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Fabrication, Launching and Towing of Submerged Production Unit

A Technology Development Project of
Subsea7

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Submission date: June 2018
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Just for you - Mom & Dad

Abstract

The demand for fossil fuels drives for an advancement in the existing subsea technology. The developments evolved as the search for hydrocarbons moved from onshore to offshore, followed by a transition from shallow to deep and ultra-deep waters. Another huge milestone was achieved when production systems made a transition from topsides to subsea units for efficiency. That being said, there is an enormous drive to minimize the operational costs involved in the processing of hydrocarbons. Researches are underway towards what would be yet another significant feat in the oil and gas industry, which is by moving the processing systems to subsea. One such impressive concept which is being developed, is the Submerged Production Unit (SPU).

This study is an initial attempt to investigate the challenges associated with the SPU focusing on the factors influencing fabrication, launching and towing. This thesis revolves around finding an optimized solution for the challenges associated with the integration of Glass Reinforced Plastic (GRP) and subsea buoyancy material for the assembly, which is one of the main objectives of this thesis. Industrial visits to GRP fabricator, subsea buoyancy material fabricator and the assembly yard coupled with inputs from Subsea 7 engineers, formed the base for this research work. A design concept that goes back and forth from performance and design spaces was used in solving the complexity that revolved around SPU assembly. Analytical Hierarchy Process (AHP), an effective tool dealing with complex decision making was used to decide the best possible location for assembly and launching of the SPU. Finally, OrcaFlex software was used for towing analysis. End force in global X direction on towline, obtained from static analysis was used to identify the Bollard Pull (BP) required for towing the SPU. Dynamic analysis was performed for different environment conditions to identify the maximum effective tension on the towline.

The research work resulted in the development of a 3D Joint, using Autodesk Inventor software for the SPU assembly. This joint provided a one way access to connect all the SPU sub assemblies. The AHP suggested the use of syncrolift for launching the SPU by making pairwise comparisons between the yards chosen and the evaluation criteria cost, safety, fabrication facilities and commissioning facilities. BP requirement of 100T was estimated from static analysis. The maximum effective tension experienced on the lead tug towline was 837KN for waves in 180°, wave period of 20s, wave height of 7m along with current in 90°at a speed of 1m/s.

Acknowledgement

It's been a wonderful journey in last two years of my life in Norway. Being an international master's student in Norwegian University of Science and Technology (NTNU), Trondheim brought in major changes in my life. I had developed as a person by exploring the nature and doing many things for the first time in my life.

I would like to thank all my professors in NTNU first for sharing their knowledge with me. I take this space to convey my heart felt thanks to my Supervisor, Prof. Bernt Johan Leira for accepting me as his master thesis candidate and by providing full support and freedom throughout the semester. With immense pleasure, a special thanks to Prof. Kjell Larsen for being my Supervisor of specialization project and also as a Co-Supervisor of my master's thesis. The time spent with him on learnings and discussions of marine operations topic is one of the precious moments of my life.

It was a great experience as a master's student writing thesis with Subsea 7. I would like to thank my Co-Supervisor, Prof. Daniel Karunakaran for his weekly review meetings that added consistent progress to my research work. A special thanks to Sigbjørn Daasvatn for giving me the opportunity and guidance to work on his technology development project of the Submerged Production Unit(SPU). Finally, I'm so blessed to work under the guidance of Lise Soyland, Rasmus Juhlin, Morten Sæterdal, Øystein Døskeland, and Adekunle Peter Orimolade, who have given me the opportunity to explore their development project and grooming me with regards to subsea engineering knowledge in last five months.

I'm so grateful to all my friends from Trondheim and Stavanger for all the fun, help, support, motivation and life time memories.

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Abbreviations

SPU = Submerged Production Unit
GRP = Glass Reinforced Plastic
CDTM = Controlled Depth Tow Method
PWMS = Produced Water Management System
DPS = Dual Pipe Separator
CFU = Compact Flotation Unit
FPSO = Floating Production Storage and Offloading
U.K. = United Kingdom
ROV = Remotely Operated Vehicle
BP = Bollard Pull
NOK = Norwegian Kroner
LOA = Length Overall
OSPAR = The Oil Spill Prevention Administration and Response
EOR = Enhanced Oil Recovery
EOT = Electrical Overhead Travelling
MSL = Mean Sea Level
PLET = Pipeline End Termination
GC = Gas Chromatography
FID = Flame Ionization Detection
m = Metre
kg = Kilogram
msw = mean sea water
t = tonne
nos = Numbers
ft = Feat
mm = Millimeter
KPa = Kilo Pascal
W/mK = Watt per meter by Kelvin
MN = Mega Newton
ppm = parts-per-million

Chapter 1

Introduction

Oil and gas reserves from natural reservoirs under the seabed are produced based on exploration, exploration drilling, production plan and production. Onshore to offshore explorations over the past years clearly indicate the need for fossil fuels and relevant technological advancements. Deepwater and ultra-deepwater are being explored in search of hydrocarbon reserves, resulting in the concept of subsea field development with production facilities on the seabed. Due to steady technological advancements, the oil and gas industry aims to transfer the functions of processing hydrocarbons to the seabed. Over the years, the experience gained by the subsea engineers in design and installation of towed pipeline bundles, subsea plants along with usage of new materials led to the development of Submerged Production Unit (SPU) [8]. This chapter explains the background and motivation for this thesis work with its main objectives and structure.

1.1 Background

The Submerged Production Unit (SPU) in brief can be termed as a towed installation frame serving the purpose of subsea processing which is built, tested and flooded out from a dock. For favouring circumstances, the whole unit is designed to be able to relocate. The motivation for developing the SPU is for mitigating flow assurance issues associated with the transfer of hydrocarbons prior to reaching the offshore platforms in order to maximize profit and mitigate risks. The motivation behind this thesis is to determine optimized solutions for the challenges associated with fabrication, launching and towing processes of SPU. The SPU comprises of steel bottom frame with pontoons, Glass Reinforced Plastic (GRP) beams and pillars with subsea buoyancy materials, processing equipment, control module and GRP covers. Fabrication process discussed in this thesis is focused on buoyancy material and GRP, and assembling them together. Limitations of fabrication facilities, snag points, water depth, cost, equipment dimensions, and subsea buoyancy material fabrication methods are some driving factors involved in modelling the SPU. Different launching methods such as Dry docks, Floating docks, Syncrolifts, and Airbags have been considered and ranked based on Analytical Hierarchy Process (AHP). The conventional way of lifting the equipment using cranes of construction vessels on site during deployment is avoided as the structure is heavy consisting of all equipment for processing. So, Controlled Depth Tow Method (CDTM) has been used in the analysis to tow the structure to the field.

1.2 Main Objectives

- The main objective of this thesis is to optimize the fabrication plan by looking into the best way of assembly of all equipment, buoyancy modules, GRP structural section units etc., for a SPU with an efficient method to connect the structural joints.

- The logistics and production of GRP; especially the different ways (split or tubular) it can be fabricated are to be determined based on the facilities available, suppliers expertise, storage requirements, cost and time.

- Review and analyze the advantages and disadvantages of various production facilities for fabrication and launching, and select the best based on its facilities and resources in Norway to optimize the production plan.

- Finally, to come up with launching plan and towing analysis of the SPU using OrcaFlex software with measured data from model test at Sintef Ocean AS.

- With all the materials, equipment details and assembly plan known, lead time analysis for each item has to be performed with major focus on structural fabrication and assembly process.

1.3 Thesis Structure

The work presented in this thesis is a result of three main processes, fabrication, launching and towing involved in the development of SPU. This thesis is structured as follows, Chapter 2 discusses about the literature survey focusing on the evolution of subsea production and processing systems, Chapter 3 presents a detailed description of the Produced Water Management System (PWMS), which is the function of the SPU considered in this thesis. Chapter 4 explains about the insight of fabrication methodologies of the SPU. Chapters 5 about the approach used in the thesis for solving the fabrication challenges associated with the SPU. Chapter 6 brings out the evolution of SPU's 3D model. Chapter 7 and 8 discusses about launching options and towing analysis performed. Chapter 9 presents the discussion and evaluation of the analysis with a final assembly plan. Chapter 10 concludes the thesis and discusses the potential direction for future work.

Oria and science direct were the main websites used in finding the relevant information for this thesis.

Chapter 2

Evolution of Subsea Production and Processing Systems

World's energy consumption is increasing steadily since 1950s [4]. Despite being focused on renewable energy sources by the developed nations in the recent years, the consumption of fossil fuels accounts for 80% of the world's total energy consumption as depicted in Figure 2.1 [4]. In order to sustain stability and improvement in the world's energy supply, oil and gas production has been paid continuous attention owing to the fact that they hold high significance in the consumption of fossil fuels as mentioned earlier.

The inception of offshore oil and gas industry roots back to 1947 when Kerr-McGee completed the first successful offshore well in the Gulf of Mexico off Louisiana in 15 ft of water [4]. Shallow water hydrocarbon reserves were exploited to the best in 1960s and 1970s with the production system on the topside of the offshore platform or onshore. The increase in demand for oil and gas resulted in the growth in numbers of wells and platforms shedding a spotlight on needs for advancement in technology, water depths, and increased distance from the host facility. Depletion of oil reserves in shallow water later became a huge challenge to the oil and gas industry to explore deepwaters.

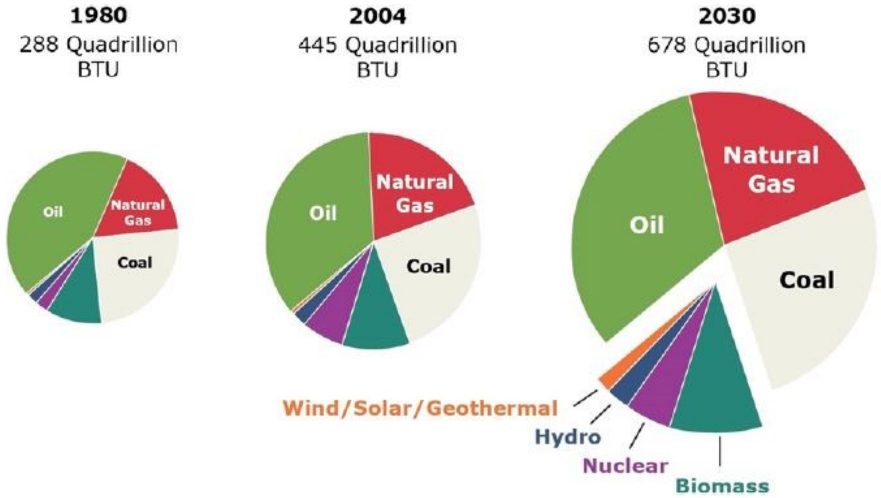


Figure 2.1: Fossil Fuel Consumption History and Prediction [4]

2.1 Process Flow of Hydrocarbon Production

Oil and gas reserves from the natural reservoirs under seabed are produced based on the following sequence [17]:

- **Exploration**: Creating seismic maps using an offshore vessel is the first step in the development of an oil field. The maps generated by the seismic vessel details the structural formation of the rocks under the seabed. These maps are then processed and analyzed by geologists to locate the possible reserves and point a location to drill.

- **Exploratory drilling**: Once the potential for the reserve is found satisfactory by the geologists, a permit for exploratory drilling is obtained. In Norway, the Petroleum Safety Authority Norway and the Climate and Pollution Agency provides the permit [17]. After which, a drillship or a floating drilling rig is brought in, to carry out the process.

- **Production Plan**: Confirmation of enough oil or gas reserve with a development to be financially sustainable leads to the demanding process called production planning. The rock that contains hydrocarbons is unique in terms of temperature, pressure, depth and climatic conditions. So, each individual production system is specially planned and made in order to achieve optimal function and production [17].

- **Production**: The subsea installation is deployed on the seabed once the access to the reservoir has been secured [17]. The installations are of huge dimension and is because of some of the key components that have to be incorporated. The pressure in the reservoir is controlled with a pump. The next important component is the separator. As the gas mixes with oil and water, a separator is required to separate these elements. Transformers and regulators are used for power supply from the shore through pipelines. Due to enormous pressure losses because of the distance and topology of the transport, a compressor is also needed to help transport the gas to the desired location.

2.2 Conventional Subsea Production Systems

Depletion of hydrocarbons on onshore and offshore shallow waters moved the attention of oil and gas companies towards deepwaters. Deepwater explorations for the quest of hydrocarbon reserves resulted in the concept of subsea field development with wellhead and production equipment on the seabed. Subsea technology was first developed and used commercially in the Gulf of Mexico and offshore California in the early 1960's by various operators [23]. The world's first subsea completion was installed in 1961 at West Cameron 192 in 55 ft of water and was designed for deepwater operation using through-flowline technology with 20 subsea satellite wells with gas lift and multiple-zone completions producing the conception field to a platform offshore California [21]. Norway focused primarily on the possible methods to move the production down on to the seabed in the early 80s.

Subsea production systems comprise of wells and seabed equipment. Subsea wells have different varieties of configurations like satellite wells, single-satellite wells connected to a nearby manifold, and steel-template wells with manifolds as shown in Figure 2.2.

A subsea production system uses a subsea wellhead production system and underwater submarine tree as the core of an oil production system. They are suitable for a variety of different floating platforms like semi-submersibles, tension leg platforms, spar platform and FPSO [4]. It involves engineering of almost all kinds being engaged with a basic requirement for efficient integration technique.

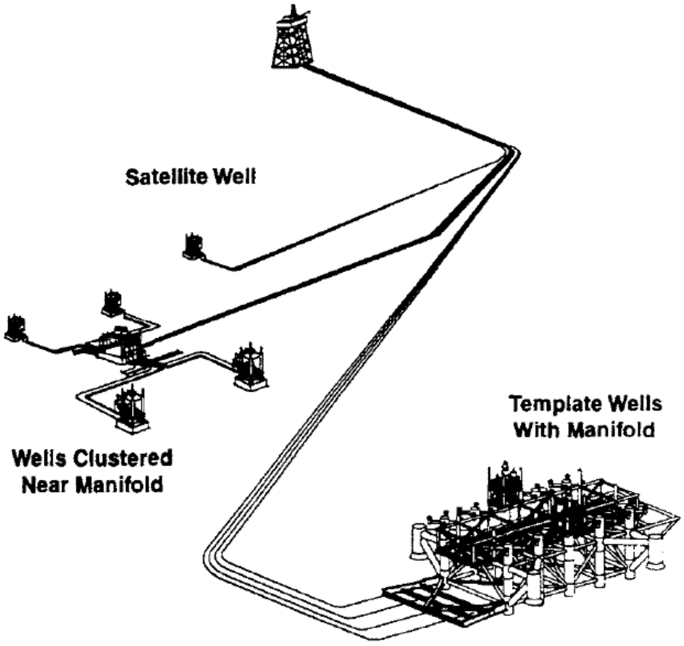


Figure 2.2: Subsea Design Configuration [21]

Decisions taken to develop a field are based on the limited knowledge about the reservoir. To ascertain the abundant resources for investment and the feasible conditions of the resources to be produced from the reservoir, a large number of wells must be drilled. The recovery process involved the usage of water and gas injection for maintaining the pressure.

2.2.1 Subsea Production Field Layout

The components that form a subsea production unit are as follows [4],

1. Christmas tree
2. Subsea wellhead manifold
3. Umbilical and riser systems
4. Tie-in and flow-line systems
5. Underwater control system

A typical subsea field layout as shown in Figure 2.3 has number of wells with pressure control valves and ports for chemical injection. Jumpers are used in the transfer of produced fluid from wells to the manifold. Commingling of the produced fluid takes place in the manifold. The produced fluid from the manifold is then taken to a subsea boosting pump station. This pump provides the energy required to transfer the produced fluids through pipeline end terminations (PLET) and through flow-lines and risers to the platform deck. The electric and hydraulic power requirements for subsea control functions are supplied from the platform deck using integrated umbilical. The produced fluids are then processed in the platform or onshore.

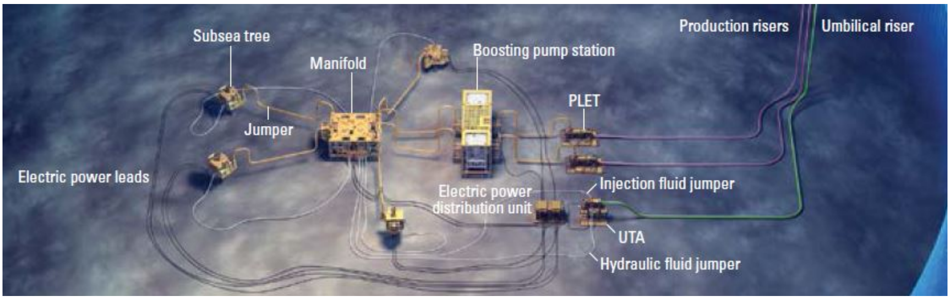


Figure 2.3: Subsea Infrastructure [45]

2.3 Subsea Interventions

The U.K. sector water depths have favoured diver assist technology, while some deeper-water developments in the Norwegian sector have required diver-less technology for subsea marine operations [21]. This resulted in the development of underwater installation and maintenance approach that uses a free-flying device called a Remotely Operated Vehicle (ROV). Installation in an offshore environment is a challenging activity, and heavy lifting is avoided as much as possible. This is achieved fully by subsea equipment and structures that are transmitted to the installation site by installation vessels. At the same time, with new technological development, such as subsea separation, boosting and multiphase metering, and better understanding and control of hydrates, corrosion, paraffin, and scale; improved the range of subsea applicability and reduced the need for intervention [21]. Most of the subsea production systems are installed and maintained using the ROV's in the recent years.

2.4 Requirement for Submerged Production Unit

The hydrocarbons from the reservoirs are processed after production using processing equipment. Separations, produced water cleaning, sea water cleaning, heating or cooling, gas drying, are some of the processing equipment functions. Detection of availability of natural resources under the seabed paved way for tie back of subsea wells over the past decades. Brown-fields with small pool developments and geographically remote areas requires connection between them to an existing production facility in the form of tie-backs for efficient production [39]. As tie-backs are becoming more marginal to develop, both from technical and economical perspectives, subsea processing functions are evaluated for many future field developments [8]. Considering the economics, the longer tie-backs are governed by the following factors [39].

- Distance from existing installations
- Fluid temperature and pressure
- Water depth
- Recoverable volumes, reservoir size, and fluid properties.

Effective subsea field development solutions eliminates the need for traditional platforms having processing facilities at the topside. Therefore, the industry aims for replacing the need for topside processing by transforming the functions to the seabed, where all required processing functions are performed subsea before exporting out of the field. The trend towards a higher degree of standardization and continuous improvement in the quality of products being offered led to the development of SPU [8]. It is a production plant inside a structure that contains buoyancy objects like bottom tubulars, pillars and the top volumes [39]. It is a cost effective technology platform for modular integration of provider's technologies into larger subsea production and processing plants. The SPU contains the modules needed for subsea processing. The research and development work behind subsea processing is for handling and treatment of the produced fluids for mitigating flow assurance issues prior to reaching the platform. The whole structure is complex in nature and is compared with the structural building body of a topside structure [8]. The structure is termed complex because of its requirement with various solution providers of technology to find the overall solution [8]. The various systems integrated in forming the SPU as a complete solution provider for subsea processing is elucidated as a conceptual model in the Figure 2.4.

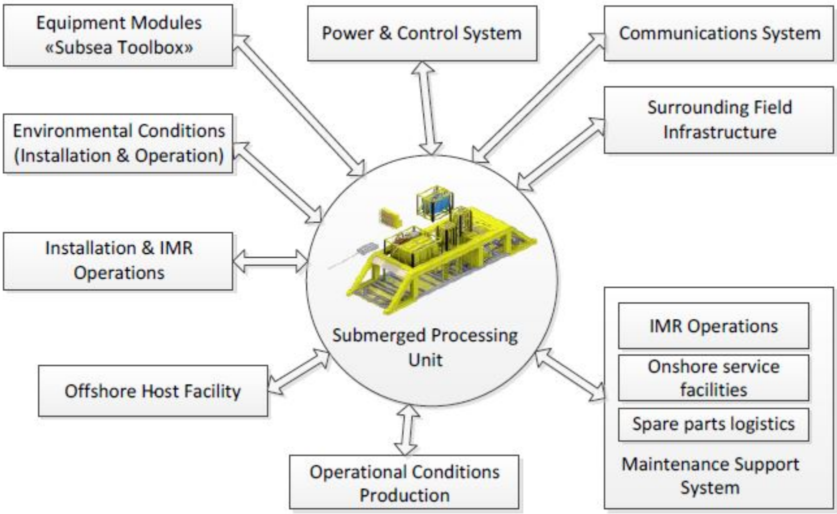


Figure 2.4: Integrated Systems of SPU [8]

Chapter 3

Produced Water Management System

It has been expected to have produced water volumes to rise to over 340 Bn barrels by 2020 [47]. The main objective behind the development of Produced Water Management System (PWMS) is to increase the hydrocarbons flow capacity of the export line by restricting the flow of produced water to the platform or to onshore processing facilities.

3.1 Functions of PWMS

Produced water is a byproduct from hydrocarbon reservoirs along with oil and gas. This water is also referred as brine, saltwater or formation water. It is trapped underground and flows out during oil and gas exploration and production. The cost involved in produced water management is a significant factor in the profitability of oil and gas production. The cost includes the following [43]:

- The cost of constructing treatment and disposal facilities, including equipment acquisitions.
- The cost involved in operating the treatment and disposal facilities, including chemical additives and utilities.
- The cost of managing the byproducts obtained from the treatment of produced water.
- Permitting, monitoring, reporting and transportation costs.

The crux decision of shutting down the well is taken once the cost of managing the produced water exceeds the value of the hydrocarbon produced from the well [43].

3.1.1 Management of Produced Water

A way to manage produced water is to re-inject the produced water into the same formation or another suitable formation [39]. This process involves the transportation of produced water from the separation facility to the injection site. Normally 30% in a reservoir can be extracted but water injection increases this percentage. This water re-injection is required for reservoir pressure maintenance in order to maintain or increase production. Mostly produced water is not sufficient enough for injection, therefore seawater, aquifer water and river water are used in addition. Produced water can also be recycled and reused. Irrigation, livestock or wildlife watering and habitats, vehicle washing, power-plant are some fields where produced water can be reused onshore [24].

3.1.2 Produced Water Treatment

Produced water can be also discharged into the sea. Sand and oil particles from the produced water must be removed before discharging to the sea according to offshore discharge regulations. Under the 2002, Offshore Waste Treatment Guidelines, the hydrocarbon concentration of produced water must be reduced to acceptable levels prior to discharge into the ocean [31]. Countries having significant offshore oil and gas production are with the environment regulatory agencies enforcing limits on the concentration of oil and grease that can be present in produced water destined for discharge into the sea [31]. Different countries have proposed different standards for measuring oil in produced water. The different methods measure different fractions of the total organic chemicals in produced water and therefore, gives different results. In The Oil Spill Prevention Administration And Response (OSPAR) countries, the total oil is defined as the sum of the concentrations of compounds extractable with n-pentane, not adsorbed on Florisil, that can be quantified by gas chromatography/flame ionization detection (GC/FID) with retention times between those of n-heptane and n-tetracontane, excluding toluene, ethylbenzene, and xylenes [31].

The minimum regulatory standard for the treatment and/or disposal of wastes associated with the routine operations of drilling and production installations offshore for OSPAR countries like Norway is a 30-day weighted average of oil in discharged produced water of 30 mg/L as shown in Table 3.1.

