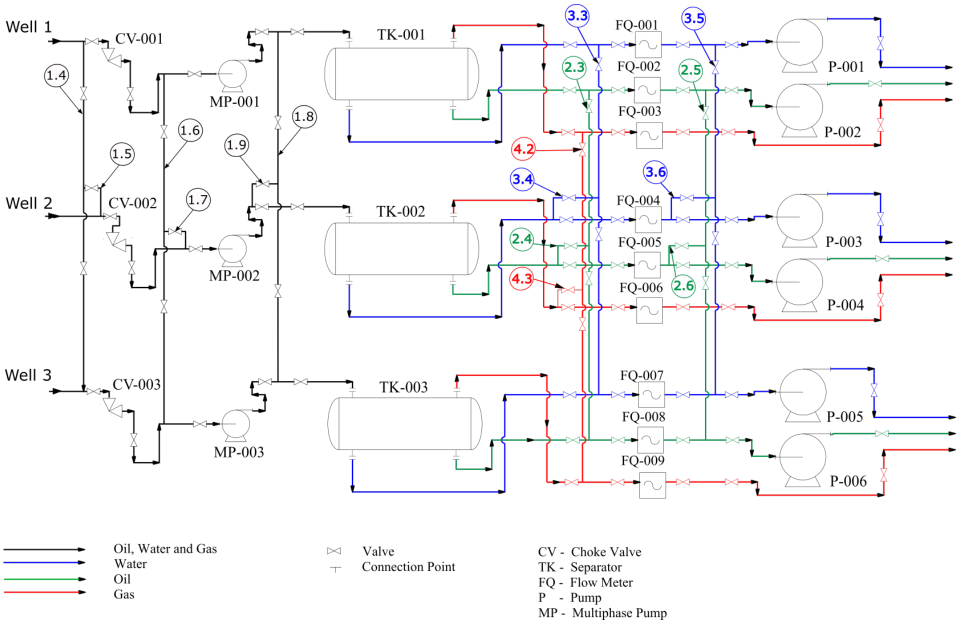


Figure 4.9: Overview of the process with rerouting possibilities between the trains.

On Figure 4.9, it is illustrated that the three phases oil, water, and gas from three process trains have separate outlets. Water-, oil- and gas production from these trains can be commingled into one line, but with regard to simplicity, this option is not included.

Architecture and Process Overview

Figure 4.10 and 4.11 shows the process drawings described earlier placed within the module frames. As in Case 1, Figure 4.10 only illustrates two connectors on the metering module. Since the system is shown from the side, only the foremost connectors are visible. Hence, production lines for oil, water, and gas appears to go through the same connectors. In reality these lines will have their own connectors placed behind each other.

On Figure 4.11, an overview of the process trains is presented. Flow lines, which on the figure appears to be routed between the modules, are originally installed in the production base and would not be visible. However, to show an overall view of the process, it is included. Additionally, connectors between modules are not illustrated in this figure, and although the pumps in the outlet booster modules are placed in the same module as in Case 1, they can be retrieved separately. The same applies for the chokes.

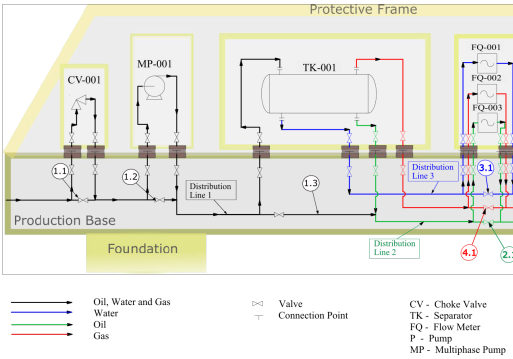


Figure 4.10: Side view of modules with process.

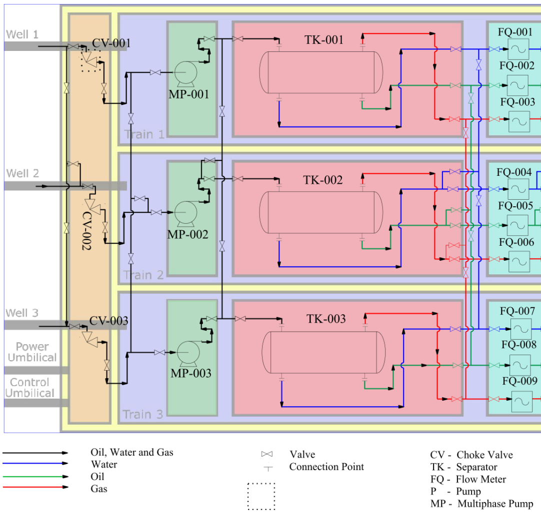


Figure 4.11: Process overview with module architecture.

4.4 Multibore Connection Approach

The illustrations presented in Case 1 and 2, only illustrated connectors and lines for production flow. When electric and control lines are included in the system, number of connection points increases significantly. Further, connection options for electrical and hydraulic supply will be presented with illustrations for both Case 1 and 2. The figures are highly simplified, and does not include all necessary control lines to operate the system. The only purpose is to show the general principle behind the connection solution.

Figure 4.12 shows an overview of the setup in Case 1 with separate inlets for electrical and control signals on one module. All the equipment modules in the system requires some kind of power supply, but to simplify, it is only included on the separator modules. In this case, control supply is integrated in the manifold where it is distributed to the modules, through several connectors supplying control and electric power. These connectors can either be mounted on the modules as the flow connectors, or connected by a ROV through the use of flying leads, as described in Section 2.2.3.

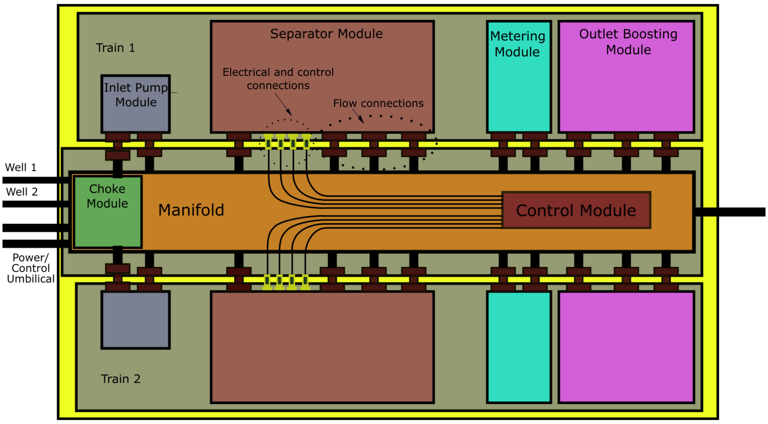


Figure 4.12: Module overview with separate power and control connections.

Figure 4.13 shows the same setup as before, but only with electric and control signals routed through the horizontal connectors for production fluids. By integrating all these lines into one or more flow connectors as explained in Section 3.3.3, the number of connectors in the system can be reduced. The same is illustrated with the setup presented in case 2 on Figure 4.14, except that in that case, the control module is placed in the production base.

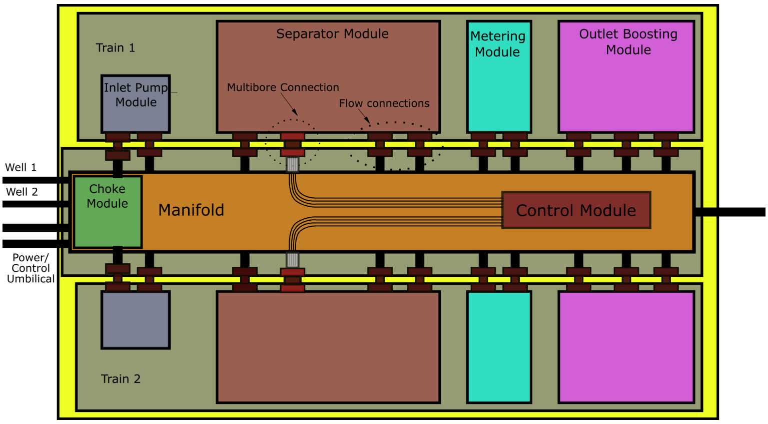


Figure 4.13: Overview of module architecture with horizontal connectors, where power, control and production are fed through multibore connectors.