Table 3.1: Monthly Average and Daily Maximum Concentrations of Total Oil and Grease Permitted by Several Countries for Produced Water Destined for Ocean Disposal [31]

Country	Monthly Average (mg/L)	Daily Maximum (mg/L)
Canada	30	60
USA	29	42
OSPAR (NE Atlantic)	30	-
Mediterranean Sea	40	100
Western Australia	30	50
Nigeria	40	72
Brazil	-	20

Produced water treatment is very important before discharging to the sea because of the harmful effects it can cause on the receiving environment. This involves removal of solids and dispersed non-aqueous liquids from the waste water, scales, suspended solids, including dispersed oil, and bacterial particles. The most volatile hydrocarbons and corrosive gases like CO_2 and H_2S are also removed [31]. The concentrations of volatile and dissolved hydrocarbons are reduced to acceptable levels for ocean disposal, if the dispersed oil is removed based on the experience by the offshore oil industry. If the treated waste water is intended for disposal to freshwater, recycling for steam generation for the various thermal Enhanced Oil Recovery (EOR) technologies, or for re-injection into the formation, most of the dissolved salts and metals should also be removed. If the discharge is into the ocean, removal of salt is not necessarily important.

Usually the process of removing oil and gas from the produced water takes place in the platform or at the shore treatment facility. This report is based on the development project focusing on PWMS to be operated subsea, in order to enhance the hydrocarbon flow rate to the platform by discharging the produced water to the subsea.

3.2 Basic Equipment Required for PWMS

The main objective of the PWMS is to separate oil/gas/water mixture from each other through separation devices. There are various types of equipment that are used for the treatment of produced water. Mechanical and hydraulic gas flotation units, coalescers, skimmers, hydroclones, and filters are some of those. Chemicals can also be added to the process stream to improve the efficiency of oil/gas/water separation. The combination of mechanical and chemical treatment is effective in removal of volatile compounds and dispersed oil but it is not efficient enough in removing dissolved organics, ions and metals. The oil and water separation achieved is not 100%, although most advanced separation equipment are used. A brief description of the equipment that were considered in this thesis for the separation process is discussed below.

3.2.1 Gas Harp

Gas harp is used prior to all other separation equipment as it separates gas from liquid. It consists of a multiphase fluid inlet passing through a main horizontal pipe with a series of vertical pipes connected to each other, where the actual separation happens as shown in Figure 3.1. There are two different outlets for liquid and gas and the separation is based on the density difference between gas and liquid following inline separation technique. The gas outlet leads to the platform and the liquid outlet leads to further processing equipment before disposal.

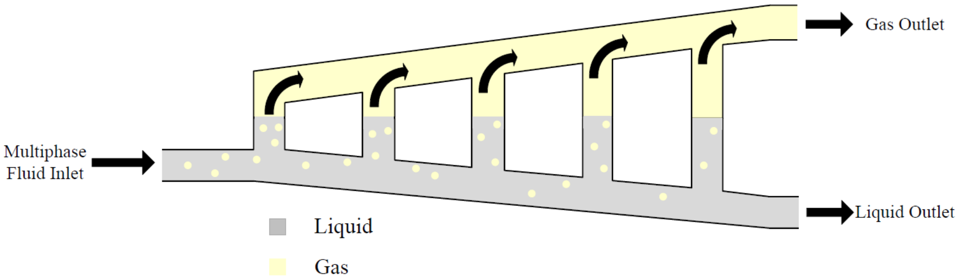


Figure 3.1: Schematic Representation of Gas Harp [39]

3.2.2 Dual Pipe Separator

The liquid outlet from gas harp contains both water and oil. Dual Pipe Separator (DPS) performs bulk removal of oil from water and then treating the produced water locally. The main advantage of water treatment in seabed is the transport of gas and oil only from the well to the platform. This reduces the cost and increases revenue through accelerated production. The working mechanism involves the usage of a set of multiple small separator pipes. These separator pipes can function in series or parallel and has the advantage over the conventional gravity separators by using smaller diameter pipes. The smaller diameter pipes are used as it can withstand the external pressure at higher water depths which resulted in less wall thickness. This also enables debottlenecking of asset infrastructure and reduces the effect of ”back-out” arrangements [38]. Figure 3.2 represents a typical DPS.

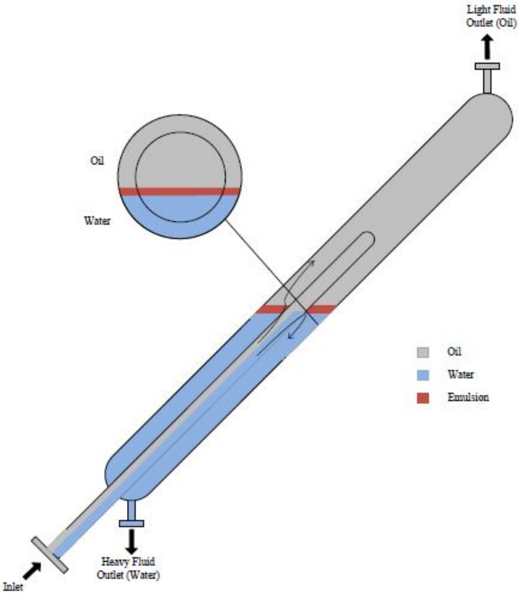


Figure 3.2: Schematic Representation of Dual Pipe Separator [39]

3.2.3 Compact Flotation Unit

DPS is used for bulk separation of water from oil. In order to meet the subsea produced water disposal requirements, the low oil-in-water from DPS has to be processed again. Compact Flotation Unit (CFU) is used for the final processing. Gas flotation, oil droplet coalescence and centrifugal separation processes are combined into a single process technology forming the basis for CFU. This unit uses centrifugal force to direct the heavier water droplets to the outside and the lighter oil droplets to the core of the unit. The process involves injection of gas which results in getting coated by the oil to be removed. In addition, oil in water separation can be achieved by the usage of inertial forces. The water level in the CFU tank is monitored using a level indicator with a control valve to ensure that the excess oil does not flow into the water. A flowmeter is also fixed to the CFU module water outlet providing feedback to the control system in the topside for maintaining the optimum gas injection flow rate. Figure 3.3 represent a typical CFU.

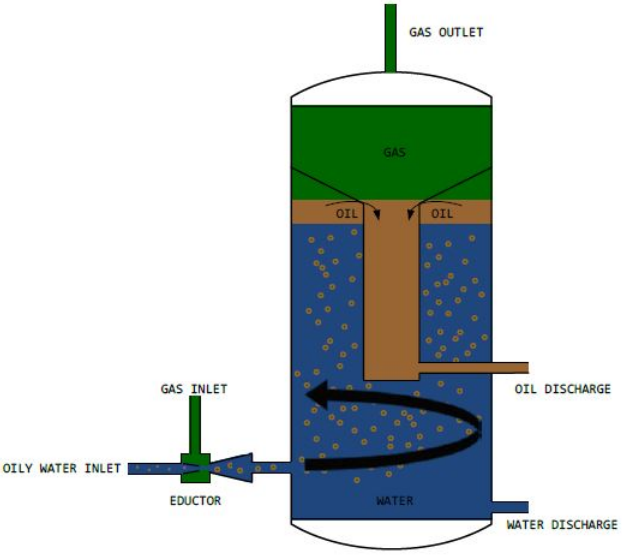


Figure 3.3: Schematic Representation of Compact Flotation Unit [39]

3.2.4 Oil in Water Analysers

PWMS requires oil in water analysers used for monitoring, reporting, and controlling the water outlet for disposal against acceptable limits. This system consists of an ultrasonic sensor that indicates the parts per million (ppm) of oil content in water. These sensors are coupled with the topside control systems to operate the bypass valve, if the acceptable limits are not reached.

3.3 Structural Configuration

The main structural component of the SPU is made of GRP. Steel structures are avoided to the maximum in order to minimize the structural weight for the main reason and also to make the SPU buoyant with GRP and subsea buoyancy modules. Moreover anodes are required to protect the steel structure from corrosive subsea environment. Periodical maintenance of anodes has to be followed as well, which necessitates the use of GRP in the SPU. The SPU consists of five major components and are elucidated in the following subsections.

3.3.1 Steel Frame

The steel frame acts like a deck with foundation for the processing modules of the PWMS as shown in Figure 3.4. The steel frame consists of two pipes connected with stiffeners for buoyancy. These pipes have ballasting facility which helps in launching, lowering and raising of the unit during towing and installation.

Figure 3.4: Bottom Steel Frame of SPU [39]

3.3.2 Transport and Installation Frame and Silo

A standardized Transport and Installation Frame (TIF) as shown in Figure 3.5 is developed to fulfill the following requirements:

- To simplify the transport, installation and retrieval of equipment
- To reduce variability between the suppliers

TIF forms the interface between processing unit and SPU, protecting the equipment during transportation and installation [25]. TIF with the processing unit can be installed either through moonpool or by the side of the vessel based on the unit's size and weight. It is also equipped with the connection points for power supply and processing functions. In addition TIF provides access for intervention during operational lifetime of the SPU. Silo is a metal frame fixed to the stations on the SPU steel frame through which the TIF slides in.

3.3.3 Glass Reinforced Plastics

The Glass Reinforced Plastic (GRP) forms the superstructure of the unit and its main function is to provide protection against dropped objects and trawling. It also provides solid buoyancy to the structure which is essential for generating uplift. Bolted and connected together with the steel deck, the steel deck and GRP superstructure forms a truss structure to carry the heavy pay loads from the processing plant during towing and installation as shown in Figure 3.6 [8].

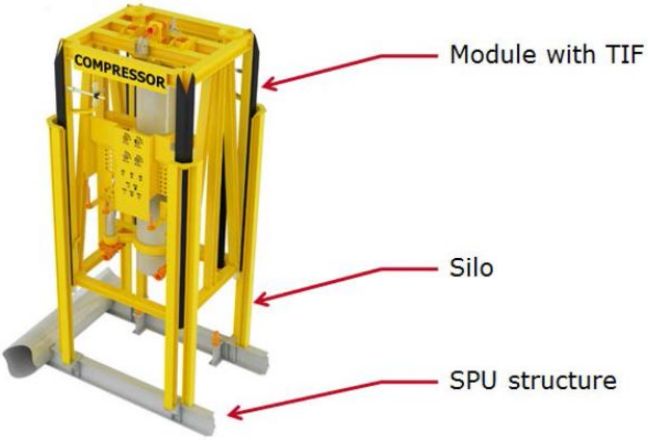


Figure 3.5: Transport And Installation Frame of SPU [39]

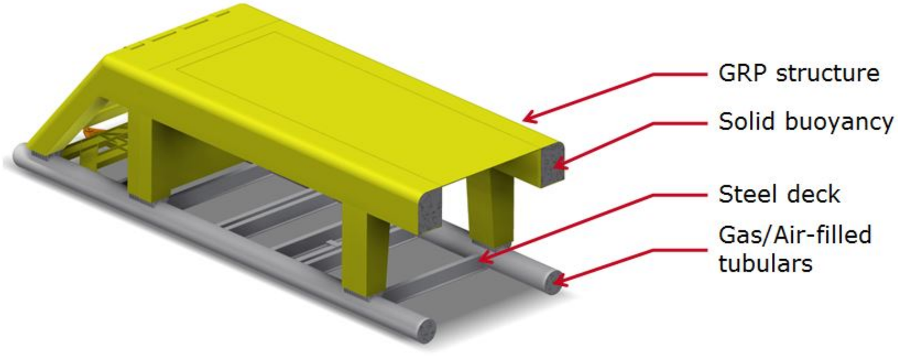


Figure 3.6: Structural Components of SPU [39]

3.3.4 Solid Buoyancy

The space within the GRP beams are filled with solid buoyancy materials like syntactic foam or macrospheres (plastic air balls). This is the major contributor for the uplift generated by the solid buoyancy. The design requirement for solid buoyancy is to withstand the pressure at the field location and to avoid GRP buckling. The solid buoyancy materials are illustrated in Figure 3.7.

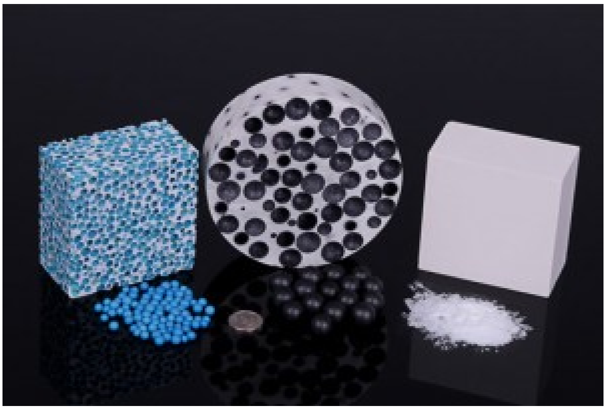


Figure 3.7: Solid Buoyancy Materials [40]

3.3.5 Hatch Covers

The main purpose of hatch covers are to prevent the flow of water or any sea-living organisms entrapment into the equipment during tow. Once the field location is reached the hatch covers are removed using the ROV. The hatch covers are illustrated in Figure 3.8.

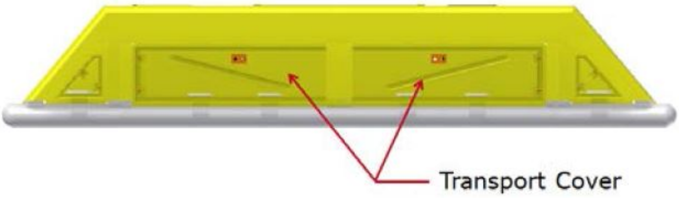


Figure 3.8: Hatch Covers of SPU [39]

3.4 Maintenance and Regulation Requirements

Establishing a maintenance free design is one of the major objectives during the development process of the SPU. Annual visual inspection is recommended to ensure that no external damage or hazards are present affecting the system's integrity. Basic inspection list for SPU is as follows [39],

- Foundation settlement
- Marine Growth
- Check for leakages in piping/control system

- Anodes and excessive corrosion
- Structural damage

Among all the equipment, Dual Pipe Separator (DPS) and oil-in-water analyser needs periodic maintenance. ROV's are used for surveys and repairs in deepwater systems. As the SPU components are modular, it has the built-in redundancy to expedite retrievals in case of failure.

The discharge of produced water is from topsides for decades and the requirements for discharge for various countries is shown in Table 3.1. As the discharge of produced water in subsea concept is in the developmental stage, there are no regulation and guidelines at present.

Chapter 4

Background of the Project

The main objective of this thesis is to optimize the fabrication plan by looking into the best way to assemble all equipment, modules, and structural section units. Subsea 7's main focus is to identify the best possible method to assemble the GRP structural joints along with the subsea buoyancy materials.

4.1 GRP and Buoyancy Material Connection Overview

GRP is a composite consisting of a polymer resin, usually unsaturated polyester, vinyl ester or epoxy resin, mixed with catalyst and hardener and reinforcing fibres in chopped strand, rovings or mat form [14]. Chopped glass fibre strands forms the base of the GRP as shown in Figure 4.1.

4.1.1 Challenges Associated

In the process of fabrication and assembly, the challenges are associated with four structural joints as shown in Figure 4.2.

The joint types with the challenges associated are explained below:

- Type 1 connection depicts the joining of GRP longitudinal beams.
- Type 2 connection shows the joining of GRP vertical beam with steel pontoon.
- Type 3 connection illustrates the joining of GRP longitudinal beam with vertical and transverse GRP beams. This joint connection is more challenging than the other connection types.

- Type 4 connection elucidates the joint connection for fabricating the beam itself.

Figure 4.1: Glass-Fibre Strands

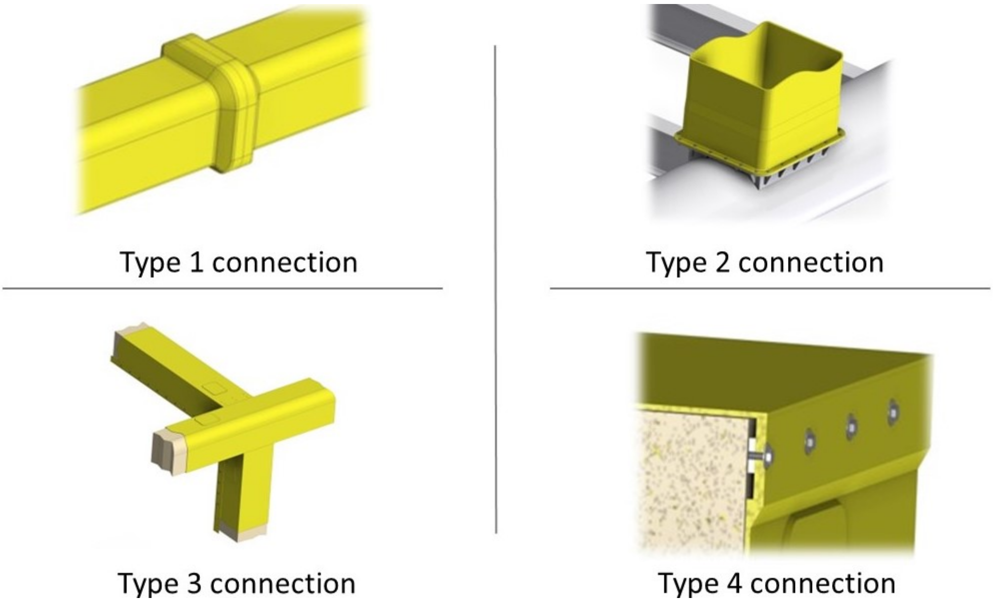


Figure 4.2: Connection Types [41]

All the joint connections are performed from inside. Therefore, the work flow here is to have a manhole opening to access the joint for connecting the beams and then filling the opening with subsea buoyancy materials later. The challenge here for the author is to minimize these joint connections and also to find a better alternative solution for connecting the beams.

4.1.2 Design Consideration

In order to achieve the objective, some factors associated with fabrication and design of the SPU were considered. They are as follows:

- Snag points on the structure should be avoided because it could get in contact with the fishing gears resulting in damage to the whole structure.
- Fabrication limitations imposed by the fabrication yards like maximum principal dimensions, crane capacity, transportation facilities, etc.
- A question of how buoyancy materials are assembled inside GRP beams.
- Equipment dimensions leading to change in main dimension.
- Water depth also plays an important role as it is the main criterion for selecting the buoyancy material based on the density requirement.
- Cost.

4.1.3 Fabrication Methodology of GRP

Vacuum Infusion process is used in the GRP manufacturing process. It is a technique that uses vacuum pressure to drive resin into a laminate [18]. Vacuum infusion utilizes a vacuum bag to debulk or compact a part's complete laminate ply schedule of reinforcements with or without core materials laid onto the mould [7]. After debulking, the resin is introduced, which is driven by the vacuum pressure where they are sucked into the reinforcements and eliminate all air voids in the laminate structure.

This process in comparison with traditional open moulding technique has the following main effects [7]:

- Emission of gas to the outer and inner environment is reduced.
- Fibre to resin ratio is better.
- High quality laminates are achieved.

- Increase in weight/strength ration.
- Water ingressment in deepwater and high pressure is eliminated with minimal voids.

Further development techniques includes injection with integrated foam stiffeners, which reduces the requirement for secondary bonding operations. Hand layup method can also be used for GRP fabrication. A separate moulding room with ventilation is required to perform this operation [7].

4.2 Possible Fabrication Methods

There are different ways in which GRP and buoyancy materials can be fabricated and assembled. This section explains some fabrication and assembly methods which provides an insight of the issues associated with it.

4.2.1 Buoyancy Material as a Mould for GRP

The solid buoyancy material can be used as a mould to fabricate the GRP beam. Figure 4.3 shows that the buoyancy material is attached to a roller and the glass fibre sheets are then rolled over the buoyancy material. In this way, the complete beam can be fabricated. This method has its limitation in fabricating the complex shapes.

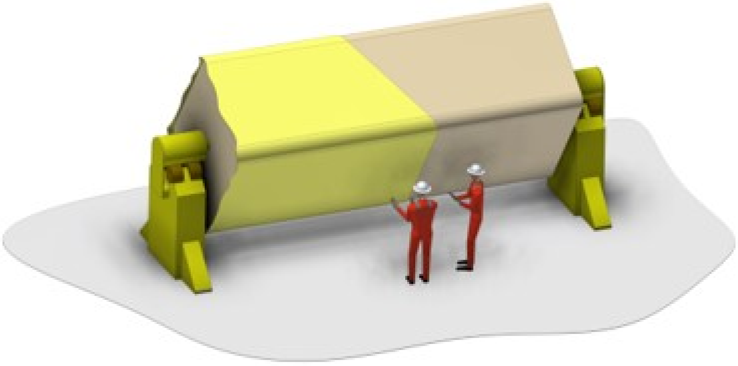


Figure 4.3: GRP Fabrication Method 1 [41]

4.2.2 Buoyancy Material Pushed into GRP

The other way of fabricating the beam is by making the GRP beam as a whole unit and then pushing the pre-fabricated buoyancy module inside using hydraulic jacks as shown in Figure 4.4. This method also has its limitations in fabricating the complex shapes.

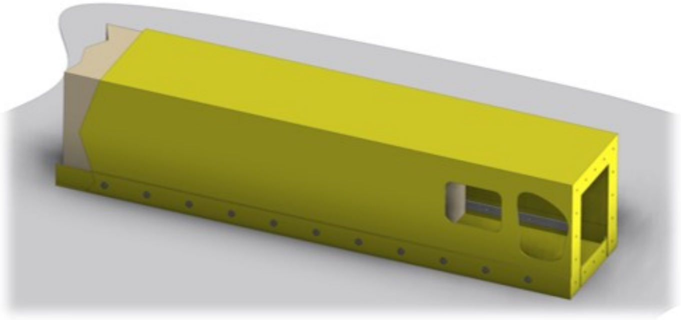


Figure 4.4: GRP Fabrication Method 2 [41]

4.2.3 Buoyancy Material Assembled into GRP

In this method the GRP beam is split into a base and a top. Pre-fabricated buoyancy material is assembled on the GRP beam base and then the GRP beam top is fixed in position. Finally, the GRP beam base and top are aligned and connected using nuts and bolts. For complex shapes, the buoyancy materials are shaped by chamfering to fit the GRP base. This is illustrated in Figure 4.5.

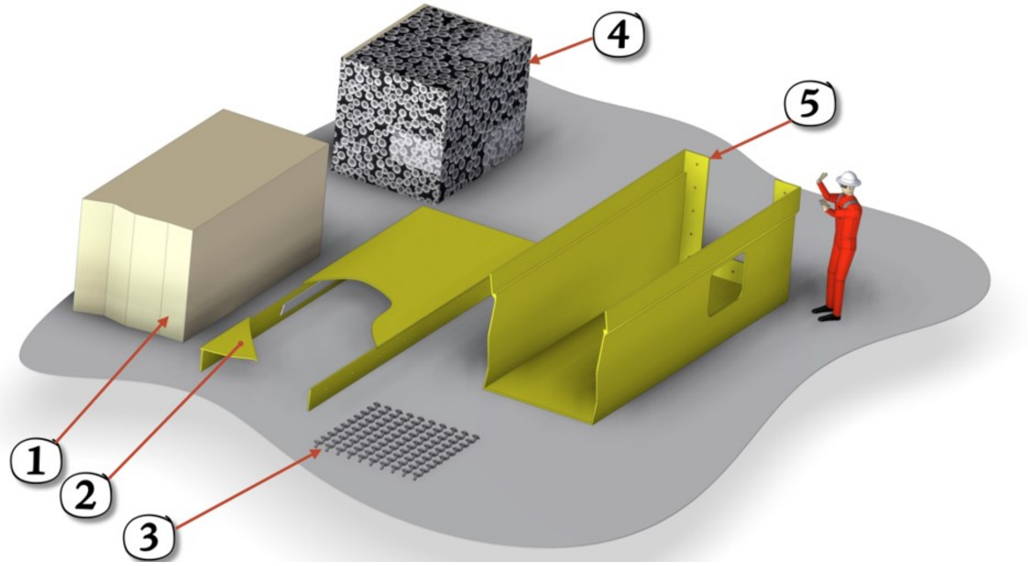


Figure 4.5: GRP Fabrication Method 3 [41]

The information provided in this chapter are the inputs about the project describing the complexity and options considered for solving various problems. These background information formed the base for this research work to explore the options available for solving the mentioned challenges.

Chapter 5

Step-by-step Approach

Deductive logic pattern, typically forms the basis for most engineering disciplines to find the solution for a problem or to design a product [15]. This can be explained in simple terms as:

$$D + K_a \overset{Analysis}{\rightarrow} I_f$$

Where, D refers to the object description, K_a represents the analysis knowledge which takes D as input and I_f refers to the set of performances achieved. Turning this pattern around results in starting with a set of performance requirements leading to a design description as,

$$I_{req} \overset{Design}{\rightarrow} D$$

In this way, the obtained engineering knowledge cannot be applied directly in order to find a solution [15]. Using this engineering knowledge in an indirect way will certainly result in many feasible solutions. The objective here is to identify the best possible solution with constraints of a design objective such as cost and risk reduction. This can be achieved by following a design process that goes back and forth between the form and functional spaces as elucidated in Figure 5.1. The form space to get familiarized, includes the descriptions of design in the form of main dimensions, material, colour etc. The functional space includes the performances of design like cost, safety, weight, speed etc.

This thesis mainly follows this concept of going back and forth between the decision and performance space to achieve optimized results. This will be explained in detail in the following chapters. An industrial visit to enhance the knowledge of performance requirements was the starting point of this thesis.

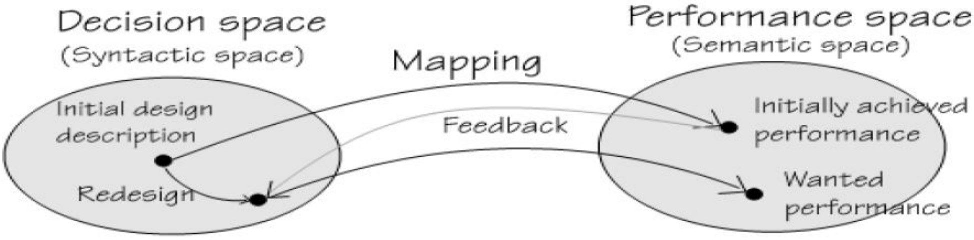


Figure 5.1: Design Process [15]

With all the background and inputs, a step-by-step approach was adopted to find the optimized assembly plan. All the connection joints and fabrication methods mentioned in Chapter 4 were reviewed before the visit to the GRP fabricator of Subsea 7.

5.1 Visit to GRP Fabricator

GRP material fabricator located in Norway was visited. This industrial visit resulted in identifying the crux areas in the design of SPU. The background of the visit is to develop a fabrication friendly design by identifying the limitations in fabrication. Shop dimensions, crane capacities, internal transport facilities and the existing logistics resources were noted in order to design the SPU with desired dimensions.

5.1.1 Production Facilities in Norway

Arendal yard had 4 Electric Overhead Travelling (EOT) cranes each of 15t capacity. The fabrication shop was split into two, so the maximum lifting capacity was 30t. The maximum door width for fabrication of GRP structures was 11m. GRP structures were fabricated based on vacuum infusion method using DNV-OS-C501, a standard for composite materials. The yard had special purpose areas for moulding and cutting covering 500m^2. It also had curling ovens, compressed air system and vacuum system for fabrication. A quay of 300m length with water depth of 12m was located besides the fabrication shop for transportation purpose. 40t trolley of 10x4m was used for internal transportation. It had a crane of capacity 120t at the quay [6].

Table 5.1: Production Hall Dimensions [6], [5]

Location	Length(m)	Width(m)	Height(m)
Norway Hall 1	60	16	11
Norway Hall 2	114	11	5
Lithuania Hall 1	78	20	9
Lithuania Hall 2	36	30	20

5.1.2 Production Facilities in Lithuania

The GRP vendor also have their fabrication yard in Lithuania. The method of fabrication is the same as in Norway with special purpose areas, curling ovens, compressed air, vacuum system and quay area. The fabrication hall has 4 cranes with 18 to 25t capacity [5]. It also has 40t trolley of 10x4m for internal transportation. The production hall dimensions in Norway and Lithuania are specified in Table 5.1.

5.2 Outcome of the Visit

A good knowledge of the production facilities and techniques resulted in solving the issues associated with GRP structural joint connections. An input to fabricate GRP beam in two pieces as shown in Figure 5.2, rather than making it in a single tubular form was taken as an important consideration for the next fabrication processes. The reason for choosing such fabrication method is to reuse the GRP moulds and is discussed in detail in Chapter 9, Results and Discussion.

Another conclusion after the industrial visit was with regards to Type 4 connection as shown in Figure 5.3. The initial plan of bolting the top and base of the beam was changed to lamination of the joints. Laminating the GRP top and base will result in cost reduction comparatively as the usage of super duplex steel bolts and nuts are avoided.

5.3 Logistics Plan

The efficient logistics plan was made with focus on space, cost and time based on the existing logistics plan of the GRP fabricators in Norway. The common mode of transportation is by using bulk carriers of size 60*10*7m in Norway. Standard container size is 40(12.2)*8(2.43)*8.5(2.59m)ft. Using Open-top containers, three GRP sections of 12m length can be stacked to save cost. One Open-top container can be rented for 5000 Norwegian Kroner (NOK) per day in Norway which saves 30% of the cost compared to the closed containers. For internal transportation, a trolley of 40t and 120t quay crane can be used. An illustration of an Open-top container is shown in Figure 5.4. So, the use of Open-top container on bulk carriers was chosen for transportation of GRP beams to assembly yard.

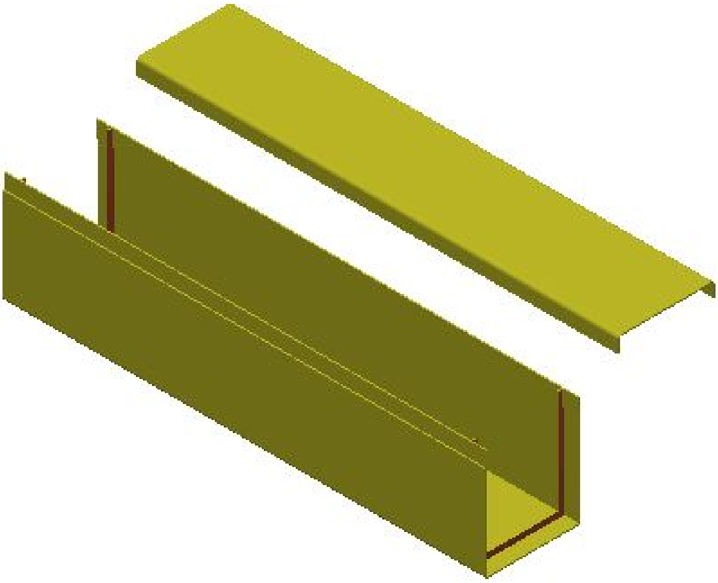


Figure 5.2: Split Beam

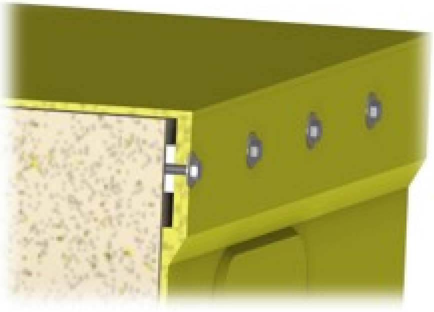


Figure 5.3: Type 4 Connection [41]

Figure 5.4: Open-top Container [10]

5.4 Modelling of SPU

After the industrial visit, it was decided that Type 2 connection as shown in Figure 4.2 does not require any further attention. Discussions with Subsea 7 structural engineers led to the conclusion of using the same joint type for connecting the vertical GRP beams with steel pontoons. So, Type 1 and Type 3 connections became the next targets. With all this background information, a preliminary design for the joint connections was performed using Autodesk Inventor software.

5.5 Autodesk Inventor

Autodesk Inventor Professional 2018 was used in the modelling of SPU. It is a 3D CAD software for product development offering professional-grade 3D mechanical design, documentation, and product simulation tools [2]. Inventor 2018 is built for the continually evolving needs of the modern design and engineering professional. The software has many features like product design and modelling, collaboration and design automation, modelling, automation, inter-operability, simulation and visualization.

5.6 Initial Model

Before modelling the SPU, practical difficulties associated with the assembly of buoyancy material and GRP as mentioned before were considered. Initially, the bolt and nut connections from the inside of GRP beams for Type 1 and Type 3 connections was opted as the solution, which is shown in Figure 5.5.

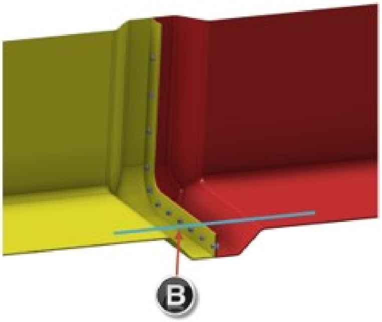


Figure 5.5: Bolt Connection Inside GRP Beam [41]

It becomes more time consuming and tedious process if the joint connections are performed from inside of the GRP beam, as the buoyancy modules are to be taken inside after connecting the beams. Since fabrication friendly design is emphasized, a model was created with joint connection flanges protruding outwards for assembly. A GRP beam was modelled as shown in Figure 5.6, with flanges on both ends for bolt connections.

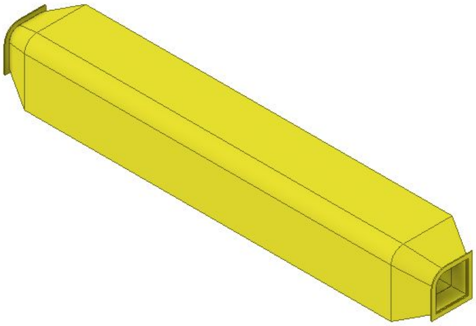


Figure 5.6: GRP Structural Beam

Though this design resulted in connecting the joints from outside, it had snag points. Knowing this, a flat bar was lapped to the beams only in one corner to avoid snag points in the boundaries as shown in Figure 5.7.

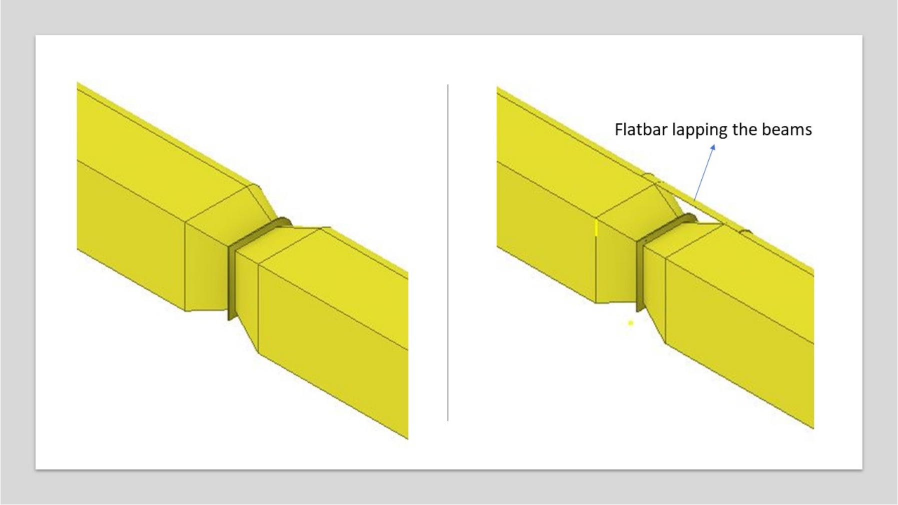


Figure 5.7: Flatbar Connecting Two GRP Beams

This seemed quite efficient as the entire SPU assembly from outside was feasible without having any requirement to access the GRP beams from inside and also a tedious process of taking the buoyancy modules inside after joint connections. The lap joint has to be glued to the beams after they are assembled. Although it seemed feasible, the lap joint could rupture if the structure was lifted during assembly.

5.7 Modified Model

The possibility of lap joint failure as a consequence of lifting was considered and the model was redesigned. The beam was designed in a way to have a curved flat bar attached to the flange as shown in Figure 5.8.

The objective of this design was to have a smooth outer structure avoiding snag points, lap joint failure and to have access for connecting the beams using nuts and bolts from outside. The difference in the beam design is illustrated in Figure 5.9. In this way the whole SPU was modelled with longitudinal, transverse and vertical beams. Complete SPU model with smooth finish on the boundaries is shown in Figure 5.10.

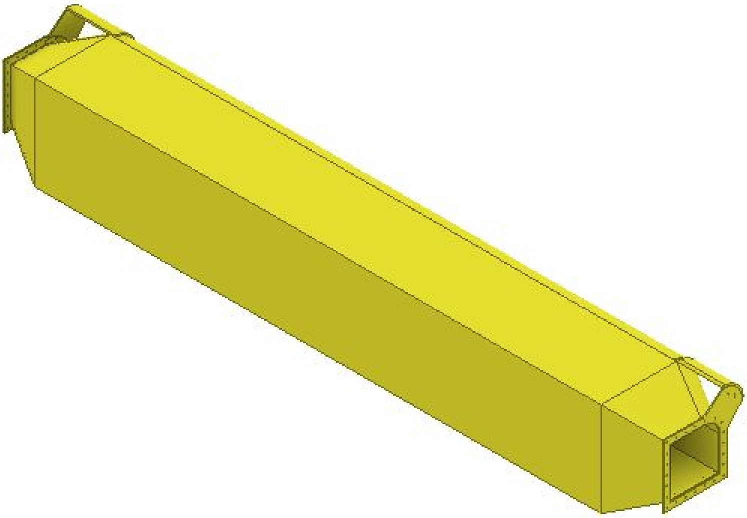


Figure 5.8: Modified Beam

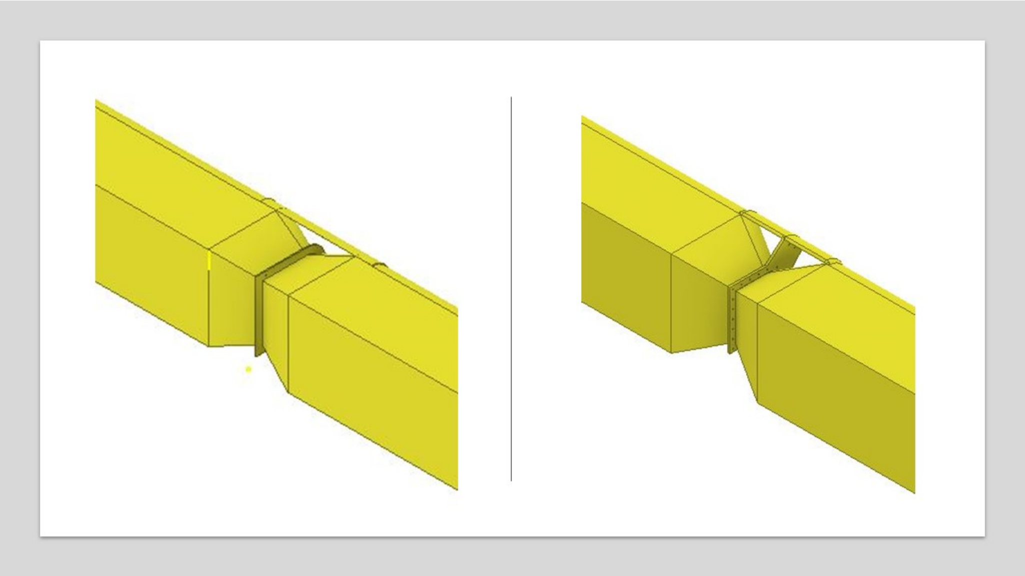


Figure 5.9: Difference in Beam Design

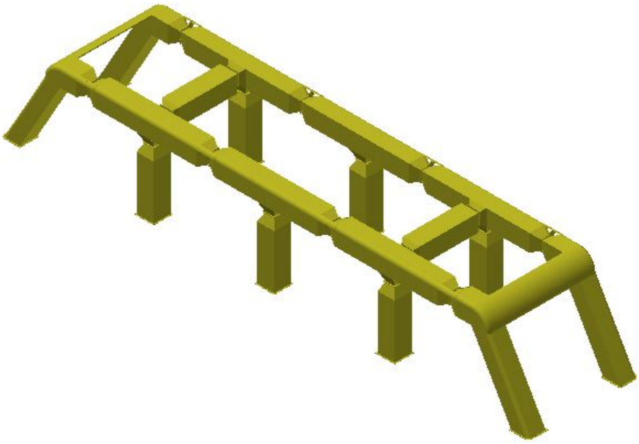


Figure 5.10: Modified SPU Model

5.7.1 Advantage of Model

If carbon steel bolts and nuts are to be used, then having the GRP beam joint connections inside will result in usage of sacrificial anodes to prevent corrosion. Sea water flow inside the beam has to be ensured for the function of anodes. This demands openings in the beam creating complexity during the assembly process. This issue is completely avoided with this new model having joint connections and anodes outside the GRP beam.

5.8 Critical Decision

The model was then reviewed for approval by Subsea 7 engineers. Upon serious discussion, it was concluded to decline this design concept. The reasons are specified below:

- There were many uncertainties in the design. In particular the reduced cross section of the beam at the ends. This led to the loss of buoyancy material at the ends of beams. As this type of connection was uniform for all joints, it was expected to have more loss of buoyancy of the SPU.
- Moreover, it became quite obvious to have high stress concentrations at the reduced cross-section, which could result in loss of strength.
- The SPU being modelled is first of a kind and is in the developmental stage. Considering this fact, it was decided to have a robust design.

So, the critical decision of avoiding the reduced cross-section of the beams and the usage of carbon steel bolts and nuts was taken. Inconel Alloy 625 bolts suitable for subsea environment without the requirement of sacrificial anodes were considered for connecting the GRP beams. Figure 5.11 depicts the reduced cross-section of the beam.

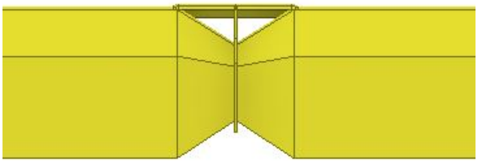


Figure 5.11: Reduced Cross-section

This process clearly explains the design method being followed in this thesis. As explained in this chapter, the concept of moving back and forth between the performance and design space is followed throughout this thesis as in GRP beam modelling, till the optimized solutions are obtained.

Chapter 6

Evolution of the SPU Model

This chapter explains in detail about the evolution of the SPU model. With the inputs from Subsea 7 engineers and their vendors, a new model was visualized and created in Autodesk Inventor.

6.1 Finalizing the Structural Dimensions

Before creating the assembly plan, a detailed study was performed and more importance was given to distribute the buoyancy material across the structure without any buoyancy loss. The buoyancy material of volume 3.997E+11m^3 and density 450kg/m^3 was taken from the SPU study report [39]. The report was made for the same SPU being discussed in this thesis. So, from the study report results, the main dimensions of the SPU were fixed. [39]. The main particulars are:

- Length: 43m
- Width: 9.5m
- Height: 7.7m
- Weight in air: 616t (in air)
- Weight in water during tow -30t (buoyant)
- Weight on seabed: 110t

As mentioned in Chapter 3, the dimensions of three main equipment gas harp, dual pipe separator and compact flotation unit were taken into account in order to distribute the buoyancy material based on the main dimensions. The length of the dual pipe separator is 10.7m, which is the maximum of all equipment dimensions. There were two CFU's each of length 6m and 2.5m assembled parallel. With all these inputs a 2D drawing of the profile was generated initially in AutoCAD and then a 3D model in Autodesk Inventor. The wall thickness of the GRP structure was taken as 21mm and the flange thickness as 36mm based on Subsea 7 engineer's input. A preliminary equipment arrangement plan is illustrated in Figure 6.1.

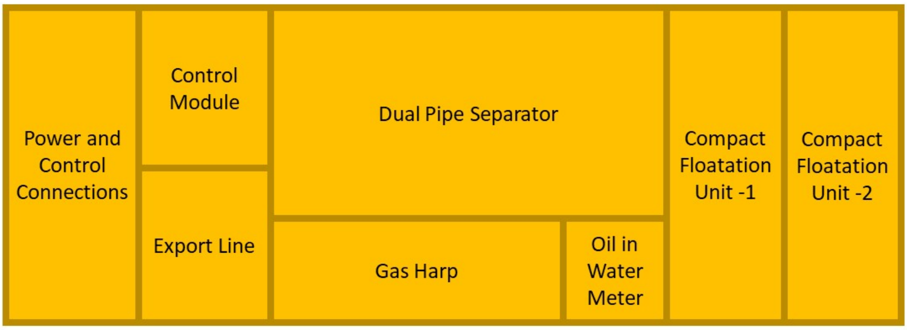


Figure 6.1: Equipment Arrangement Plan

6.2 Standardizing the Beams

A preliminary model was created with all the background information. In order to standardize the design, the cross-sectional dimensions of the beam were maintained the same throughout the length. Longitudinal beams, transverse beams, end beams and vertical beams were planned in the design.

6.2.1 Longitudinal Beam

The SPU structure consists of a steel base with pontoons. From the SPU report, it was noted that the volume requirement of buoyancy material was high, and the height of the steel base and overall SPU height was fixed to 1.5m and 7.7m respectively. With all these considerations, the height of the longitudinal beam was calculated as 2.4m in order to distribute the volume of the buoyancy material. The beams were designed in two different lengths in order to account for smooth installation and retrieval of all equipment. The dimensions of the beam are as follows:

- Dimension of type 1 beam – 10000*2400*1400mm
- Quantity of type 1 beam – 2 nos
- Dimension of type 2 beam – 5600*2400*1400mm
- Quantity of type 2 beam – 4 nos

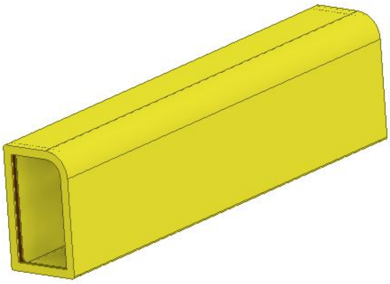


Figure 6.2: Longitudinal Beam

In total, 6 longitudinal beams were modelled for both port and starboard sides. Figure 6.2 shows a typical longitudinal beam modelled in Autodesk Inventor with a smooth finish on one edge, throughout the length to avoid snag points.

6.2.2 Vertical Beam

The next step was to model the vertical beam. This beam is in connection with the longitudinal beam and the steel pontoon. The beam dimensions are as follows,

- Dimension – 3200*1400*1400mm
- Quantity – 8 nos

The Figure 6.3 shows a typical vertical beam modelled in Inventor.

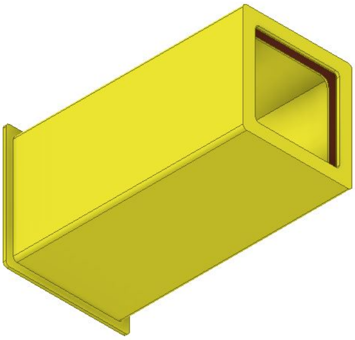


Figure 6.3: Vertical Beam

6.2.3 Transverse Beam

This beam connects the port and starboard longitudinal beams. The beam dimensions are as follows,

- Dimension: 5500*1400*1400mm
- Quantity: 4 nos

Figure 6.4 shows a typical transverse beam modelled in Inventor.

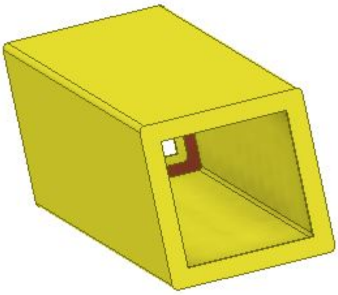


Figure 6.4: Transverse Beam

6.2.4 End Beam

This beam has a curvature extruded from the end of the longitudinal beam to the steel pontoon.

- Dimension: 5700*2400*1400mm
- Quantity: 4 nos

The Figure 6.5 depicts the end beam modelled in Inventor.