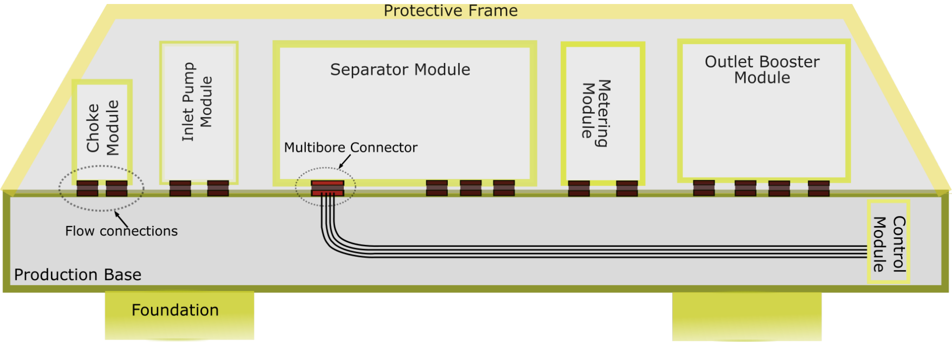


Figure 4.14: Process train seen from the side, with vertical multibore connector for power, control and production.

Chapter Summary

The main elements presented in this chapter, included:

- The Subsea Gate Box concept.
- Structural and functional requirements.
- Suggestions for module architecture and interfaces.
- Multibore connection approach.

This chapter forms the basis for the discussion presented in the next chapter.

Chapter 5

Discussion

This chapter, compares the two presented cases against each other, to determine how well they fit the requirements stated in Section 4.2. The purpose is to highlight advantages and drawbacks with both solutions, and thereby be able to point out the most advantageous setup.

5.1 General Requirements

In Section 4.2, some requirements for the Gate Box concept were stated. However, not all of them are illustrated and explained in the two cases. Rather they are listed as general requirements that should be considered in the development of the Subsea Gate Box concept. Some of them will be discussed in the following section.

5.1.1 Standardization

As one for the goals for the Subsea Gate Box is to accommodate several well configurations, a degree of versatility in the system architecture should be allowed. However, as explained in Section 3.3.4, some standardization of the functional building blocks will be beneficial in terms of future operations and development costs. Equipment placed within the modules may vary depending on the requirement from the wells. Additionally, the requirements stated in Section 4.2, point out that module interfaces are to be standardized in terms of connector system and their location on the modules. This feature is supposed to ensure the versatility and interchangeability of the system, where the same structural module frames can be used, to accommodate tailor made equipment in the frame. Standardized modules enable interchangeability across various Gate Box systems. However, an important factor to have in mind, is that standardization should not come in the way of further enhancements, and not compromise either quality or functionality of the system. After all, the goal is to obtain these features.

5.1.2 System Size

In Section 3.3.2, it is stated that size an weight of modules should be kept as low as possible. As indicated in the figures of the presented cases, the systems might be extensive. For instance, the Tordis separator presented in Section 3.2.1, is 17 meters long, and have a diameter of 2.1 meters. Such dimensions, and weight may be a limiting factor for realizing the system. Thereby, the applicability of compact solutions, for instance, separation, should be examined to decrease the overall system size.

5.1.3 Vessel Requirements

Marine operations related to installation and IMR-operations for subsea systems, represents significant costs for the operators. High demands for safety, competence and call outs at any time, are some of the elements that drives the cost up. To meet all demands, both operations and IMR-vessels has to be "state of the art". Associated costs for these operations are naturally necessary to ensure the desired availability. However, by improving the efficiency of the operations, costs may be reduced.

Since module design for both cases are equal, the corresponding vessel requirements for both of them are alike. The only difference, is the production train architecture. From the requirements in Section 4.2.6, it is stated that the modules in the Gate Box should allow use of already existing vessels for installation and IMR operations. As described, size and weight of modules are of significant interest and should be within reasonable limits. The main reason is the handling capacity for intended vessels. From Table 3.4, it is seen that module size should not exceed 70 metric tons or the dimension of 7.2 x 7.2 meters. In general, lighter and more compact modules enable use of lighter vessels, which in turn are more reliable and affordable to hire.