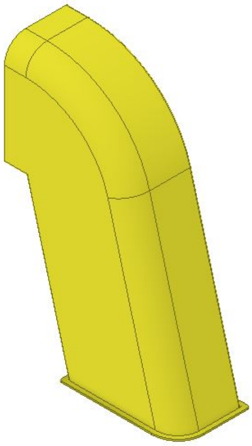


Figure 6.5: End beam

6.3 Buoyancy Module Assembly

As mentioned in section 5.2, split fabrication of GRP beam was preferred. The components forming the structural beam are GRP beam base, GRP beam top and the buoyancy module as shown in Figure 6.6.

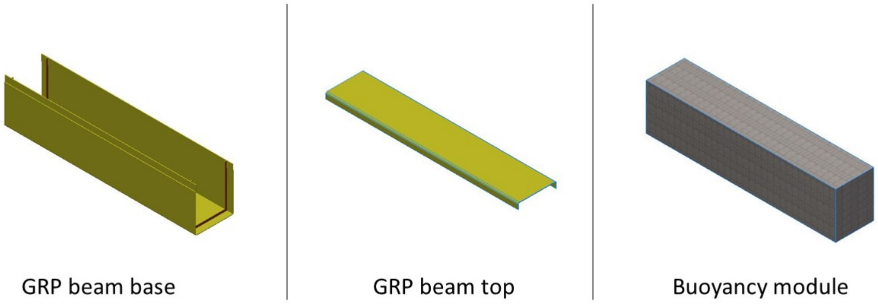


Figure 6.6: Beam Components

The buoyancy modules are to be prefabricated by the vendors to desired shapes and supplied to the GRP beam fabricator for the assembly. Buoyancy module is then assembled on to the GRP beam base and laminated with the GRP beam top as shown in Figure 6.7.

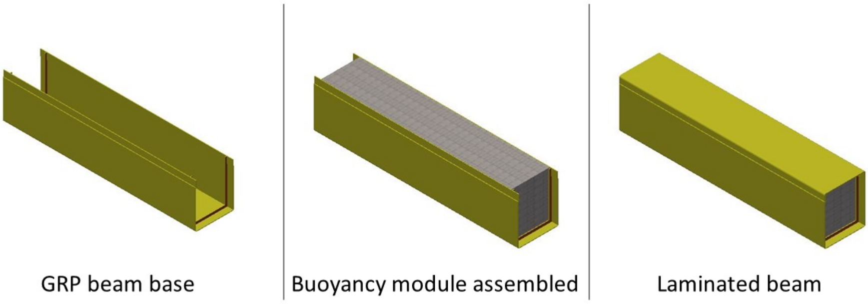


Figure 6.7: SPU Beam Assembly

In this way all the longitudinal, transverse, vertical and end beams are to be fabricated with buoyancy modules inside. An important consideration of having the buoyancy stoppers on both sides of all the beams fabricated was incorporated in the design for efficient assembly as shown in Figure 6.8.

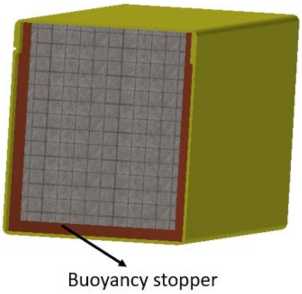


Figure 6.8: Buoyancy Material Stopper

6.4 3D Joint

The crux part next is to assemble all the pre fabricated GRP beams containing the buoyancy modules. A GRP 3D joint was modelled with a manhole opening on top for access as shown in Figure 6.9

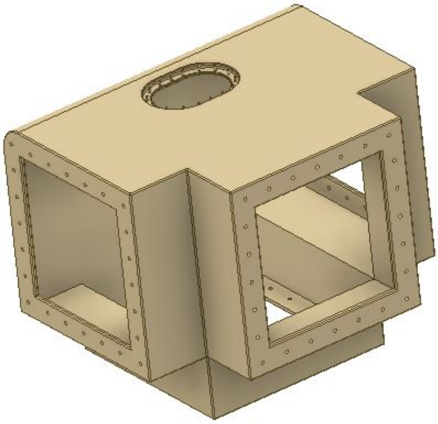


Figure 6.9: 3D Joint

This joint was designed to be without the buoyancy module initially. The purpose of keeping the 3D joint void is to access the longitudinal, transverse, vertical and end beams flanges for bolt connections.

- Dimensions: 2400*1400*2500mm (with 500mm additional protrusion in Y and Z axis)
- Quantity: 8 nos

The main reason for using the buoyancy stopper is to have void space for accessing the flanges of the GRP beams to connect with the 3D joint. This joint is used as a one way access to connect it with longitudinal, transverse and vertical beams. The assembly plan is shown in Figure 6.10.

6.5 Buoyancy Module Fabrication

The buoyancy modules can be made of different materials as they are immensely versatile. The subsea buoyancy materials fall in three main groups as shown in Figure 6.11, defined in general terms as:

- Polyurethane Foam
- Co-Polymer Foam

- Syntactic Foam

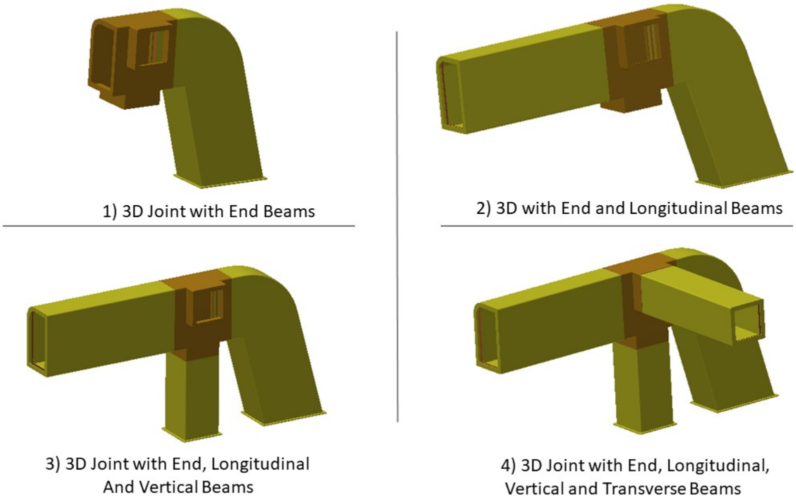


Figure 6.10: 3D Joint Assembly with Adjacent Beams

Figure 6.11: Subsea Buoyancy Materials

The selection of buoyancy material is based on its operating conditions [32], which includes:

Table 6.1: Typical Polyurethane Foam Properties [32]

Property	Value
Density	$160 kg/m^3$
Tensile strength	1000KPa
Compression strength	1700KPa
Thermal conductivity	0.033W/mK

- Operating depth and duty cycle
- Maximum depth
- Buoyancy required
- Geometry of element
- Method of attachment
- Method of installation

6.5.1 Polyurethane Foam

Polyurethane foams are manufactured under controlled conditions by mixing together a blend of liquid chemicals. During the process, the material expands and cures, forming a rigid closed cell foam [32]. The properties of the material are based on the original formulation, and mixing and casting conditions. This material has operating water depths less than 100 metre seawater (msw).

Polyurethane foams must be encapsulated to prevent water ingressment. Foam core directly exposed to the sea water could result in sea water absorption leading to the collapse of individual foam cells under hydrostatic pressure. These foams can be encapsulated in a homogeneous skin like polyurethane elastomer. This results in the increase in its operating depth to 200msw as the shell protects the foam from hydrostatic pressure directly. For subsea usage, Polyurethane foam density range is typically 50 - $250 kg/m^3$. The typical properties of Polyurethane foam are shown in Table 6.1. The relationship between water depth and density for unprotected and encapsulated foam is shown in Figure 6.14.

6.5.2 Co-Polymer Foam

Cross-linked Co-Polymer foams are rigid closed cell foams capable of withstanding hydrostatic pressure without the need for total encapsulation [32]. They are made of foam sheets laminated with adhesives. The adhesives

Table 6.2: Typical Co-Polymer Foam Properties [32]

Property	Value
Density	$200 kg/m^3$
Hydrostatic yield point	40Bar
Compression strength	4000KPa
Thermal conductivity	0.048W/mK

used should have a minimum strength that is equivalent to the material strength. The structure is then machined to get the desired shape. A polyurethane external coating may be applied for surface protection and improved appearance.

Density ratings are from 40 - $400 kg/m^3$. Depending on equipment and operating conditions this density range enables buoyancy systems to operate at depths up to 600msw [32]. The typical properties of Co-Polymer foam is shown in Table 6.2. The relationship between water depth and density for Co-Polymer foam is shown in Figure 6.14.

6.5.3 Syntactic Foam

Syntactic foams are used for deep water applications. They are available as:

- Pure Syntactic Foam
- Composite Syntactic Foam

Pure Syntactic Foam

A base polymer is the primary constituent of pure syntactic foam [32]. Process technique here is very critical as the intrusion of air leads to water absorption of polymer, resulting in a tremendous loss in buoyancy of the component.

The base polymer is almost neutrally buoyant with a specific gravity of 1.0 under normal conditions. The combination of base polymer material and microspheres forms the pure syntactic foam. The addition of microspheres to the polymer results in density reduction. Microspheres are the small hollow glass spheres varying in diameter between 20 and 150 microns as shown in Figure 6.12 [32]. The inclusion of microspheres results in the reduction of specific gravity to between 0.46 and 0.65, making them extremely strong for deep water applications. The densities of pure syntactic foam range from 380 to $650 kg/m^3$, providing an operational capability to full ocean depth [32].

Figure 6.12: Microspheres

Composite Syntactic Foam

Composite Syntactic foams are fabricated by adding macrospheres to the base polymer and microspheres. The addition of macrospheres reduces the density of the material further. Macrospheres are of three types [32]:

- Macrospheres - These are hollow spheres having an external diameter of 50 - 110mm

- Midispheres - These are hollow spheres with an external diameter of 20 - 40mm

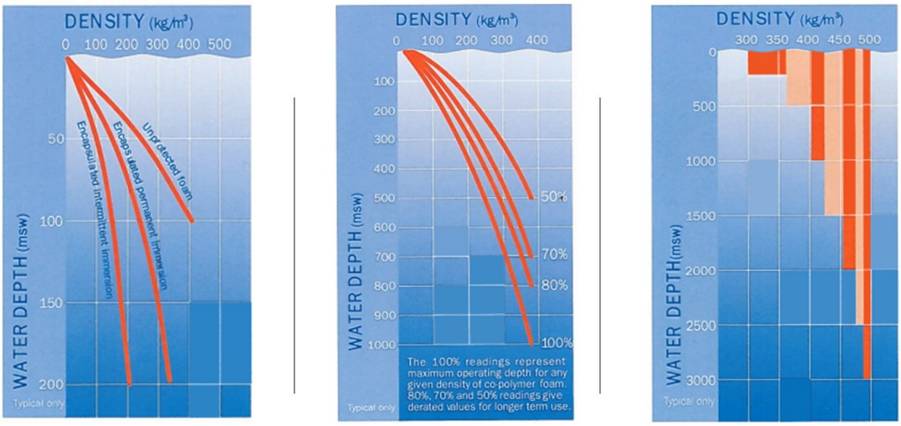
- Minispheres - These are hollow spheres having an external diameter of 10 - 15mm

Macrospheres are depicted in Figure 6.13. The inclusion of macrospheres results in the reduction of the specific gravity of foam between 0.275 and 0.56. The densities of composite syntactic foam range from 275 to $560 kg/m^3$, providing an operational capability to 4000m water depth [32]. The typical properties of syntactic foam are shown in Table 6.3. The relationship between water depth and density for syntactic foam is shown in Figure 6.14.

Table 6.3: Typical Syntactic Foam Properties [32]

Property	Value
Density	490kg/m^3
Hydrostatic crush pressure	530Bar
Bulk modulus	2050MN/m^2
Thermal conductivity	0.15W/mK

Figure 6.13: Macrospheres



Polyurethane Foam

Co-Polymer Foam

Syntactic Foam

Figure 6.14: Water Depth vs Density Chart for Subsea Buoyancy Materials [32]

The Figure 6.15 shows the applicable water depth ranges for the subsea buoyancy materials.

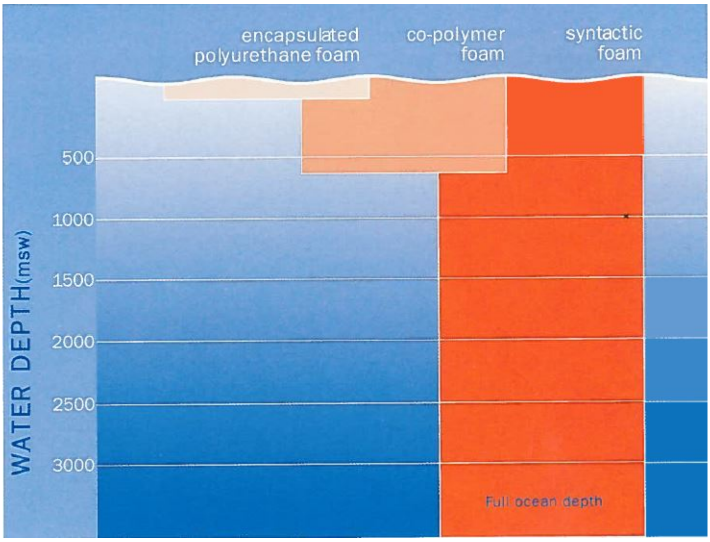


Figure 6.15: Subsea Buoyancy Materials Operational Water Depth Range [32]

All the buoyancy subsea buoyancy material discussed above undergoes buoyancy loss of 3% typically after 20 years [32]. The expected buoyancy loss percentage over the years is illustrated in Figure 6.16.

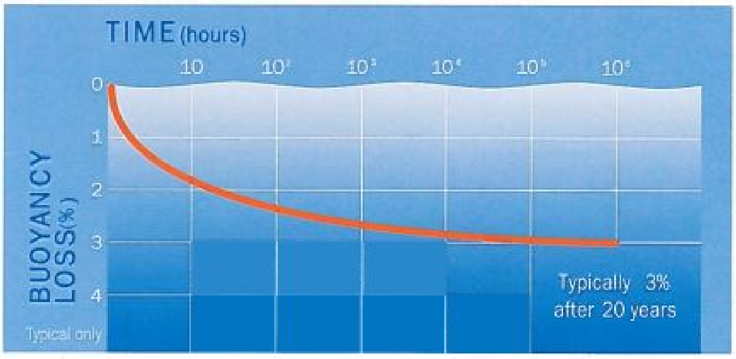


Figure 6.16: Buoyancy Loss Percentage [32]

6.6 Industrial Visit

An industrial visit to the buoyancy material vendor of Subsea 7, provided surplus information regarding the fabrication of subsea buoyancy materials with improved knowledge on the fabrication process.

6.6.1 Understanding of Fabrication Process

The fabrication methodology of composite syntactic foam was studied in detail. The buoyancy materials are usually fabricated in a steel mould to desired shapes. In general, the buoyancy modules are fabricated in the skin (e.g. Polyethylene, GRP). The skin is either rotationally moulded in Polyethylene or the glass mats laid up in the mould and impregnated with epoxy when the buoyancy system is cast. The purpose of the skin is to provide mechanical protection as well as to generate the geometrical shape for the buoyancy and also for easy removal of buoyancy module from the steel mould. The next step is to fill the skins with the designated number of macrospheres for the required buoyancy. The binder/syntactic foam is then pumped into the skin and cured either in an oven or in atmosphere depending on which fabrication system is being used. This is shown in Figure 6.17.

Figure 6.17: Cut-through Section of Composite Syntactic Foam

6.6.2 Outcome of the Visit

The best solution to assemble the buoyancy material with the GRP beams was obtained after the industrial visit. As explained earlier, the buoyancy modules are fabricated with GRP skin as a base over the steel mould. Since the buoyancy modules are to be assembled into the split GRP beam as a next step, the feasibility of using the split GRP beam as a mould was considered for further research. In this way, the use of skin in the buoyancy module can be avoided leading to cost reduction. For developing such fabrication technique, the buoyancy module fabrication facilities has to be moved to the GRP fabricators site for efficient production. Another important advantage of this method is that complex shapes can be achieved easily using the GRP beam as a mould for buoyancy module. This is further discussed in detail in Chapter 9, Results and Discussion.

Chapter 7

Final Assembly and Launching

This chapter explains in detail about the consideration of various launching methods the SPU.

7.1 Launching Methods

Launching of SPU is one of the most important procedures of the entire SPU after fabrication process. Causing a vessel to move or slide from the land, or the stocks, into the water; setting afloat; lowering a buoyant structure into the water is termed as launching [3]. There are many ways of launching a buoyant structure. Some are:

- Dry Dock
- Floating dock
- Syncrolift
- Slipways
- Airbags

7.1.1 Dry Dock

A dock is a place where a floating structure can be built or sailed in or afloated. World's first dry dock was constructed in the year 1496 [44]. Since then numerous dry docks were constructed across the world with the improvement in technology. Though there are many new methods of launching the vessels, dry docks are considered reliable and are still in existence. It is a basin which can be closed off from surrounding waters by means of a dock gate, and which is provided with water level control pumps for bringing a vessel inside the basin from a floating to a non-floating condition and vice versa [3]. During launching, once the structure is afloat it is hauled out of the dock using tug boats. The gates are closed and the water is pumped out of the dock as a last step, hence the name dry dock was coined. Figure 7.1 shows a typical dry dock.

Figure 7.1: Excavated Dock [22]

7.1.2 Floating Dock

Floating docks are technically termed as a semi-submersible platform with a ballasting and deballasting installation for lifting a vessel from a floating to a non-floating condition and vice versa [3]. It is considered to be one of the most technologically advanced structures ever designed in a marine environment [30]. It has a flat based deck on which the vessel to be launched rests. The cross section is typically U-shaped for all floating docks with side walls providing the stability when the deck is below the water level. The side walls contain pumps for controlling the water level in the pontoons below the deck. Pontoons consists of ballast tanks with partitions performing the function of lowering the whole platform during launching and vice versa. A typical floating dock is shown in Figure 7.2.

Figure 7.2: Floating Dock [9]

7.1.3 Syncrolift

The syncrolift consists of a flat platform held by a series of hoists throughout its length on both sides. The hoists are in permanent contact with the pile structures which are fixed to the sea bed. The hoists control the motion of the platform by lowering it down and up for launching and docking. The platform consists of rails extending to the dry berths. The structure to be floated is assembled on an A-frame and is moved to the syncrolift platform using transport cars on rails. The transport cars have a jack system under each A-frame which lifts the entire structure to be launched and transports it to the syncrolift platform. Figure 7.3 depicts a syncrolift platform.

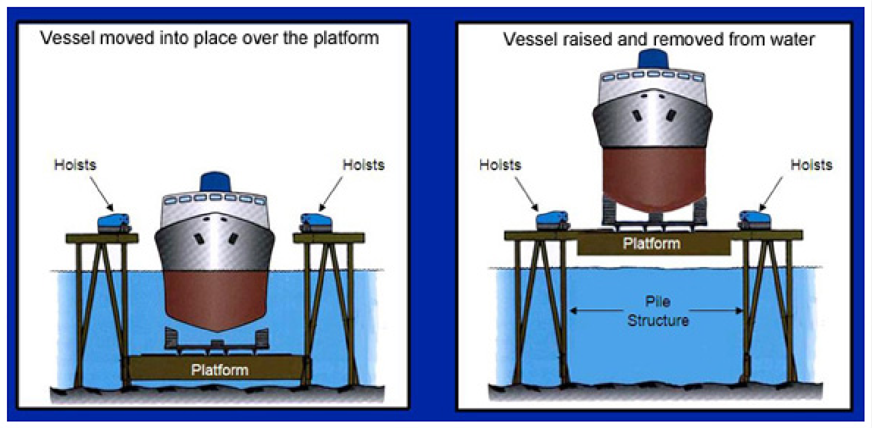


Figure 7.3: Syncrolift Platform[37]

7.1.4 Slipways

Slipways uses a fully greased sliding ramp for launching. There are three ways it could be launched [28]. These are specified below:

- The vessel can be slipped in ways that extends well below the water.
- The vessel can be tipped off from the end of the ways above water.
- The vessel can be built on piles that are intended to collapse by a sideways push on the vessel while launching.

Figure 7.4 shows the slipways launching configuration.

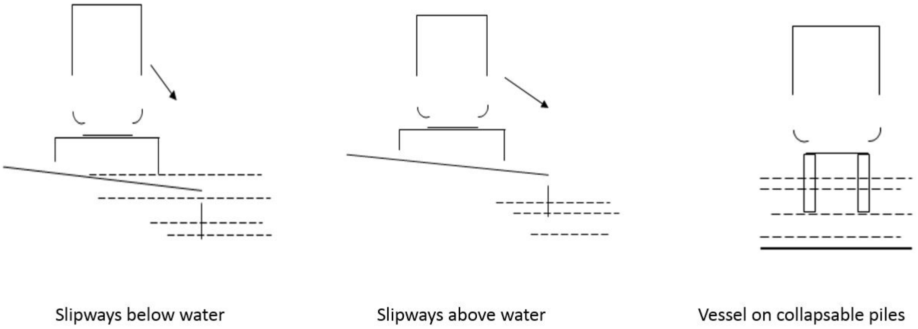


Figure 7.4: Slipways [28]

7.1.5 Airbags

An innovation in launching technology is using rubber airbags. Air bags are widely used in shipping industry in recent years. It is said to be introduced by the Chinese for use in emergency launching during the early 1980s [20]. Fixed launching track challenges are overcome using airbags. The technology is considered reliable, safe and cost effective. The airbags can be used for 7 to 15 years with reasonable maintenance and care [20]. The structure to be launched is held on top of the airbags. The structure is also connected to winches to have the control over stability while launching. During launching winches control the movement of the structure over airbags and the winch ropes are removed when it gets slacked after the structure has been launched. Figure 7.5 shows the airbags launching configuration.

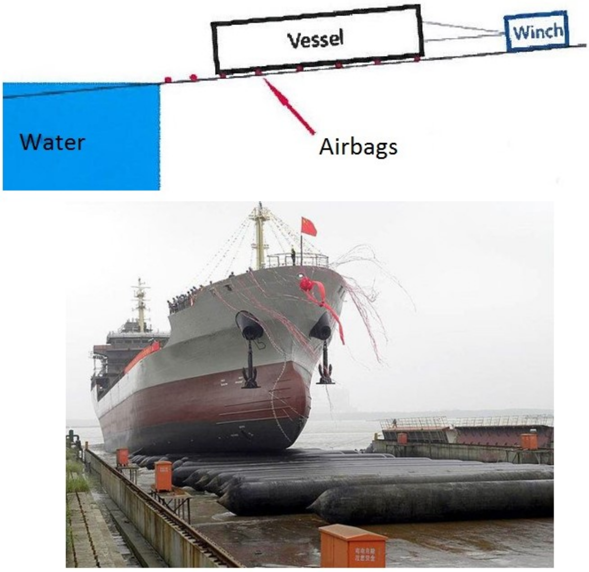


Figure 7.5: Airbags Launching Configuration [20] [16]

7.2 Yards in Norway

A detailed knowledge of various launching methods directed this thesis in search for various yards in Norway. Seven yards were considered for launching and are as follows:

- Rosenberg - This yard has two dry docks, located in Stavanger

- Westcon - This yard has a covered dry dock located in Helgeland
- Aker Solutions - They have load out facilities in Egersund
- Vard - A floating dock in Langsten
- Agility Subsea Fabrication - It has load out facilities in Tønsberg
- Bergen Group AS - A dry dock in Bergen
- Kimek - Syncrolift facility in Kirknes

7.2.1 Filtration Process

The yards mentioned above provided the various options for launching the SPU in Norway. Based on their facilities, location, and launching methods only three yards were chosen for the next process. Major yards were neglected based on their limitations in handling the SPU because of their water depth at Mean Sea Level (MSL) less than 7m, which is the depth of the SPU. Few yards were neglected as the SPU was planned to be launched and towed instead of load-out method. Taking into account the limitations in launching associated with the SPU, Rosenberg, Westcon and Kimek were the three yards chosen for further analysis. The facilities of all these yards are provided in the Appendix A.

7.3 Analytical Hierarchy Process (AHP)

AHP was used to make a decision on the yard to be chosen for launching. AHP, introduced by Thomas Saaty (1980), is an effective tool for dealing with complex decision making, and aiding the decision maker to set priorities and make the best decision [42].

7.3.1 Basic Principles of AHP

The AHP is considered to be a very flexible and powerful tool as the scores and the resulting final rankings obtained are based on the pairwise relative evaluations of both the evaluation criteria and the author's alternative options [42]. Evaluation criteria are the aspects in authors's mind, which are set up in AHP for a set of alternative options with the aim of identifying the best among them. The alternative options in this case are Rosenberg, Kimek and Westcon yards. The Saaty rating scale in Table 7.1 gives the relative importance number on a scale to be chosen between the available options for pair wise comparisons. The first step is to generate a score

Table 7.1: The Saaty Rating Scale [15]

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	When compromise is needed

based on Saaty's scale for each criterion considered according to the author's pairwise comparisons of the criteria. A criterion becomes more important when its score is high. The next step is to consider a criterion and then assigning a score based on Saaty rating scale to each alternative options according to the author's pairwise comparisons of the options taking into account the criterion considered. As a last step, the AHP combines the score of evaluation criteria and alternative options, in order to obtain a global score for each alternative option, and a consequent ranking. The global score for a given alternative option is a weighted sum of the scores it obtained with respect to all the evaluation criteria [42]. The final step in AHP is the Consistency Ratio(CR) calculation to determine how consistent the judgments have been relative to large samples of purely random judgments. If the CR is much in excess of 0.1 the judgments are untrustworthy as they are too close for comfort to randomness and the exercise becomes valueless or must be repeated [15].

7.3.2 Application of AHP

The evaluation criteria considered in AHP are:

- Cost
- Safety

- Fabrication Facilities
- Commissioning Facilities

As mentioned earlier, the first step in AHP was to create a pair wise comparison between the evaluation criteria considered. The Saaty rating scale shown in Table 7.1 was used for rating the evaluation criteria. The scores were given based on the importance level indicated in Saaty rating scale. For example, if the safety criterion is considered absolutely more important than cost criterion then the score for safety is 9 and for cost is 1/9. Higher the score in AHP matrix, more important it is. The ratings were based on author′s decision with the approval of Subsea 7 engineers.

7.3.3 AHP Matrix Creation

Table 7.2 shows the ratings for the pairwise comparisons of evaluation criteria based on the Saaty rating scale. The principal diagonal has the entry with value 1 always as each criterion was considered as important as itself. The author considered safety to be much more important than commissioning facilities, somewhat more important than fabrication facilities and slightly important than the cost. Having this in mind from the Table 7.2 the cell safety, cost was rated as 2 (safety is slightly important than cost), whereas cost, safety was rated as 1/2. The cell safety, fabrication facilities was rated as 3 (safety is somewhat more important than fabrication facilities), and so the cell fabrication facilities, safety was rated as 1/3. Similarly the cell safety, commissioning facilities was rated as 5 (safety is much more important than commissioning facilities) resulting in the cell commissioning facilities, safety as 1/5. In this way the entire matrix was generated. From the matrix it was also evident that the cost criterion was slightly important than fabrication facilities and much more important than commissioning facilities.

The next step was to generate a AHP matrix for each criterion by making pair wise comparisons of the alternative options considered. Here the ratings were based on the influence of the following factors in the alternative options:

- Fabrication shop
- Crane facilities
- Load banks
- Covered dock
- Assembly time

Table 7.2: AHP Matrix for the Evaluation Criteria

Evaluation Criteria	**Cost**	**Safety**	**Fabrication facilities**	**Commissioning facilities**
Cost	1	1/2	2	3
Safety	2	1	3	5
Fabrication facilities	1/2	1/3	1	2
Commissioning facilities	1/3	1/5	1/2	1

Table 7.3: AHP Matrix for Yards Considering Cost

Alternatives	**Rosenberg**	**Kimek**	**Westcon**
Rosenberg	1	1/3	1/2
Kimek	3	1	2
Westcon	2	1/2	1

- Quay facilities
- Internal transport cars
- Warehouse facilities
- Testing facilities

The AHP matrix was generated for all the alternative options (Rosenberg, Kimek, and Westcon) considering each evaluation criteria based on the factors mentioned above. Tables 7.3, 7.4, 7.5, 7.6 shows the AHP matrix for the evaluation criterion cost, safety, fabrication facilities and commissioning facilities respectively.

The eigen vectors are denoted as λ_{max} and were calculated for each matrix of cost, safety, fabrication facilities and commissioning facilities. A detailed explanation on calculation of λ_{max} for each evaluation criterion is provided in Appendix B. As a last step Consistency Index (CI) was calculated for all AHP matrix from,

$$(\lambda_{max} - n)(n - 1)$$

Table 7.4: AHP Matrix for Yards Considering Safety

Alternatives	**Rosenberg**	**Kimek**	**Westcon**
Rosenberg	1	1/4	1/3
Kimek	4	1	2
Westcon	3	1/2	1

Table 7.5: AHP Matrix for Yards Considering Fabrication Facilities

Alternatives	Rosenberg	Kimek	Westcon
Rosenberg	1	5	3
Kimek	1/5	1	2
Westcon	1/3	1/2	1

Table 7.6: AHP Matrix for Yards Considering Commissioning Facilities

Alternatives	Rosenberg	Kimek	Westcon
Rosenberg	1	4	3
Kimek	1/4	1	2
Westcon	1/3	1/2	1

where, n is the no of alternative options whose value is 3.

The CI for cost, safety, fabrication facilities and commissioning facilities were 0.018, 0.036, 0.326, 0.216 respectively. This is elucidated in Appendix B. The Consistency Ratio (CR) iss calculated as,

$$\frac{CI}{RI}$$

where RI is the Random Index. The value of RI for the corresponding n value can be taken from the Table 7.7. RI was 0.58 for all matrix as the value of n is 3.

When,

$$CR < 0.1$$

the results are considered consistent and reliable. Though $CR > 0.1$ is considered inconsistent, it is tolerated to a certain extent according to Saaty. A CR value, as high as 0.9 would mean that the pairwise judgments are just about random and are completely untrustworthy. In this way the CR was calculated for all evaluation criteria as 0.03, 0.06, 0.56 and 0.37 for cost, safety, fabrication facilities and commissioning facilities respectively. The CR for cost and safety were well below 0.1 proving the results to be consistent. Whereas, the CR for fabrication and commissioning facilities were slightly inconsistent but acceptable as they were below 0.9. Therefore, the

Table 7.7: Values of the Random Index (RI) [42]

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Table 7.8: Overall Performance Matrix of Eigen Vectors

OPM	**Cost**	**Safety**	**Fabrication Facilities**	**Commissioning Facilities**
Rosenberg	0.163	0.122	0.657	0.630
Kimek	0.540	0.558	0.196	0.218
Westcon	0.297	0.320	0.147	0.151

Overall Performance Matrix (OPM) was generated with the eigen vectors calculated from AHP matrix for each evaluation criterion and is shown in Table 7.8. A detailed discussion of the Table 7.8 is provided in Chapter 9, to finalize a yard for launching with an optimized assembly plan.

Chapter 8

Towing Analysis of SPU

Subsea equipment are installed on the sea bed using expensive specialized offshore construction and heavy-lift vessels [8]. As the SPU contains all the equipment for produced water processing, the structure is heavy for lifting and so avoiding the usage of more expensive offshore installation vessel is desirable. With the main aim of reducing the cost involved in installation of SPU, it was decided to install it by towing. More importantly, the weather window during installation is so uncertain which also changes the direction towards towing as a better alternative. According to DNV-RP-H103 [12], the reasons for selecting submerged tow for installations are:

- to utilize installation vessels with limited deck space or insufficient crane capacity.
- to increase operational up-time by avoiding offshore operations with low limiting criteria such as lifting off barges and/or lowering through the splash zone

8.1 Controlled Depth Tow Method

Controlled Depth Tow Method (CDTM) is for submerged towing of objects. It is mainly used for pipeline bundles to be towed to the installation site. The biggest advantage of using CDTM is that, the structure is not subjected to the effects of waves and surface current.

The SPU is designed to be launched from a dry dock/ floating dock/ syncrolift with the net buoyancy. The net buoyancy for the structure is 30T. According to DNV-RP-H103, the steps involved in towing operation are [12]:

- Inshore transfer to towing configuration
- Tow to offshore installation site
- Offshore transfer to installation configuration.

When the SPU is in afloat condition after launching, it is surface towed from the dock and then transferred inshore. The towing configuration is achieved by weighting the SPU using clump weights or chains to a certain depth below sea water level. Towing wires are used to connect the SPU with the clump weights and then the clump weights with the lead and trail tug boats. The towing configuration is schematically represented in Figure 8.1.

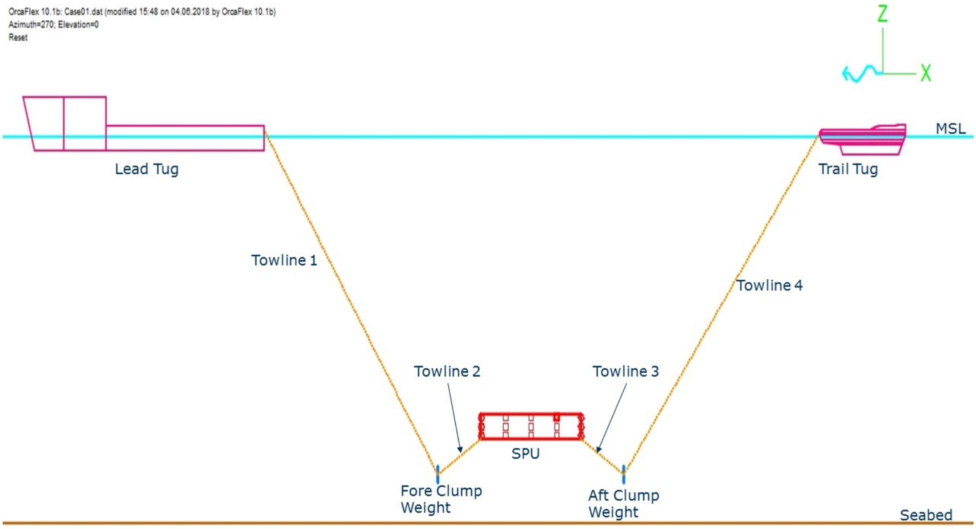


Figure 8.1: Towing Configuration

Once the SPU is transferred from inshore to the desired towing configuration, it is towed to the installation site by CDTM. Time domain simulations were performed in OrcaFlex software for towing the SPU to installation site to identify the lead tug towline tension and the required Bollard Pull (BP).

8.2 OrcaFlex

OrcaFlex is one of the leading software packages for the design and analysis of a wide range of offshore marine systems [36]. It has wide range of applications in risers, moorings, installation analysis, buoy systems, hose systems, towed systems, defence and renewable energy. In this thesis, the software was used to perform towing analysis.

8.3 Modelling in OrcaFlex

In order to create the towing configuration in OrcaFlex, lead vessel, trail vessel, SPU, clump weights and towlines were modelled.

8.3.1 Lead Vessel

A lead vessel is a tug boat that helps in maneuvering the floating structure by either pulling or pushing them by direct contact or with the towlines. In this case, the lead vessel hauls the SPU along with clump weights and trail vessel using towlines. It was modelled in OrcaFlex as a vessel and connected to the SPU with fore clump weights and towlines having the following particulars:

- Length = 103.7m
- Breadth = 19.7m
- Depth = 8.08m
- Draft = 4.4m
- Pitch peak period = 9.3s
- Roll peak period = 12.5s

The coordinates and displacement Response Amplitude Operator (RAO) used in modelling the lead vessel is shown in Appendix C.

8.3.2 Trail Vessel

The trail vessel is also a tug boat attached to the aft of the SPU through aft clump weights and towlines. The main purpose of the trail vessel is to control the disturbed motion of the SPU due to forward speed, wave and current effects. It was also modelled as a vessel with the following particulars:

- Length = 37m
- Breadth = 14m
- Depth = 7.9m

- Draft = 5.6m
- Pitch peak period = 6.2s
- Roll peak period = 6.7s

The lead vessel has higher bollard pull requirements and so it was modelled larger than the trail vessel.

8.3.3 Clump Weights

Clump weights are additional weights added in the towing configuration to make the buoyant SPU submerged to a desired depth. They were modelled as 3D buoy in OrcaFlex. 3D buoys are the simplified point elements without rotational degrees of freedom [33]. They only have translational degrees of freedom in X, Y and Z direction without any rotational properties and moments. 3D buoys are aligned with global axes G_{XYZ} as shown in Figure 8.2. Clump weights were provided in fore and aft of the SPU model as shown in Figure 8.1. Mild steel of density 7850 kg/m^3 was the material used for clump weight. A drag coefficient of 1.05 in X direction was given for clump weights.

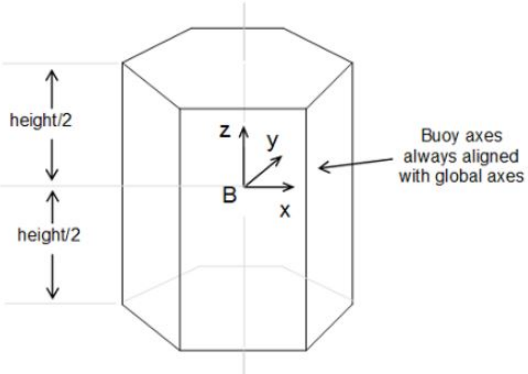


Figure 8.2: 3D Buoy [33]

8.3.4 Towlines

Steel catenary wire ropes of outer diameter 83mm were used for towlines. Four towlines were used in the simulation. Towline 1 connected the lead vessel's hang-off point with the centre of the fore clump weight. Towline 2 connected the fore clump weight at its centre with the SPU's fore bottom frame pad eye. Towline 3 connected the SPU's aft bottom frame pad eye with aft clump weight's centre. Towline 4 connected the centre of the aft clump weight with the trail vessel's hang-off point. The axial stiffness and the submerged weight of the ropes, which are the important parameters for towing simulations were considered less sensitive for this towing method. The main reason for such consideration is because of the spring effect caused by the clump weight dominating the flexibility of the towline [13].

8.3.5 SPU Model

6D Buoy in OrcaFlex was used to model the SPU. Those are the rigid bodies with all six degrees of freedom. In OrcaFlex, 6D buoy are available in 3 types as lumped buoys, spar buoys and towed fish [34]. Lumped buoys were used in modelling as they are the simplest with abstract shape, restricting the accuracy with which the interactions with the water surface are modelled. These buoys are specified relative to its local frame of reference B_{XYZ} as shown in Figure 8.3. The whole SPU was split into 64 buoys and were positioned based on its principal dimensions. The reason for developing the model with 64 buoys was to distribute the point of action of hydrodynamic forces on the SPU. Among 64 buoys, 18 buoys were modelled with an inclination of 40° to account for the inclined shape of the SPU in fore and aft. Volume, height, and the other hydrodynamic properties were equally distributed between the 64 buoys. In order to achieve global results, all the 64 buoys were connected to a single 6D buoy with negligible properties. The 6D buoy SPU model is shown in Figure 8.4.

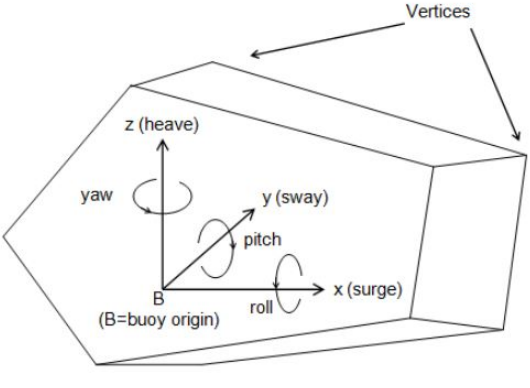


Figure 8.3: 6D Buoy [35]

Table 8.1: Structural Properties of SPU

Parameters	Value
Weight in air	616t
Weight submerged	-30t
Principle Dimensions	43*9.5*7.7
CoG (Long., Trans., Vert.)	0, 0, 4.5m

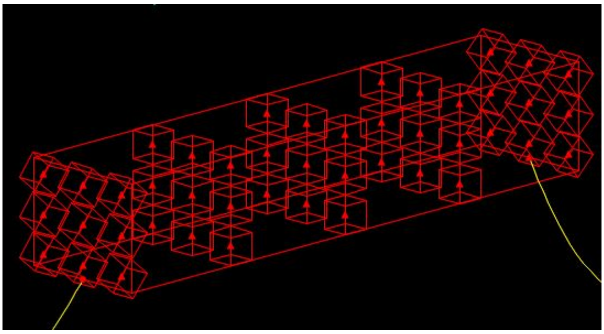


Figure 8.4: SPU Model

8.4 Analysis

According to DNV-RP-H103 [12], the tow configuration is dependent on the following:

- Weight of the SPU submerged in water
- Use of temporary clump weight/buoyancy
- Tow speed and towline length
- Back tension of the trail vessel
- Drag loading due to current

The towing speed used in the analysis was 4knots. The water depth of the installation site is 120m and is in North Sea. The structural properties of SPU used in the analysis are mentioned in the Table 8.1.

The centre of gravity (CoG) of the SPU was taken as 4.5m from the bottom of the SPU. The centre of buoyancy (CoB) was taken 2m above the CoG in the analysis. The CoG and CoB were considered reasonable because of the stringent weight control during production and also the SPU will be levelled with buoyancy modules while in the dock.

Table 8.2: Hydrodynamic Properties of a Buoy

Properties	X	Y	Z	Units
Buoy dimensions	6.143	3.167	2.567	m
Mass moment of Inertia	60.832	162.248	174.841	t.m^2
Drag area	10.608	13.398	16.529	m^2
Drag coefficient	0.268	0.656	0.656	-
Added mass coefficient	0.243	0.666	0.989	-

8.4.1 Model Test Inputs

Model tests for the similar SPU were carried out in Sintef Ocean AS by Subsea 7. The results from the model tests were used to calculate some hydrodynamic properties of the SPU. The towing force in global X- direction (Fx) for the full scale obtained from clamped model towing test was 189KN. This force was used to determine the drag coefficients for the simulations using Morison's equation. As mentioned earlier, the whole SPU was modelled using 64 buoys. Depending upon their exposure to wave forces in global X, Y and Z direction the coefficients were specified in the corresponding directions for the buoys.

8.4.2 6D Buoy Properties

The overall volume of the SPU was $2729m^3$. This volume was divided between 64 buoys and the value was $43.317m^3$ with the mass of 43.924t. The other hydrodynamic properties of the buoy used in the analysis are specified in the Table 8.2.

8.4.3 Static Analysis

The main objective for performing static analysis is to identify the equilibrium configuration of the SPU, which becomes the starting configuration for the dynamic analysis. The initial position of the free bodies like 6D buoys, 3D buoys, lead vessel, and trail vessel connected by the towlines were specified in OrcaFlex. This results in the calculation of equilibrium configuration for each towline with the assumption of fixed towline ends. The out of balance force acting on the free bodies are calculated resulting in static towing configuration. So static analysis results in determining the end forces on the towline for towing, using which the required Bollard Pull (BP) is calculated.

The initial tow configuration is set up with clump weights, towlines, lead vessel, trail vessel and the SPU. As the water depth is 120m, it was decided to achieve a depth of 50m from the SPU top to Mean Sea Level (MSL) in the static configuration in order to avoid surface wave effects on the SPU. This towing configuration provided spring effect with the clump weights between the SPU, and the lead and trail vessel. The required horizontal pull on the SPU increased resulting in lifting of clump weight and the SPU and decreased the spring effect in the towline. In order to compensate this decreased spring effect it became necessary to increase the weight of the clump weight. So, several combinations of clump weights in fore and aft, and the depth of the SPU and clump weights in still water condition were tried to achieve the SPU tow depth of 50m in static configuration. The final still water configuration resulted in having a fore clump weight of 50t and aft clump weight of 30t with SPU at a depth of 85m and clump weights at a depth of 100m. The length of the towlines used in the static analysis were 125, 18, 18 and 120m for the towlines from 1 to 4 respectively. The static tow configuration with the depth of SPU and clump weights from the MSL is shown in Figure 8.5. The distance between the lead vessel and the trail vessel was 266m in static configuration.

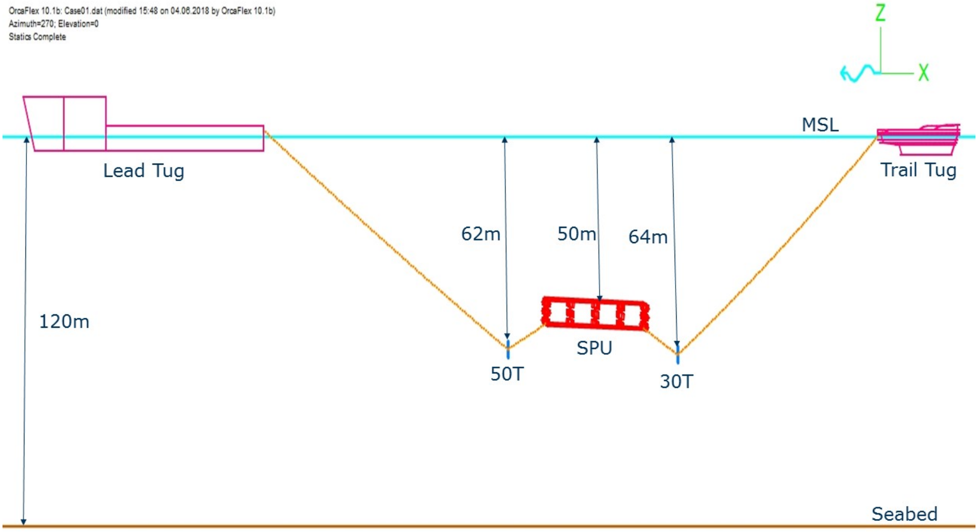


Figure 8.5: Static Towing Configuration

8.4.4 Dynamic Analysis

The dynamic analysis is a time domain simulation of the motions of the SPU over a specified period of time, starting from the position derived by the static analysis [29]. Dynamic forces are generated when the SPU moves. The forces are mainly based on the SPU's shape and displacement, motions due to lead tug, and environmental effects. Regular wave simulations in steady tow conditions were performed using wave height, wave period and direction of propagation. Dean Stream was the wave type used in OrcaFlex, which is based on the stream function theory of Dean [29]. The analysis was run for wave periods from 6s to 24s with the interval of 1s and for the waves in $0°, 45°, 90°, 135°$ and $180°$. The wave height used in the analysis was 7m because, towing was planned as a weather restricted operation with significant wave height (Hs) of 3.5m. The tug boats also had limitations with respect to wave height. The main objective of performing dynamic analysis was to find the maximum effective tension in the Towline 1. The results for all the cases considered are specified in Appendix C.

Current Effects

Dynamic analysis was performed for all the cases specified above again with the current of 1m/s in 90 degrees direction. The main objective here was to determine the maximum effective tension on Towline 1 with wave and current effects. The results for all the cases considered are provided in Appendix C.

The results of static and dynamic analysis are provided and discussed in detail in Chapter 9, Results and Discussion.

Chapter 9

Results and Discussion

Many aspects of engineering were considered in this thesis. Fabrication methodologies, materials, connection components, logistics, modelling, assembly location, launching, towing and procurement to be in particular. Prolific information resulted in identifying the solutions for various problems encountered during the thesis. Results from all engineering branches were integrated to have the best plan for fabricating, launching and towing the SPU. Results of different branches are explained in detail in the beginning of this chapter with a final assembly plan at the end.

9.1 GRP Beams

Being the main structural component of the SPU, the GRP beams were decided to be split fabricated with buoyancy materials inside and laminated together. This results in reusing the moulds for fabricating similar GRP beams and avoiding Inconel Alloy 625 bolts to a certain extent providing an alternate solution for Type 4 connection.