IMR vessels are equipped with work ROVs for assisting installation and intervention tasks. Tooling interfaces on equipment should be in compliance with standardized ROV tools. In terms of inspection, as presented in Section 2.6.5, there are recently ongoing developments within underwater vehicles that can contribute to reduce inspection costs. These vehicles are intended to be permanently placed on the seabed. This means that inspections can be performed from onshore, instead of sending an IMR-vessel for deploying an ROV which is dependent on an umbilical extended from the vessel. Compared to traditional ROV systems, the AUV system can be a promising system for the future, since it can maneuver into more confined spaces, and are independent from weather conditions. This advantage may potentially contribute to a more compact system design. The AUV systems are not investigated in detail in this thesis, but are a technology that should be further considered for the Subsea Gate Box.

5.1.4 Control Systems

As stated in Section 4.2.5, the control system for the Gate Box should in a least possible manner rely on ROV support, and instead ,if possible, be based on an all-electric control system approach. As described in Section 2.3, an all-electric system has several benefits with regard to actuation time and reduced umbilical costs.

However, for actuation of connectors, a hydraulic system is in this case assumed. This thesis does not go into detail on the control system itself, but briefly describes the different types, as it can be a factor that contributes to decrease actuation time, and furthermore affect the maintainability. A more thoroughly study on this feature should be considered.

5.1.5 Monitoring and Maintenance Strategy

The simplified example presented in Section 3.1.2 shows that implementation of a condition based maintenance strategy can bring great benefits. Being able to predict future events gives a better basis for planning and scheduling of maintenance operations. In turn, this leads to reduced downtime and reduced costs for the operations.

Implementation of performance monitoring as presented in Section 3.1.3, regarding the Gjøa Field, proves the obtained benefits by implementing monitoring on the performance of the producing system. This has given indispensable information which enable the ability to plan maintenance and predict upcoming incidents.

A similar system should be considered for development of the Gate Box concept. A processing system contains a large number of valves and connectors. Subsea leak detection is a technology under development that would be interesting to implement in the concept.

5.2 Case 1

The setup in Case 1, as seen in Figure 4.5, consists of two process trains, with a manifold placed between them. In this section both advantages and disadvantages will be discussed.

5.2.1 Advantages

For Case 1, modules from the two trains are connected to the manifold by horizontal connectors with a stroking mechanism. In this setup, it is allowed enough space between the manifold and the modules. As a result, an ROV can access and actuate the locking mechanism directly onto the connector assemblies. This space also contributes to easier inspection, and access to modules in both process trains. Because of the direct access to connectors, there is no need for any complex latching system. As stated in Section 2.2.1, and Table 2.1, this configuration only requires a simple clamp connector operated by a torque tool.

An additional advantage is that changing seals is rather easy, and can be accomplished without retrieving any modules, since the stroking feature can be used to achieve access. The horizontal connection configuration also allows separate retrieval of all modules in the process trains, including the manifold, but in the latter case, all connections must be disconnected. Retrieval of the flow meters, outlet booster pumps, and chokes, can both be removed separately, and in one operation. This solution can contribute to reducing installation and retrieval time. Additionally, rerouting of the flow can be achieved both between the two process trains, and by bypass options within them. This feature is beneficial in terms of allowing production to proceed, while performing maintenance on one of the trains.

Regarding maintenance on the connectors, it will in this case be possible to mount the connector hubs that contain the stroking feature and locking mechanism on the retrievable modules in the process trains. This is a preferable solution, as it is both easier and less costly to retrieve the smaller modules, rather than the manifold.

5.2.2 Disadvantages

Placement of the manifold is a limiting factor in terms of how many processing trains the Subsea Gate Box can accommodate. For this case, it is only possible to connect modules along the manifold sides. An option could be to place two process trains on top of each other on both sides of the manifold. However, this would affect the retrievability of the lower modules, and additionally increase the structural strength required to tolerate the added weight on the lower trains. An additional solution could be to take the manifold out of the structure, and rather locate it nearby as a separate system. In this case, it is possible to add more process trains, as the module configuration will be similar to Case 2. On the other hand, redundancy in term of rerouting between the separate trains, will not be possible to the same extent as the presented cases. Additionally, it could potentially increase the number of installation operations, as the manifold would require its own foundation structure.