9.2 Buoyancy Materials

The choice of buoyancy material went past several versatile options. Polyurethane foam, pure syntactic foam and composite syntactic foam were the main options. Depending upon the density requirements and operating depth the buoyancy materials can also be formulated. It was decided in the beginning by the author to use encapsulated polyurethane foam as the operating water depth of SPU is 120m. Since the density requirement for the structure turned out to be 450kg/m^3, the decision moved towards composite syntactic foam made of resins, macrospheres and microspheres to achieve the density requirement.

It was explained in section 7.6.1 about the fabrication process of composite syntactic foam. The usage of GRP sheets to form the skin of the buoyancy module is to provide mechanical protection and also for easy removal of the module from the steel mould. The discussion with buoyancy material supplier of Subsea 7 provided an alternative for fabricating the GRP beam and the buoyancy modules. After thorough understanding of the fabrication process of GRP beams and buoyancy modules, it was decided to fabricate the buoyancy modules using the GRP beam base as shown in Figure 6.6 as a mould. This fabrication method will result in avoiding the usage of GRP skin on the buoyancy modules, thus saving cost. So, the industrial visits to the GRP and subsea buoyancy material fabricator of Subsea 7 resulted in a fabrication methodology which integrates the production of buoyancy materials with the GRP beams. The final fabrication process is to pump in the macrospheres and the resins on to the GRP beam base to form the integrated GRP beam. SPU has complex shapes at the ends, this type of production will result in achieving the complex shaped buoyancy modules without major difficulties of creating a complex steel mould as in conventional method of fabricating the buoyancy modules. This methodology has its limitations with regards to the buoyancy modules fabrication, as they are to be cured in oven to maintain its properties, if the operating depth of the subsea buoyancy module exceeds 800m water depth. This is not an issue for the SPU considered in this thesis as its operating depth is well below 800m.

9.3 Joint Connection

Though the complexity of taking in the buoyancy module to a GRP beam has been solved, there were uncertainties in connecting the GRP beams. The main challenge was to join the vertical, transverse and longitudinal beam together from inside. It is impossible to join the GRP beams with buoyancy material inside. The only option is, to have a void space inside a GRP beam to connect them with the other beams and then filling the void space with the buoyancy material later. In search for the best possible method to assemble, a 3D joint was modelled as explained in section 7.4. For a robust design without reduced cross-section it has been decided to use Inconel Alloy 625 bolts and nuts according to NORSOK M-001, for marine operations to connect the GRP beams together to prevent from corrosion. The main objective of designing a 3D joint was to have a single point access to connect the longitudinal, vertical and transverse beams together. Despite avoiding the complexity in the assembly, the use of 3D joint resulted in increasing the number of bolts and nuts compared to other assembly options. The void space in 3D joints can be filled by pumping in the macrospheres with or without resins depending upon the buoyancy requirements as a final step before launching.

The challenge associated with Type 3 connection mentioned in section 4.1 has been solved with the development of 3D joint. Type 1 joint mentioned in section 4.1, connecting the two longitudinal GRP joints has been avoided by the author in modelling the SPU. The preliminary model developed in Autodesk Inventor taking into account, the principal dimensions of SPU, volume and density of subsea buoyancy module, equipment weight and dimension resulted in having a longitudinal beam of maximum length 10m. This solution is feasible for this PWMS of SPU. If the capacity has to be increased leading to the increase in length of the SPU, ultimately increases the length of the GRP beams. For easier transportation, open-top containers are used as discussed in Chapter 5. This limits the length of the GRP beam to be less than 12m. Considering this limitation a joint like Type 1 connection is required for larger SPU's. The best solution for this would be to increase the 3D joint's length. In worst case scenario, a new insert replacing the 3D joint connection with a new void joint that simply connects the two longitudinal beams as shown in Figure 9.1 can be used. This solution solves the uncertainties associated with the Type 1 and Type 3 connections.

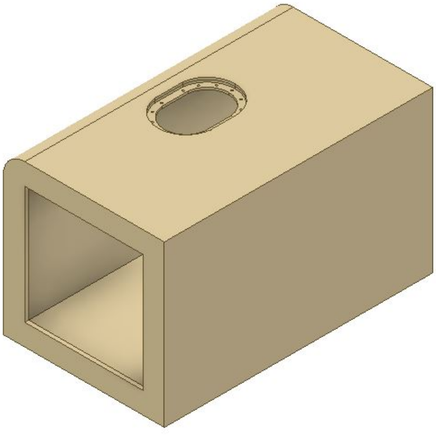


Figure 9.1: Modified 3D Joint

9.4 Launching

The comparison between Rosenberg, Kimek and Westcon based on the evaluation criteria is pictorially represented in Figure 9.2. Table 7.8 provided the ranking between three main yards considered. Based on the evaluation criteria considered the Overall Performance Matrix (OPM) resulted in the following:

- Considering cost, Kimek yard with syncrolift facility ranked high with a score of 0.54.
- Considering safety, Kimek yard again ranked high among the three with a score of 0.558
- Considering fabrication facilities, Rosenberg yard with dry dock stands separate with a score of 0.657
- Considering commissioning facilities, Rosenberg yard holds the highest score with 0.630

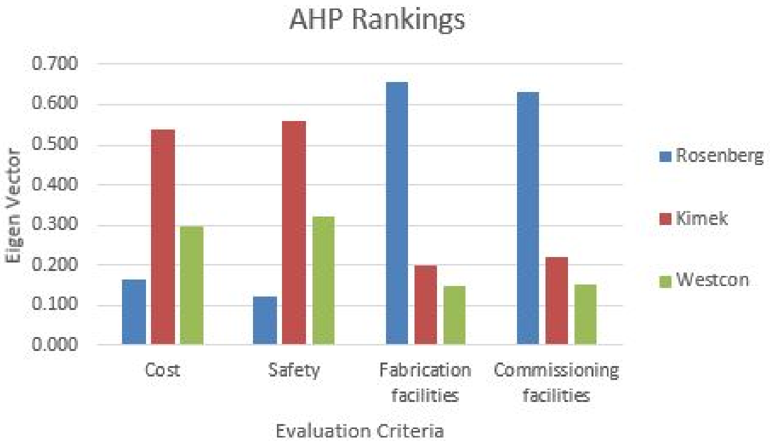


Figure 9.2: AHP Rankings

9.4.1 Final Decision

As the SPU is in the developmental stage, it is quite unclear to prioritize the factors to choose one particular yard for launching. But, the results from AHP provided options for the author to choose Kimek for the cost and safety criteria, and Rosenberg yard for the criteria, fabrication and commissioning facilities. Therefore final assembly of SPU and launching plan was made for both the yards.

Rosenberg Assembly Plan

Rosenberg yard is located in Stavanger, Norway and has two dry docks. It has a huge completely covered fabrication hall. The fabrication hall layout is shown in Figure 9.3.

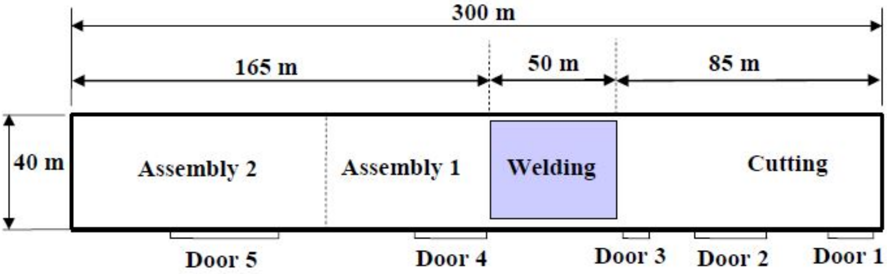


Figure 9.3: Fabrication Hall Layout [19]

A thorough understanding of the yard facilities after the industrial visit resulted in splitting the entire SPU into three main sub-assemblies as:

- Port beam
- Starboard beam
- Bottom steel frame

From the fabrication hall layout, it is evident that it is possible to perform welding activities inside the hall for a length of 50m. This provided the solution for fabrication of the bottom steel frame in the area allotted for welding. The yard has good quay facilities for handling the container vessel in order to transport the GRP modules from GRP fabricator to the Rosenberg yard. The GRP modules can then be moved into the fabrication hall using forklifts or heavy lifts. There are two specific regions mentioned in the hall layout for assembly options. Any one of the assembly regions can be used to assemble the entire port beam completely. The entire structural weight of the port beam is 80t and the crane capacity of 180t is available in the assembly region. Therefore, it is feasible to assemble the entire port beam on the assembly region with a flat base. This reduces the usage of scaffolding for accessing the 3D joints for nuts and bolts connections. The port beam components are four 3D joint, three longitudinal GRP beams, two end beams and four vertical beams. The completely assembled port beam is shown in Figure 9.4. In the same way starboard beam can also be assembled. The final assembly is not possible inside the fabrication hall because of the limitations in lifting capacities. The whole SPU weighs 616t with all the equipment and is much more than the lifting and transportation capacities in the fabrication hall and the dry dock. So the final decision taken is to assemble the sub assemblies with equipment in the dry dock. The sub-assembled components are transferred to the dock using heavy lift transporters as shown in 9.5. It has a maximum lifting capacity of 250t. The final assembly is performed as shown in Figure 9.6 using the dry dock cranes.

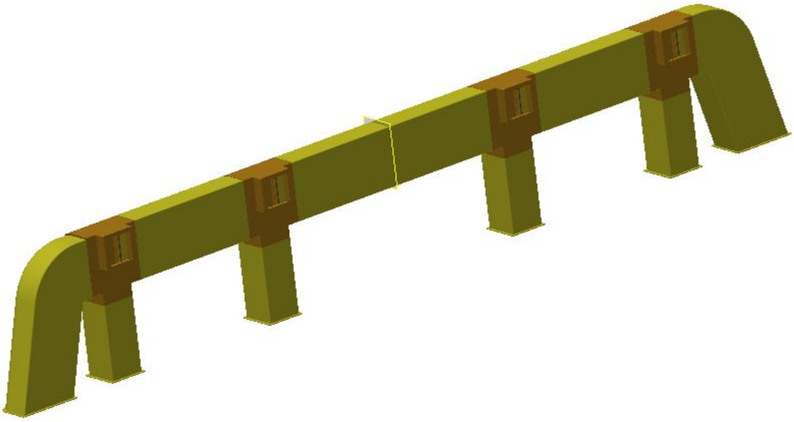


Figure 9.4: Port GRP Beam

Figure 9.5: Heavy Lift Transporter [26]

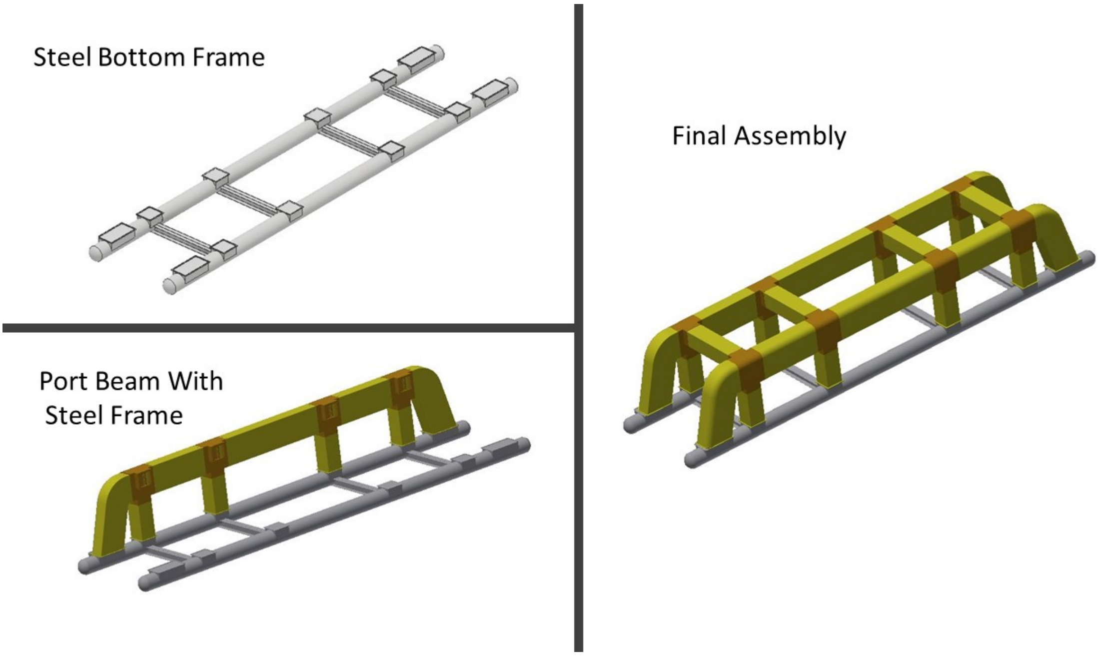


Figure 9.6: Final Assembly of the Structure

The final assembly plan is pictorially represented in Figure 9.7

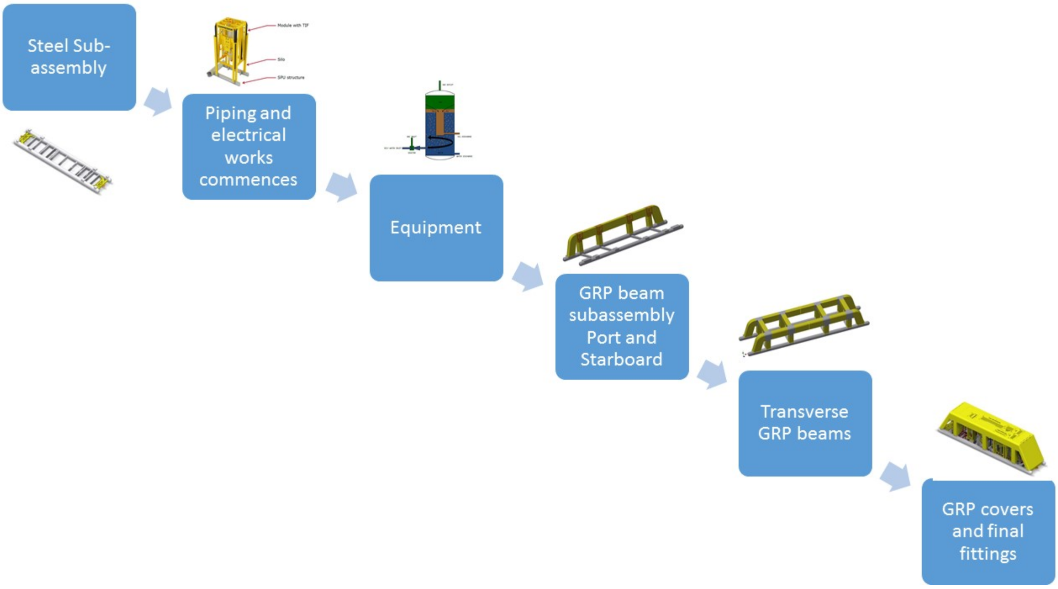


Figure 9.7: Assembly Sequence of SPU

Kimek Assembly Plan

The decision to make an assembly plan for Kimek is because of its high rankings in cost and safety factors as shown in Figure 9.2. The reasons are because of the syncrolift launching system of 117*24m and 5000t capacity. It has a heated ship hall of 80*40*33.6m with 100t crane capacity. The main advantage of the syncrolift system is that, the whole SPU with bottom steel frame, port beam, starboard beam, all equipment, pipelines, cables, GRP covers and final fittings can be done inside the hall. Once the SPU is assembled it is transferred to the syncrolift platform using internal transport cars as shown in Figure 9.8.

The reason for high rankings with respect to cost and safety factors is that the entire assembly is done inside the fabrication hall and it is brought out on the day of launching on to the syncrolift. It saves cost because the equipment has to be tested for which it has to be launched and dry docked. Syncrolift will help in easy testing as the structure can be launched and dry docked on the same day. As the whole assembly takes place inside the hall, all equipment are prevented from damage ensuring more safety and also the time spent on rigging and transportation of sub-assemblies are avoided. So in Kimek, the same sub-assembly plan as in Rosenberg can be followed with a change in final assembly and launching plan.

Figure 9.8: Internal Transport Cars [1]

9.4.2 Discussion on Yard Location

The parameters contributing to the weightage of cost factor was completely based on the type of yard, in-house facilities, resources and worker's wages. It is important to specify that, the locations of the yards were not given much consideration in this thesis because of the inadequate information to include them in AHP. Though all three yards are located in Norway, there is a significant difference in distances between them and the oil field. The location of the yards and their distances from the oil field is illustrated using a map in Figure 9.9. The farthest yard from the oil field is Kimek. Though Kimek had a good score in AHP for the cost factor, the distance from CSUB to their location is also the farthest. Two main parameters that could affect the cost factor are,

- The cost involved in transferring the GRP modules to the yard.
- The towing cost to the oil field based on the distance and weather window.

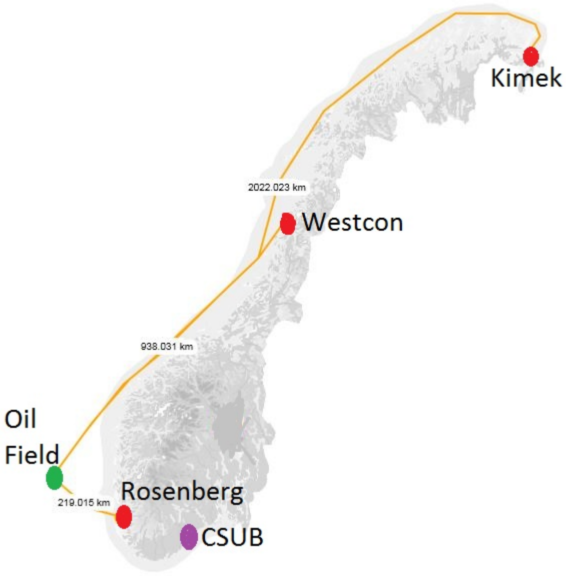


Figure 9.9: Yard Locations from Oil Field

The cost involved in renting a lead and trail tug for towing is 10,500,000 NOK per day for each vessel in Norway. Since the towing process is weather restricted, the cost involved in towing based on the speed of the lead tug and the distance from oil field has to be calculated along with the overall project cost. This cost must be compared with the towing and overall project cost involved in choosing Rosenberg for launching in order to take the final decision. This is the future scope in terms of launching the SPU.

9.5 Towing Results

Static analysis of towing in OrcaFlex resulted in finding the end force in global X direction on Towline 1 to be 422KN. The value seems reasonable because the drag coefficients used are based on 189KN towing force in X direction obtained from the model test and also the trail vessel had an applied load of 200KN. 50T and 30T clump weights were used in fore and aft respectively for the static and dynamic analysis, maintaining 50m tow depth. DNV-OS-H202 was used to calculate the tug efficiency factor, using which the required Bollard Pull (BP) was calculated. The tug efficiency factor was calculated based on the following equation [11],

$$\gamma_{TE} = [80 - (18 - 0.0417 * LOA * \sqrt{BP - 20}) * (H_s - 1)]/100$$

Where:
γ_{TE}: Tug efficiency factor
LOA: Tug overall length, LOA = 45m to be used for all LOA $>$ 45m
BP: Tug bollard pull, BP $\geq$ 20t and BP = 100t to be used for all BP $>$ 100t
$1m \leq H_s \leq 5m$.

The above equation resulted with a BP of 100t for the SPU. BP calculation is presented in Appendix C.

Maximum effective tension on the lead tug towline (Towline 1) from dynamic analysis is of significant importance and the value is 837KN. This value is obtained for the environmental conditions shown in Table 9.1. The minimum effective tension value of the Towline 1 is 298KN and the associated environmental conditions are specified in Table 9.2. The maximum and minimum value of effective tension on trail towline (Towline 4) are 492 and 59KN respectively, and the environmental conditions are the same as for the minimum lead tension of Towline 1 specified in Table 9.2.

Table 9.1: Maximum Lead Tension Environmental Conditions

Environment data	Value
Wave height	7m
Wave period	20s
Wave direction	180°
Current velocity	1m/s
Current direction	90°

Table 9.2: Minimum Lead Tension Environmental Conditions

Environment data	Value
Wave height	7m
Wave period	6s
Wave direction	45°
Without current	

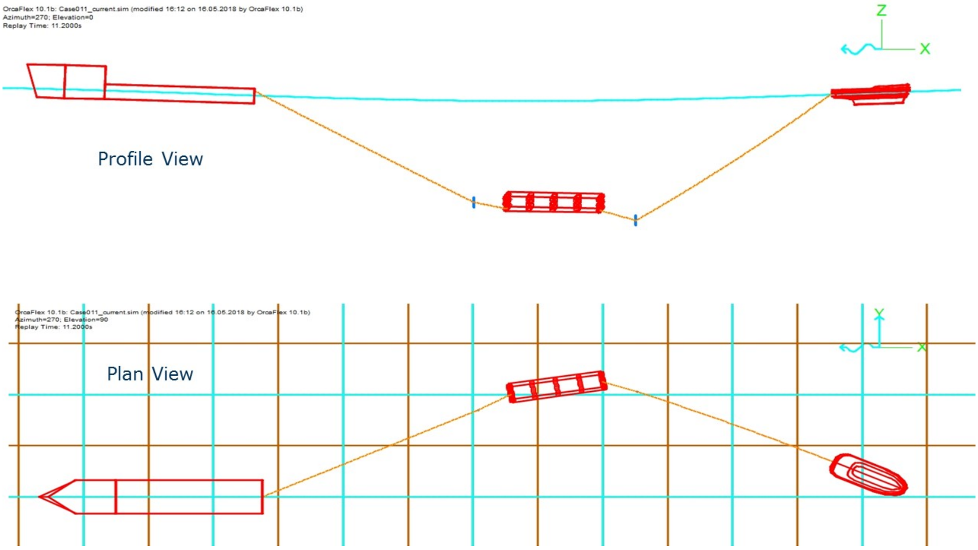


Figure 9.10: Dynamic Towing Configuration

Figure 9.10 shows the dynamic towing configuration for the maximum tension experienced on Towline 1 in profile and plan view. The profile shows that the towlines are stretched to their maximum with the increase in angle between the adjacent towlines corresponding to the maximum towline forces. The plan view shows the SPU being drifted by current and held back within the tow range by trail tug with applied load of 200KN.