Regarding sufficient access to equipment, there is a trade-off involved in achieving a compact solution, and at the same time facilitate for adequate inspection and availability to components. A result may be an increase of the structural footprint in addition to the weight. This can further affect the installation operation, since one may need a larger installation vessel, which again can increase the cost of the operation.

As previously explained, rerouting options for the flow has its benefits. However, it also has some disadvantages. The number of valves required in the system increases, and because all of them need some kind of control, it becomes more complex. This can also affect the total weight and cost of the structure. Hence, it can be important during the development phase to evaluate at which extent one need rerouting possibilities for all the equipment modules. In general, components that require more frequent maintenance should be prioritized.

Regarding the duration for performing connection of the functional modules, as stated in Table 2.1, this setup will be relatively slow and challenging. This problem occurs because the ROV has to physically access all the different connectors in which both the stroking and locking mechanism must be initiated.

As explained in Section 4.3.3, connectors into the metering modules and inlet to the outlet booster module, appears to contain several lines. This was not the case, as they were instead routed through separate connectors placed above each other. With this setup as elaborated in Section 3.3.3, one should be aware of potential misalignment problems. Placing connectors too far apart in either horizontal or vertical direction, can result in complications during stroking of the assemblies towards the opposite facing hubs. Small deviations on the base frame, or module frame can therefore result in an incomplete connection. For longer rigid tie-in spools, it is usually room for some flexibility and alignment is consequently relatively easy. However, on intermodular connections tie-in distances are quite short. This affects the flexibility of the pipes, and corrections for misalignment can be more difficult. A guiding system for retrievable modules, that can handle the required alignment tolerances, can be an important feature to include in the design.

5.3 Case 2

Figure 4.10 and 4.11 shows the setup of Case 2, which consist of three process trains placed on top of a production base. As in Case 1, this solution also has its advantages and disadvantages.

5.3.1 Advantages

The fact that Case 2 accommodates three processing trains, is just used as an example. It can consist of a variety of different train configurations, depending on the number of wells to host. This contributes to increase the versatility of the system, as it potentially can serve more wells compared with the setup in Case 1. Naturally, there are limitations regarding size and weight, as installation may become too challenging and costly.

Regarding retrievability of components in this setup, as in Case 1, all equipment modules in the process trains can be retrieved separately. Additionally, rerouting options between them are facilitated to the same extent as Case 1.

In Case 2, connectors are placed at the bottom of the module frame, and direct ROV access is not possible. Actuation of the connectors will in this case need to be conducted from an ROV-panel placed in distance from the assemblies. Such solution would require an integrated hydraulic system that is routed to all the connectors. This may be an advantage where actuation of the different connectors can be conducted relatively fast. The main reason is that there are less connector tools that must be deployed, and an ROV does not have to move around inside the structure as in Case 1. The only action needed from the ROV, is to apply hydraulic power into the panel.

Landing the modules onto the connectors on the production base can, in this case, be conducted relatively easy. As in Case 1, one should keep in mind possible misalignment complications and assure a proper guidance system, to ensure that the modules fit the tolerance requirements.

5.3.2 Disadvantages

As mentioned in the previous section, all the modules in the process trains can be retrieved separately. However, unlike in Case 1, the manifold function which in this case is located in the production base, cannot be retrieved separately. This action would require retrieval of all the other modules first, and can be a drawback in terms of availability of components, such as the subsea control module. As illustrated in Figure 4.14, the SCM is placed in the production base. To be able to reach this component, it should be located in a place where sufficient access is provided.

Access to the modules in the process trains may in this case be restricted compared to Case 1. As explained in Section 3.3.1, this mainly includes the middle train, where the two other trains potentially can restrict both access and view to the equipment. A solution could be to facilitate for easy access from above.

In Case 2, the connector assembly containing hydraulic actuation mechanism, is mounted on the production base. This is because hydraulic supply has to be available during actuation. By placing it on the retrievable modules, actuation will not be achieved during installation, as the module at this point is separated from the production base. Maintenance on a connector will therefore require retrieval of the production base, which, as mentioned earlier, requires disconnection and retrieval of all the modules. However, this can be avoided with some kind of hydraulic connection system that is integrated into the interface between the modules and the production base. With this solution, the connector assemblies can be mounted onto modules in the process trains instead. To achieve connection when modules are landed on the base structure, hydraulic supply from lines on the modules actuates the connector mechanism. Another solution could be to implement a retrieval solution for the connector assemblies. In this case it is only necessary to remove the equipment modules, and subsequently retrieve the connectors. These solutions is not studied in this thesis but can be important factors that should be further investigated.

Regarding change-out of connector seals, it is probably more difficult in this configuration, as equipment modules must be removed to achieve access to the connector assembly.

5.4 Case Summary

Table 5.1 summarizes the advantages and disadvantages presented previously for the two cases. This is done by comparing them against several criteria, and indicate which of the two cases that fulfills them. All the criteria mentioned is related to the stated requirements. The columns for Case 1 and Case 2 contain either a **1** or a **0**. A **1** symbolizes the case that satisfies the criteria the most, and **0** the case that fulfills it the least.

Table 5.1: Case comparison.

Criteria	**Case 1**	**Case 2**
Redundancy	1	1
Accessibility	1	0
Connection duration	0	1
Low ROV dependence	0	1
Number of Trains	0	1
Seal change	1	0
Compactness	0	1
Retrievability	1	0
Sum	4	5

As seen from the summation on the bottom row of the table, both cases has almost equal scores. Regardless of this, Case 2 appears to be the best solution. However, some of these criteria are more significant than others, and that is not considered. For instance, considering retrievability, it is possible to separately remove all the functional modules in both cases. The only difference, is that the manifold in Case 2 is restricted by the trains placed on top. This is why Case 1 is indicated as a better solution in this criterion. On the other hand, retrieval of a manifold for maintenance is not that common compared with pumps, chokes, etc. Additionally, connection and disconnection of modules in Case 2 are both simpler, faster, and less ROV dependent than Case 1. As stated in the table, Case 2 also has less restrictions on number of process trains it can contain, and it has potential to be a more compact solution, compared to Case 1. In terms of redundancy, they both provide the same extent of rerouting options. The only down sides are the possible accessibility and seal change restrictions.

5.5 IPB Connector Configuration

In Section 4.4, a suggestion for including production and control lines in the same connector is presented. As described in Section 3.3.3, the main advantage with this setup, is that it can decrease the amount of connectors needed in the system. Hence, time spent on connection operations during installation or maintenance, can potentially be reduced.

Apart from the possible advantages, connecting several lines within one assembly may also have some potential challenges. As one can imagine, the size of the individual connectors will probably increase due to the added lines. Additionally, the amount of individual lines on the connector interface may contribute to further increase complexity of the connector. Also, due to the added size, the weight of the assembly may be affected.

It should be mentioned that there is some uncertainties regarding this specific subject. This is mainly because it was not found any literature on already existing systems that have integrated this solution for intermodular connections. The only similar use that was found in the literature, had included this setup in a tie-in spool between X-mas tree and manifold, as showed on Figure 2.17. Although, as little information about the applicability of this specific solution were found, the potential benefits it can provide, regarding installation and maintenance, can be significant. Consequently, a further investigation into the subject should be conducted.

Chapter 6

Conclusion and Further Work

6.1 Conclusion

Based on the literature study, it was found that to obtain a subsea production and processing system, that is both versatile and enables easy installation and retrieval of modules, the following requirements should be fulfilled:

- Standardized module interfaces.
- Sufficient access to important equipment.
- Easy module retrievability.
- Redundancy and rerouting options.
- Module design in accordance to requirements from already existing IMR-vessels.
- Implementation of condition and performance monitoring to optimized intervention frequency.