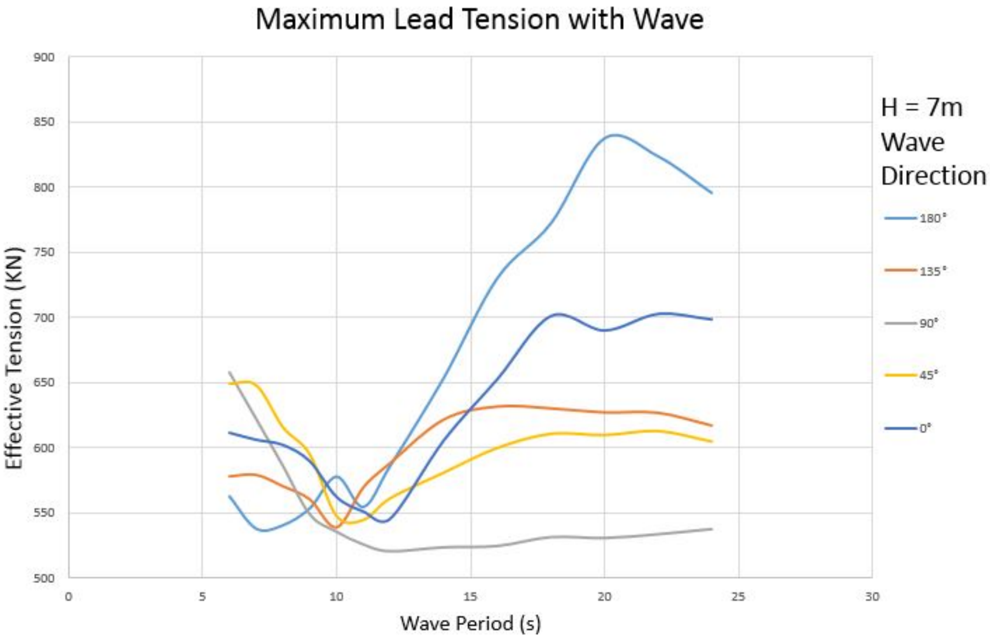


Figure 9.11: Maximum Lead Tension with Wave

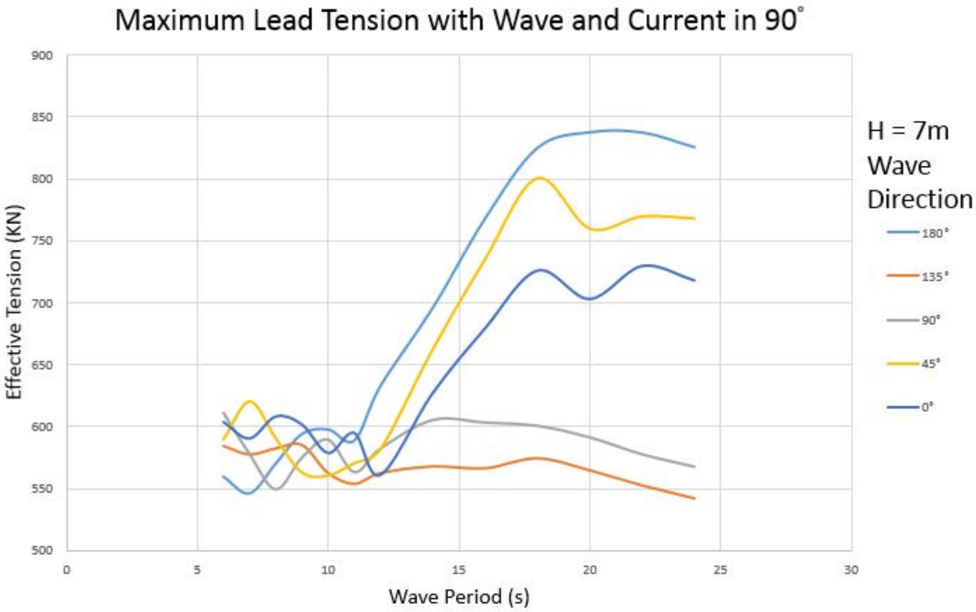


Figure 9.12: Maximum Lead Tension with Wave and Current

Figures 9.11 and 9.12 shows the maximum lead line tension with wave, and wave and current respectively for the cases considered. Both the figures indicate that the lead line tension is increasing steadily from the wave period of 10s and the maximum is experienced for a wave period of 20s and wave direction of 180 degrees. In comparison between the figures, the effective tension is slightly higher with the effect of wave and current together. Figures representing the maximum and minimum trail tension for the 130 cases considered are provided in Appendix C.

Finally, the set down is performed by continuous pay-out on the Towlines 1 and 4 until the clump weights rest on the seabed. As a last step, chains are placed on the SPU along with the assistance of ROV to rest the SPU on the seabed.

Chapter 10

Conclusion

The scope of work in this thesis incorporated challenges that led to the exploration of various subsea engineering branches. Working on this project was more lively as it revolved around a real time project involving more discussions with experienced engineers of Subsea 7 and their vendors. With all the knowledge obtained about the SPU, along with author's academic and industrial experience resulted in finding optimized solutions for fabrication, launching and towing with regards to the various challenges associated with the SPU. The findings of this research work are,

- In terms of fabrication, an optimized solution for Type 1, Type 3, and Type 4 joint connections were found with the development of 3D joint. Overall, it is recommended to integrate the fabrication of GRP beams and subsea buoyancy modules. Split fabrication of GRP beams and using it as a mould for subsea buoyancy modules serves the purpose by saving cost and time.

- Considering different launching options, based on cost and safety criteria author finds syncrolift to be the ultimate option for SPU from AHP. It is preferred over other launching options exclusively for SPU as the unit has to be launched and dry docked for commissioning purposes. This becomes critical in terms of cost, if other launching options are considered. The other major advantage is the assembly of the whole unit inside a hall providing safe enclosure for equipment, material and personnel from weather exposure. The launching cost considered does not take into account the cost of the cost of transportation of the GRP beams to the assembly yard and then the SPU to the oil field. Considering this, Rosenberg yard in Stavanger with high ratings in AHP for fabrication and commissioning facilities criteria was also taken into account for final assembly. So, the assembly plan was made for the SPU with both the yards. The final decision has to be taken based on the priorities of Subsea 7 over the evaluation criteria considered.

- CDTM was used as an alternative for installing the SPU. Heavy construction vessels are avoided and the effect of surface waves on the SPU is avoided using CDTM. The results from model tests were used as inputs in the form of drag coefficients for performing towing analysis in OrcaFlex software. Static analysis resulted in identifying the optimum clump weight requirements in fore and aft of the SPU along with the required Bollard Pull of 100t. Dynamic analysis resulted in identifying the maximum towline tension of the lead tug to be 837KN.

10.1 Recommendations and Future Work

- In this thesis, only consideration in connecting the structure during assembly was using Inconel Alloy 625 bolts. An alternative to this is using adhesives for joint connections. Carrying out this study will help us to compare the cost factor between them.

- Structural analysis of the model explained in Chapter 5 with reduced cross section has to be performed to determine the percentage loss in buoyancy and strength to check for its applicability.

- The cost of transportation of GRP beams to the assembly yard and then the SPU to the oil field has to be paid attention in real life project.

- Forces acting on the structure during towing, impact loading, stability check, bolt calculations and abandonment procedures for the weather window are to be considered in the forthcoming research.

- Lead time analysis of the SPU components with major focus on structural fabrication and assembly process was started. But the work is kept on hold because of the time delay encountered in receiving the data from Subsea 7 vendors. This work can be completed in the future.

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Table 10.1: Rosenberg Facilities - 1

Rosenberg Dry Dock 1
Main particulars

Principle Particulars	Values
Length of dock	138m
Width of dock	22.4m
Depth to dock sill	7.22m
Water depth at MSL	8.67m
Dock handling capacity	22,000dwt
Crane capacity	100T

Rosenberg Dry Dock 2

Principle Particulars	Values
Length of dock	280m
Width of dock	43m
Depth to dock sill	7.59m
Water depth at MSL	8.53m
Dock handling capacity	160,000dwt
Crane capacity (Gantry)	2*100T
Crane capacity (Gantry)	130T

Appendix A - Yard Facilities

1. Rosenberg - Stavanger. The yard details were obtained from the industrial visit and are shown in Tables 10.1 and 10.2.
2. Kimek – Kirknes. The details were taken from their official website and are provided in Table 10.3.
3. Westcon – Helgeland. The details are obtained from their official website and are provided in Table 10.4.

Table 10.2: Rosenberg Facilities - 2

Other facilities

Particulars	**Values**
Quay length	90m
Minimum water depth at quay	11.7m
Electric power at testing site	10MW 690V
Load test bank	5MW
Compressed air	6 to 8 bars

Fabrication hall facilities

Particulars	**Values**
Cutting and preparation area	85m*35.6m
Welding plane area	50m*35.6m
assembly area 1&2	165m*35.6m
Crane capacities in fabrication hall	2*90t
Crane capacities in fabrication hall	1*50t
Crane capacities in fabrication hall	1*20t
Crane capacities in fabrication hall	3*15t
Crane capacities in fabrication hall	1*20t
Crane capacities in fabrication hall	1*15t
Crane capacities in fabrication hall	3*5t
Hall maximum height	34.7m

Table 10.3: Kimek Facilities [27]

Kimek
Syncrolift

Principal Particulars	Values
Length of syncrolift	117m
Width of syncrolift	24m
Syncrolift lifting capacity	5000t
Fabication hall length	80m
Fabication hall breadth	40m
Fabication hall height	33.6m
Crane capacity inside fabrication hall	2*50t
Quay length	280m
Quay depth	5.5 to 8m
Prefabrication welding shop	
Electromechanical workshop	
Motors and machining workshop	
Barracks for own and hired personnel	

Table 10.4: Westcon Facilities [46]

Westcon Helgeland
Covered Dry Dock

Principal Particulars	Values
Length of dock	97m
Length of covered dock	97m
Maximum vessel width	25m
Maximum vessel draft	7m
Crane capacity	2*50t
Crane capacity	10t and 16t
Quay length	60m
Quay depth	50m
Land connection	1.5MW 400V
Mooring bollards	4*200t
Indoor workshop	2300m2
Outdoor storage	20,000m2
Indoor warehouse	500m2
Mechanical and piping workshop	400m2

Appendix B - Analytical Hierarchy Process Calculation

Table 10.5: Analytical Hierarchy Process Calculation

Evaluation Criteria	Rating
Cost	2
Safety	1
Fabrication facilities	3
Commissioning facilities	5
n (no of evaluation criteria)	4
1/n	1/4

Matrix Formation

Evaluation Criteria	Cost	Safety	Fabrication facilities	Commissioning facilities	Product	nth root	Eigen vector	A	max
Cost	1	1/2	2	3	3.00	1.32	0.27	1.09	4.02
Safety	2	1	3	5	30.00	2.34	0.48	1.94	4.01
Fabrication facilities	1/2	1/3	1	2	0.33	0.76	0.16	0.63	4.02
Commissioning facilities	1/3	1/5	1/2	1	0.03	0.43	0.09	0.35	4.01
					Sum	4.84	1.00		4.01
									Satisfied

Table 10.6: Analytical Hierarchy Process Calculation Continuation

Yards considered
(Available Options)
Rosenberg - Stavanger
Kimek - Kirkenes
Westcon - Helgeland

1 Considering cost 1/n 1/3

Alternatives	**Rosenberg**	**Kimek**	**Westcon**	**Product**	**nth root**	**Eigen vector**	**A**	**max**
Rosenberg	1	1/3	1/2	0.17	0.55	0.16	0.49	3.01
Kimek	3	1	2	6.00	1.82	0.54	1.62	3.01
Westcon	2	1/2	1	1.00	1.00	0.30	0.89	3.01
				Sum	3.37	1.00		3.01

Satisfied

2 Considering safety 1/n 1/3

Alternatives	**Rosenberg**	**Kimek**	**Westcon**	**Product**	**nth root**	**Eigen vector**	**A**	**max**
Rosenberg	1	1/4	1/3	0.08	0.44	0.12	0.37	3.02
Kimek	4	1	2	8.00	2.00	0.56	1.69	3.02
Westcon	3	1/2	1	1.50	1.14	0.32	0.96	3.02
				Sum	3.58	1.00		3.02

Satisfied

Table 10.7: Analytical Hierarchy Process Calculation Continuation

3	**Considering fabrication facilities**	1/n	1/3

Alternatives	**Rosenberg**	**Kimek**	**Westcon**	**Product**	**nth root**	**Eigen vector**	**A**	**max**
Rosenberg	1	5	3	15.00	2.47	0.66	2.08	3.16
Kimek	1/5	1	2	0.40	0.74	0.20	0.62	3.16
Westcon	1/3	1/2	1	0.17	0.55	0.15	0.46	3.16
				Sum	3.75	1.00		3.16
								Satisfied

4	**Considering commissioning facilities**	1/n	1/3

Alternatives	**Rosenberg**	**Kimek**	**Westcon**	**Product**	**nth root**	**Eigen vector**	**A**	**max**
Rosenberg	1	4	3	12.00	2.29	0.63	1.96	3.11
Kimek	1/4	1	2	0.50	0.79	0.22	0.68	3.11
Westcon	1/3	1/2	1	0.17	0.55	0.15	0.47	3.11
				Sum	3.63	1.00		3.11
								Satisfied

Table 10.8: Analytical Hierarchy Process Calculation Continuation

For Evaluation Criteria

Consistency index	0.043555787	
Consistency ratio	0.048395318	Perfect according to Saaty

For Cost

Consistency index	0.018405425	
Consistency ratio	0.031733492	Perfect according to Saaty

For Safety

Consistency index	0.036589415	
Consistency ratio	0.063085198	Perfect according to Saaty

For Fabrication Facilities

Consistency index	0.326469065	
Consistency ratio	0.562877697	Can be accepted

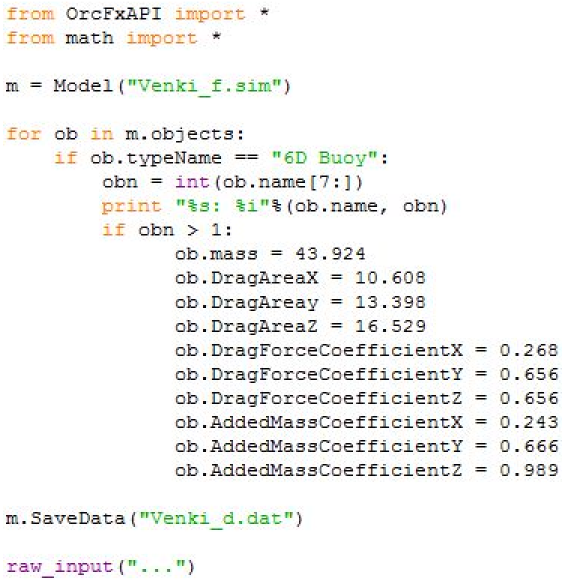
For Commissioning Facilities

Consistency index	0.215694668	
Consistency ratio	0.371887358	Can be accepted

So,

Overall Performance Matrix	**Cost**	**Safety**	**Fabrication facilities**	**Commissioning facilities**
Rosenberg	0.163	0.122	0.657	0.630
Kimek	0.540	0.558	0.196	0.218
Westcon	0.297	0.320	0.147	0.151

Appendix C - Towing Analysis



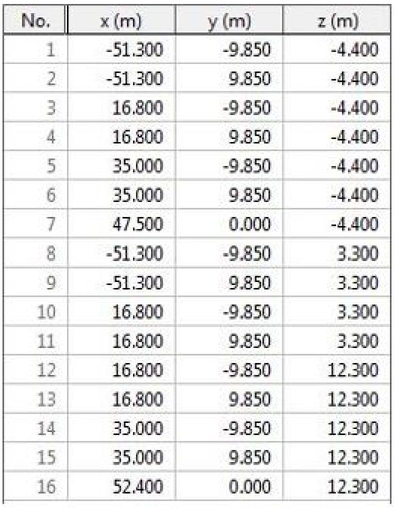
```python
from OrcFxAPI import *
from math import *

m = Model("Venki_f.sim")

for ob in m.objects:
    if ob.typeName == "6D Buoy":
        obn = int(ob.name[7:])
        print "%s: %i"%(ob.name, obn)
        if obn > 1:
              ob.mass = 43.924
              ob.DragAreaX = 10.608
              ob.DragAreay = 13.398
              ob.DragAreaZ = 16.529
              ob.DragForceCoefficientX = 0.268
              ob.DragForceCoefficientY = 0.656
              ob.DragForceCoefficientZ = 0.656
              ob.AddedMassCoefficientX = 0.243
              ob.AddedMassCoefficientY = 0.666
              ob.AddedMassCoefficientZ = 0.989

m.SaveData("Venki_d.dat")

raw_input("...")
```

Figure 10.1: Python Script for SPU Model Properties Input to OrcaFlex

```
from OrcFxAPI import *
from math import *

m = Model("Venki_14updated.dat")

totMass = 0.
totVol = 0.
countMass = 0
countVol = 0
totAMassX = 0.
totAMassY = 0.
totAMassZ = 0.
totDragX = 0.
totDragY = 0.
totDragZ = 0.
for ob in m.objects:
    if ob.typeName == "6D Buoy":
        if ob.name == "6D Buoy1" or ob.Connection == "6D Buoy1":
            totMass += ob.Mass
            totVol += ob.Volume

            totAMassX += ob.AddedMassCoefficientX*1.025*ob.Volume*cos(ob.InitialRotation2*pi/180.)
            totAMassX += ob.AddedMassCoefficientZ*1.025*ob.Volume*sin(ob.InitialRotation2*pi/180.)
            totAMassY += ob.AddedMassCoefficientY*1.025*ob.Volume
            totAMassZ += ob.AddedMassCoefficientZ*1.025*ob.Volume*cos(ob.InitialRotation2*pi/180.)
            totAMassZ += ob.AddedMassCoefficientX*1.025*ob.Volume*sin(ob.InitialRotation2*pi/180.)

            totDragX += 0.5*ob.DragForceCoefficientX*1.025*ob.DragAreaX*cos(ob.InitialRotation2*pi/180.)
            totDragX += 0.5*ob.DragForceCoefficientZ*1.025*ob.DragAreaZ*sin(ob.InitialRotation2*pi/180.)
            totDragY += 0.5*ob.DragForceCoefficientY*1.025*ob.DragAreaY
            totDragZ += 0.5*ob.DragForceCoefficientZ*1.025*ob.DragAreaZ*cos(ob.InitialRotation2*pi/180.)
            totDragZ += 0.5*ob.DragForceCoefficientX*1.025*ob.DragAreaX*sin(ob.InitialRotation2*pi/180.)

            #if ob.Mass > 0.001:
            #    print "%s: %0.1f"%(ob.name,ob.Mass)
            #    countMass += 1
            #if ob.Volume > 0.001:
            #    print "%s: %0.1f"%(ob.name,ob.Volume)
            #    countVol += 1

netWeight = totMass - totVol*1.025
```

```
#print countMass
#print countVol
#print totMass
#print totVol
print "Total mass: %0.1fTe"%totMass
print "Total volume: %0.1fm3"%totVol
print "Net weight: %0.1fTe"%netWeight
print "Total added mass X: %0.1fTe"%totAMassX
print "Total added mass Y: %0.1fTe"%totAMassY
print "Total added mass Z: %0.1fTe"%totAMassZ
print "Total drag X: %0.1fkN/(m/s)^2"%totDragX
print "Total drag Y: %0.1fkN/(m/s)^2"%totDragY
print "Total drag Z: %0.1fkN/(m/s)^2"%totDragZ
```

Figure 10.2: Python Script for Hydrodynamic Properties Verification



No.	x (m)	y (m)	z (m)
1	-51.300	-9.850	-4.400
2	-51.300	9.850	-4.400
3	16.800	-9.850	-4.400
4	16.800	9.850	-4.400
5	35.000	-9.850	-4.400
6	35.000	9.850	-4.400
7	47.500	0.000	-4.400
8	-51.300	-9.850	3.300
9	-51.300	9.850	3.300
10	16.800	-9.850	3.300
11	16.800	9.850	3.300
12	16.800	-9.850	12.300
13	16.800	9.850	12.300
14	35.000	-9.850	12.300
15	35.000	9.850	12.300
16	52.400	0.000	12.300