Two cases with different architecture and connector configuration between modules were presented. Based on the comparison of these cases in the discussion, Case 2 appears to be the most satisfactory setup in accordance with the stated requirements. A high degree of retrievability, redundancy, and versatility, is obtained in the design. However, it should be recognized that the size and weight of the two cases can be a limiting factor. Therefore, compact solutions that can contribute to mitigate these limitations, should be considered. The Subsea Gate Box concept is still at an early stage in the conceptual development, and suggesting a final solution would thereby be difficult.

Considering the possible benefits by connecting control- and production lines in the same connector, it shows good potential as it can reduce the duration of Installation and maintenance operations.

6.2 Recommendations for Further Work

This thesis presents the fundamental design factors that should be considered during the design of the Gate Box. These factors are then used as a theoretical foundation for the setups presented in the two cases. However, there are some solutions that are not included and only briefly mentioned. The main elements in this thesis that should be further investigated, includes the following tasks:

1. Perform a feasibility study on the us of Integrated Production Bundle (IPB) connectors for connections between modules.
2. Conduct an investigation on the possible effects an all-electric control system can have on the maintainability of a subsea production and processing system.
3. Investigate the feasibility of facilitating for an AUV systems to perform intervention tasks, and additionally the potential benefits this can have on the structural design, in terms of achieving a compact structure as well as easy IMR.

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Appendix A

Calculations For Maintenance Strategy

For calculating the costs in this example it is assumed that:

- It takes 24 hours (1 day) to change a pump module. Assumes that the IMR vessel is on site and the pump is tested and ready for installation.
- It takes 30 days to mobilize a spare module if the "run-to-failure" strategy is used. This time includes mobilization of IMR-vessel, crew, testing of the new module and waiting for weather etc.
- When the module is shut down the production is reduced or stopped. Lost revenue is assumed to be 4 MNOK/day.
- The cost of replacing the module is set to 8 MNOK, which is based on the costs of replacing a multiphase pump on Tordis subsea separation and injection station in 2016.(N. Lazarevic, personal communication, May 16, 2017) Overhaul costs for the replaced module is not considered in this calculation.
- The lifetime of the pump module is assumed to be 5 years. This can of course be less, and it can be more.

The assumption above for loss of revenue is not precise due to varying production rates and oil price. The same goes for the intervention costs where duration and vessel prices also change. Anyhow, the numbers give an indication of the cost involved.

Calculated costs for using the different strategies are presented below:

Strategy 1 "Run-to-failure":

When the pump breaks, the mobilization period of 30 days comes to play. The cost per failure is then:

$$Mobilization\ time * Lost\ revenue/day + Replacing\ costs \tag{A.1}$$

$$30\ days * 4\ MNOK/day + 8\ MNOK = 128\ MNOK \tag{A.2}$$

Assuming the pump is replaced once per 5 years the average cost per year will be:

$$Total\ cost/years = 128\ MNOK/5\ years = 25.6\ MNOK/year \tag{A.3}$$

Strategy 2 "Time based"

The pump is replaced every 2 years regardless of condition. The mobilization time of 30 days is eliminated and we only need the 1 day for the pump module change out. The cost of the change out is then:

$$Replacement\ time * Lost\ revenue/day + Replacing\ costs \tag{A.4}$$

$$1\ day * 4\ MNOK/days + 8\ MNOK = 12\ MNOK \tag{A.5}$$

Since the pump is replaced every 2 years the yearly costs for the pump module will be:

$$Total\ cost/years = 12\ MNOK/2years = 6\ MNOK/year \tag{A.6}$$

Strategy 3 "Just-in-time"

This strategy assumes that we are able to detect a starting fail or lack of performance 30 days in advance, so that the mobilization time is avoided. This approach is naturally not guaranteed but is assumed. In this approach, we assume that “just in time” replacement is performed once every 5 years. The costs will then be:

$$Replacement\ time * Lostrevenue/day + Replacing\ costs \tag{A.7}$$

$$1\ day * 4\ MNOK/days + 8\ MNOK = 12\ MNOK \tag{A.8}$$

The yearly cost if this strategy will then be:

$$Total\ cost/years = 12\ MNOK/5years = 2.4\ MNOK/year \tag{A.9}$$