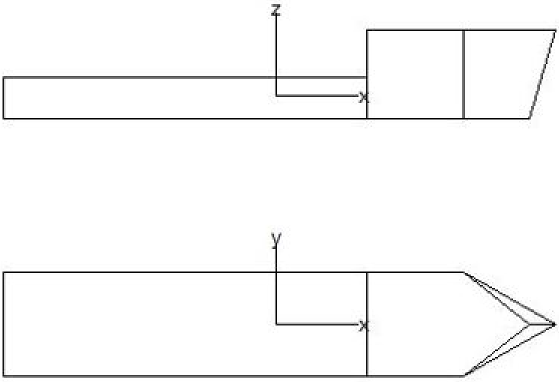


Figure 10.3: Coordinates of Lead Vessel

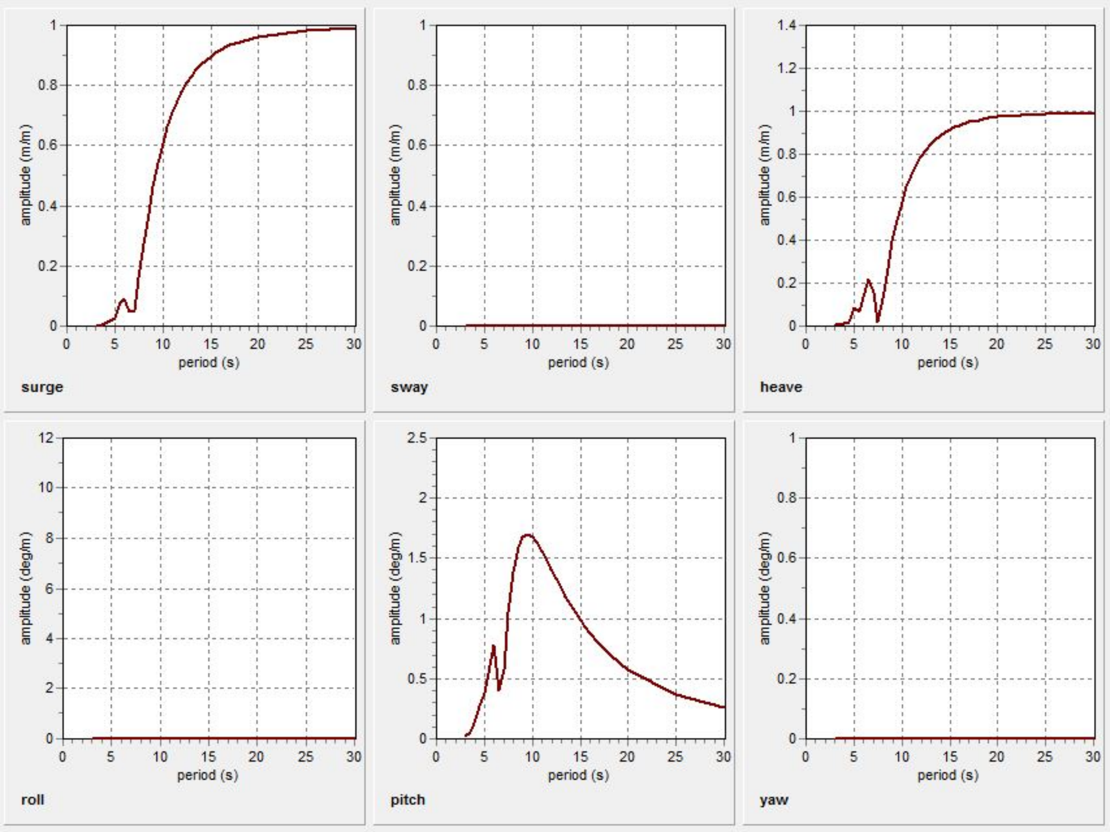


Figure 10.4: Lead Vessel RAO for 0°

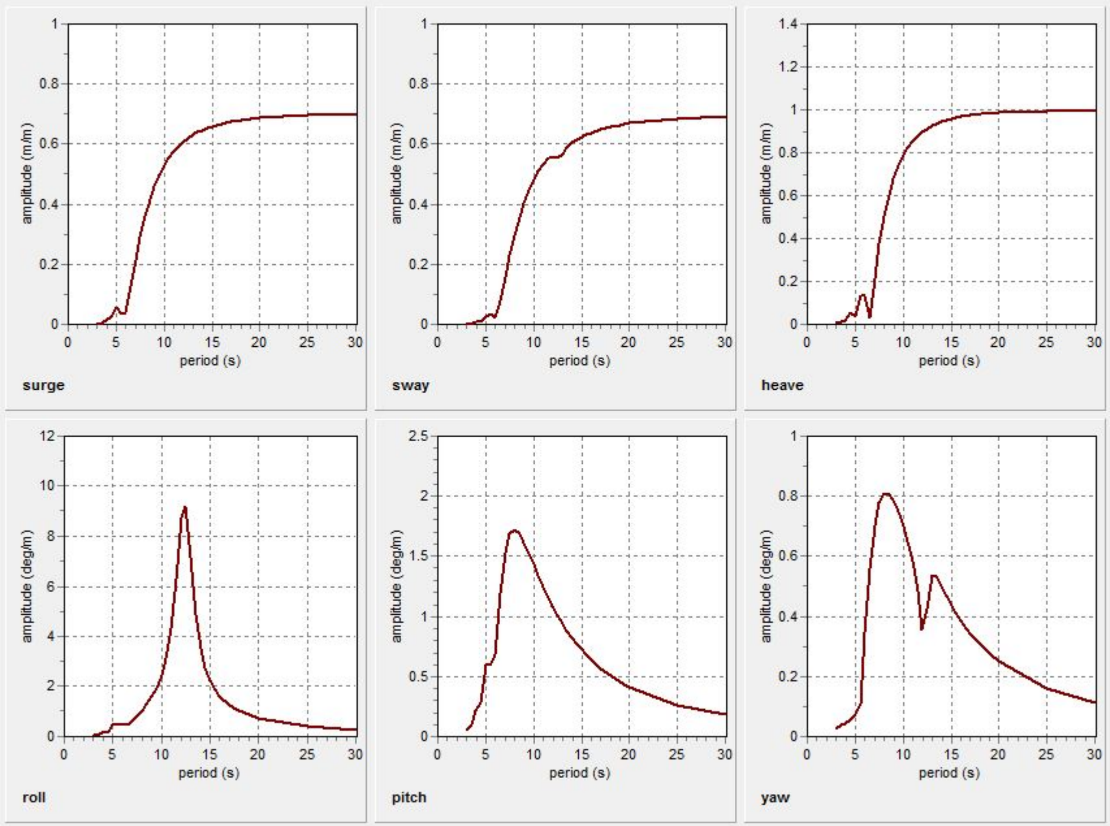


Figure 10.5: Lead Vessel RAO for 45°

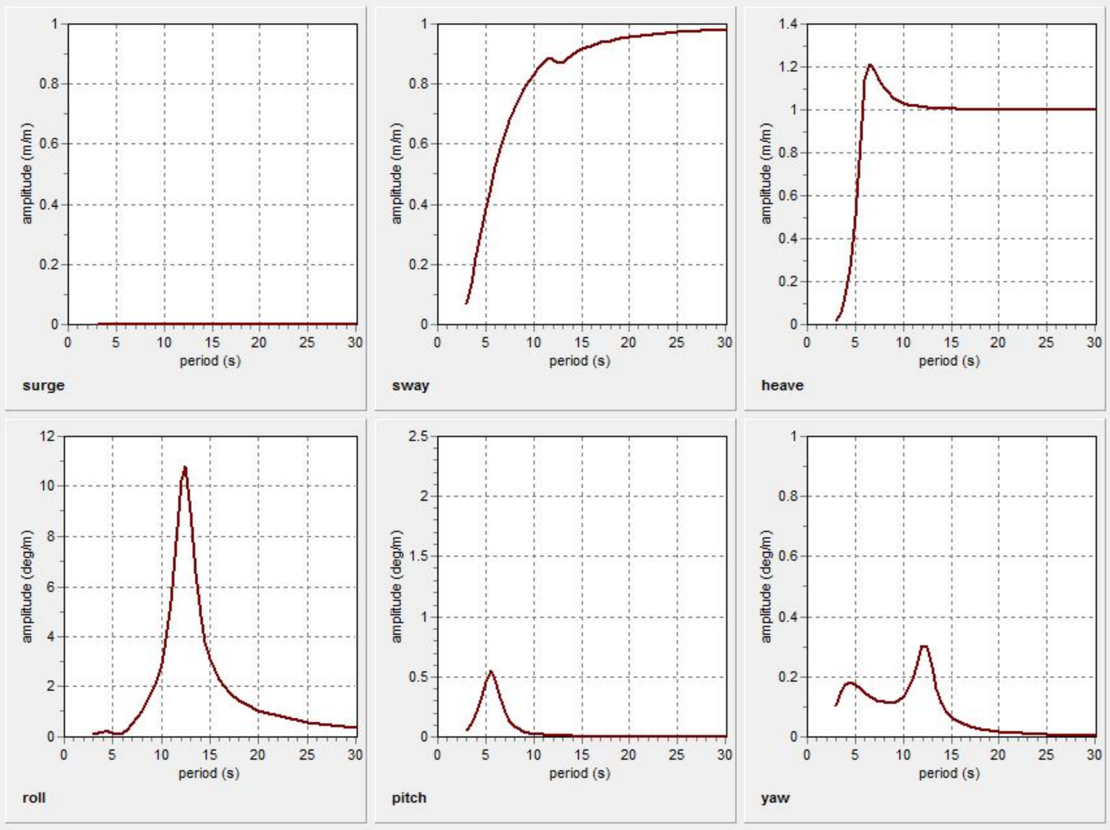
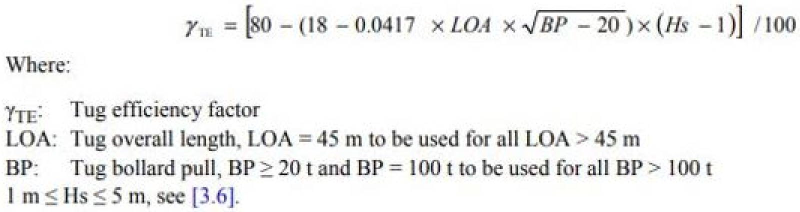


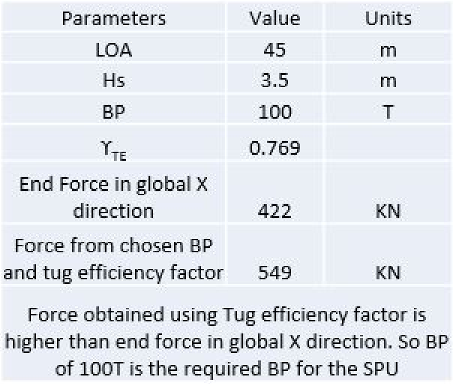
Figure 10.6: Lead Vessel RAO for 90°



$$\gamma_{TE} = \left[80 - (18 - 0.0417 \times LOA \times \sqrt{BP - 20}) \times (Hs - 1)\right] / 100$$

Where:

γ_{TE}: Tug efficiency factor
LOA: Tug overall length, LOA = 45 m to be used for all LOA > 45 m
BP: Tug bollard pull, BP ≥ 20 t and BP = 100 t to be used for all BP > 100 t
1 m ≤ Hs ≤ 5 m, see [3.6].



Parameters	Value	Units
LOA	45	m
Hs	3.5	m
BP	100	T
Υ_{TE}	0.769	
End Force in global X direction	422	KN
Force from chosen BP and tug efficiency factor	549	KN
Force obtained using Tug efficiency factor is higher than end force in global X direction. So BP of 100T is the required BP for the SPU		

Figure 10.7: Bollard Pull Calculation

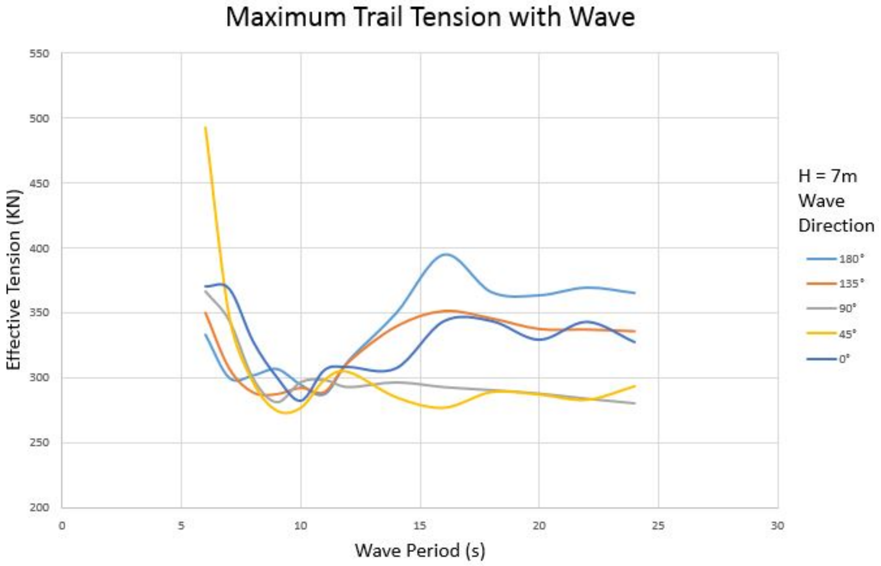


Figure 10.8: Maximum Trail Tension with Wave

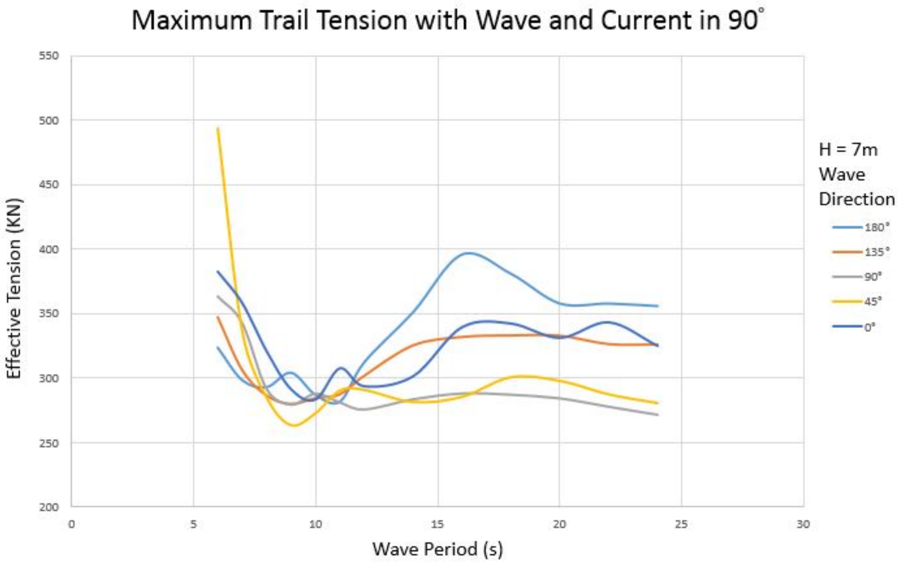


Figure 10.9: Maximum Trail Tension with Wave and Current

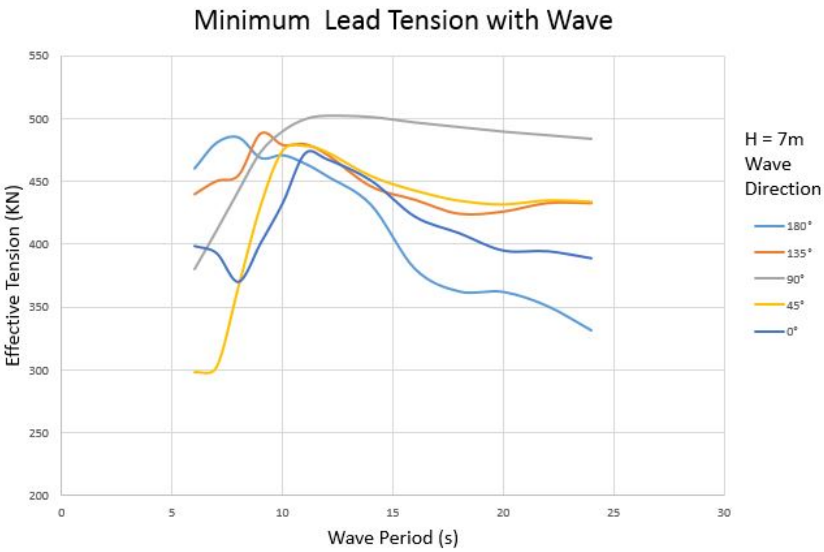


Figure 10.10: Minimum Lead Tension with Wave

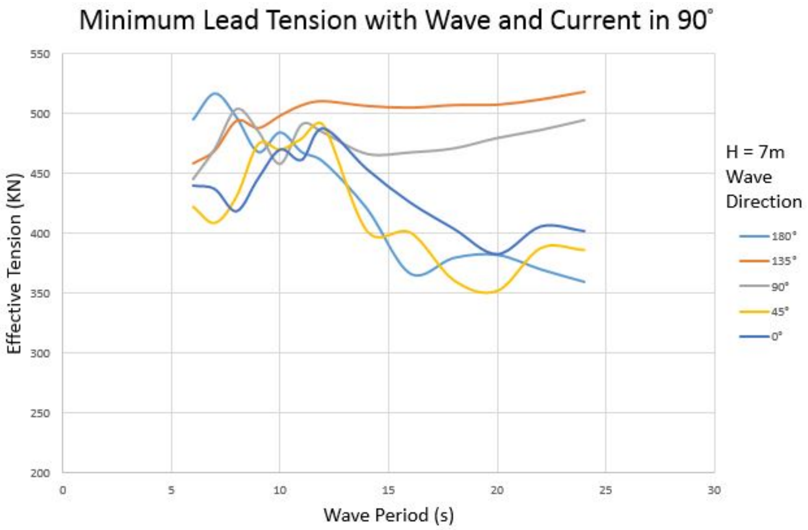


Figure 10.11: Minimum Lead Tension with Wave and Current

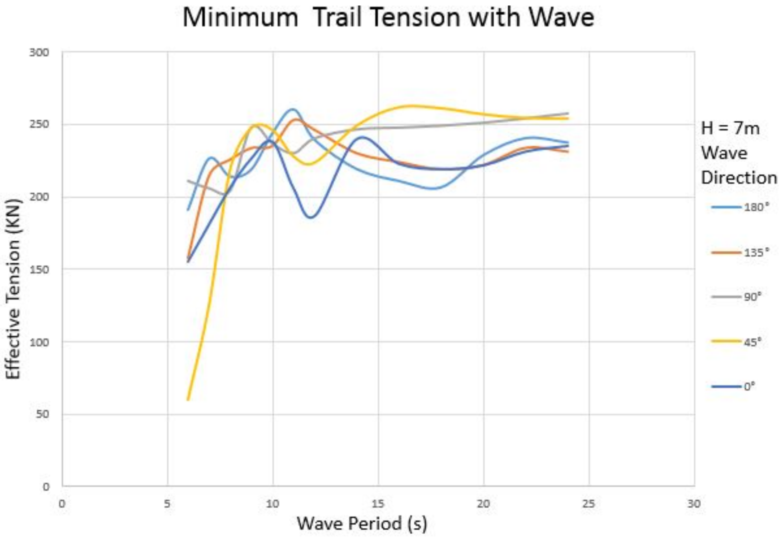


Figure 10.12: Minimum Trail Tension with Wave

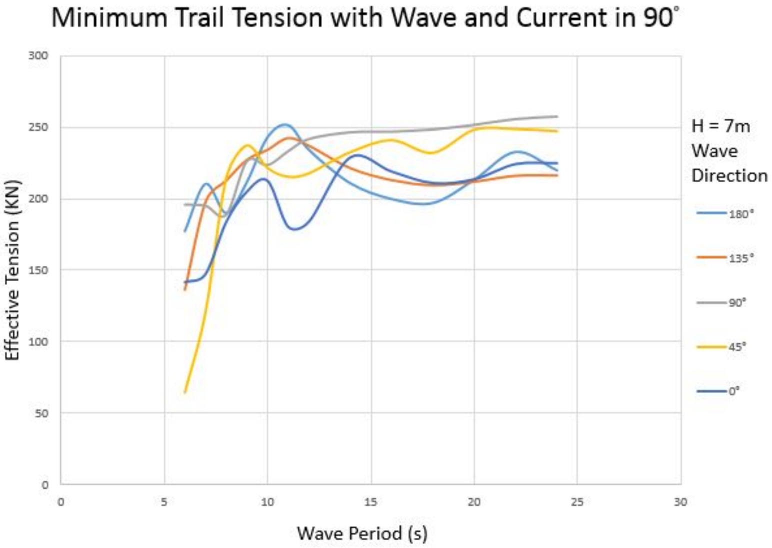


Figure 10.13: Minimum Trail Tension with Wave and Current

Table 10.9: Towing Results - Static and Dynamic Cases

Case No	Towline1 End GX-Force Static State (KN)	Towline1 Effective Lead Tension-Min (KN)	Towline1 Effective Lead Tension-Max (KN)	Towline4 Effective Trail Tension-Min (KN)	Towline4 Effective Trail Tension - Max (KN)	Wave Period (s)	Wave Direction (degrees)	Current in 90 degrees
1	422.121	460.513	562.375	191.108	333.048	6	180	No
2	422.121	480.969	537.551	226.140	299.598	7	180	No
3	422.121	485.232	540.225	213.880	301.509	8	180	No
4	422.121	468.937	553.222	218.744	306.479	9	180	No
5	422.121	471.136	577.476	243.517	294.337	10	180	No
6	422.121	464.528	554.311	259.963	287.074	11	180	No
7	422.121	454.595	585.786	239.061	312.859	12	180	No
8	422.121	431.723	653.309	219.003	349.728	14	180	No
9	422.121	380.605	729.824	210.836	395.078	16	180	No
10	422.121	362.642	771.895	206.456	365.997	18	180	No
11	422.121	362.307	837.057	228.589	363.576	20	180	No
12	422.121	351.056	823.191	240.232	369.585	22	180	No
13	422.121	331.653	795.178	237.170	365.387	24	180	No
14	422.121	439.888	577.954	157.528	350.066	6	135	No
15	422.121	450.256	579.069	214.313	307.146	7	135	No
16	422.121	454.852	570.418	225.498	288.684	8	135	No
17	422.121	487.660	560.447	233.411	287.473	9	135	No
18	422.121	478.640	539.240	234.916	292.325	10	135	No
19	422.121	479.283	569.606	252.845	289.187	11	135	No

Case No	Towline1 End GX-Force Static State (KN)	Towline1 Effective Lead Tension-Min (KN)	Towline1 Effective Lead Tension-Max (KN)	Towline4 Effective Trail Tension-Min (KN)	Towline4 Effective Trail Tension - Max (KN)	Wave Period (s)	Wave Direction (degrees)	Current in 90 degrees
20	422.121	471.213	588.081	246.002	312.174	12	135	No
21	422.121	446.049	621.177	229.852	339.594	14	135	No
22	422.121	435.489	631.103	223.725	351.482	16	135	No
23	422.121	424.491	629.650	218.742	345.787	18	135	No
24	422.121	426.197	626.605	221.765	337.624	20	135	No
25	422.121	432.880	626.284	233.560	337.212	22	135	No
26	422.121	432.866	616.599	230.930	335.912	24	135	No
27	422.121	380.123	658.169	211.127	366.636	6	90	No
28	422.121	410.787	622.365	206.019	344.098	7	90	No
29	422.121	442.479	586.344	204.494	299.527	8	90	No
30	422.121	472.938	549.195	247.909	281.285	9	90	No
31	422.121	489.402	535.851	236.806	296.758	10	90	No
32	422.121	498.865	526.119	230.225	298.441	11	90	No
33	422.121	501.616	520.923	240.439	292.959	12	90	No
34	422.121	500.651	523.952	246.612	296.591	14	90	No
35	422.121	496.351	524.963	247.805	292.906	16	90	No
36	422.121	492.694	531.782	249.109	290.600	18	90	No
37	422.121	489.103	531.071	251.152	287.902	20	90	No
38	422.121	486.299	534.002	254.177	284.001	22	90	No
39	422.121	483.393	537.954	257.542	280.438	24	90	No
40	422.121	298.007	649.390	59.692	492.609	6	45	No

Case No	**Towline1 End GX-Force Static State (KN)**	**Towline1 Effective Lead Tension-Min (KN)**	**Towline1 Effective Lead Tension-Max (KN)**	**Towline4 Effective Trail Tension-Min (KN)**	**Towline4 Effective Trail Tension - Max (KN)**	**Wave Period (s)**	**Wave Direction (degrees)**	**Current in 90 degrees**
41	422.121	302.039	648.132	125.274	346.964	7	45	No
42	422.121	366.748	615.609	219.118	296.316	8	45	No
43	422.121	431.163	594.672	247.756	274.341	9	45	No
44	422.121	474.992	547.003	246.465	276.605	10	45	No
45	422.121	478.681	544.029	228.200	298.220	11	45	No
46	422.121	473.717	560.736	223.792	304.220	12	45	No
47	422.121	454.618	580.595	249.508	284.719	14	45	No
48	422.121	442.974	599.677	262.187	276.639	16	45	No
49	422.121	434.895	610.611	261.438	288.769	18	45	No
50	422.121	431.976	609.632	257.285	286.854	20	45	No
51	422.121	435.188	612.742	254.718	282.772	22	45	No
52	422.121	434.144	604.592	254.332	293.218	24	45	No
53	422.121	398.262	611.206	154.920	369.948	6	0	No
54	422.121	392.650	605.872	180.697	368.034	7	0	No
55	422.121	369.860	601.871	205.990	327.639	8	0	No
56	422.121	400.691	589.307	225.946	300.178	9	0	No
57	422.121	432.446	561.853	237.628	282.223	10	0	No
58	422.121	471.751	550.696	205.497	305.928	11	0	No
59	422.121	467.414	545.119	186.392	308.097	12	0	No
60	422.121	450.450	605.370	239.417	307.135	14	0	No

Case No	Towline1 End GX-Force Static State (KN)	Towline1 Effective Lead Tension-Min (KN)	Towline1 Effective Lead Tension-Max (KN)	Towline4 Effective Trail Tension-Min (KN)	Towline4 Effective Trail Tension - Max (KN)	Wave Period (s)	Wave Direction (degrees)	Current in 90 degrees
61	422.121	421.674	652.497	222.317	343.257	16	0	No
62	422.121	408.561	701.086	218.708	343.375	18	0	No
63	422.121	394.714	690.003	221.298	328.987	20	0	No
64	422.121	394.171	702.703	230.801	342.723	22	0	No
65	422.121	388.555	698.453	234.687	327.202	24	0	No
66	397.219	494.704	559.830	176.819	323.830	6	180	Yes
67	397.219	516.300	546.391	209.847	298.662	7	180	Yes
68	397.219	496.324	570.485	189.568	293.180	8	180	Yes
69	397.219	467.644	594.219	211.164	304.380	9	180	Yes
70	397.219	483.974	597.897	242.622	287.207	10	180	Yes
71	397.219	467.595	588.978	250.993	282.103	11	180	Yes
72	397.219	459.446	632.872	233.731	312.585	12	180	Yes
73	397.219	420.699	695.831	210.346	351.276	14	180	Yes
74	397.219	366.811	767.864	199.341	395.794	16	180	Yes
75	397.219	379.898	824.754	196.533	380.915	18	180	Yes
76	397.219	382.392	837.385	212.849	357.913	20	180	Yes
77	397.219	370.330	837.207	232.305	357.890	22	180	Yes
78	397.219	360.031	825.313	219.371	355.927	24	180	Yes
79	397.219	457.976	584.370	136.011	346.740	6	135	Yes
80	397.219	468.838	577.548	197.531	305.866	7	135	Yes

Case No	Towline1 End GX-Force Static State (KN)	Towline1 Effective Lead Tension-Min (KN)	Towline1 Effective Lead Tension-Max (KN)	Towline4 Effective Trail Tension-Min (KN)	Towline4 Effective Trail Tension - Max (KN)	Wave Period (s)	Wave Direction (degrees)	Current in 90 degrees
81	397.219	493.911	582.420	212.488	286.175	8	135	Yes
82	397.219	487.818	585.182	227.046	279.686	9	135	Yes
83	397.219	498.214	562.364	234.068	284.209	10	135	Yes
84	397.219	507.011	553.578	242.312	287.134	11	135	Yes
85	397.219	510.403	562.317	236.921	301.524	12	135	Yes
86	397.219	506.446	567.738	221.242	324.962	14	135	Yes
87	397.219	505.006	566.234	212.833	331.401	16	135	Yes
88	397.219	507.155	574.386	209.237	332.643	18	135	Yes
89	397.219	507.489	564.562	211.694	332.414	20	135	Yes
90	397.219	511.919	552.356	215.893	325.906	22	135	Yes
91	397.219	518.336	541.787	216.084	325.568	24	135	Yes
92	397.219	444.847	611.653	195.860	363.736	6	90	Yes
93	397.219	470.230	578.023	194.977	342.897	7	90	Yes
94	397.219	503.366	549.285	188.809	291.565	8	90	Yes
95	397.219	484.637	575.202	226.349	279.333	9	90	Yes
96	397.219	457.477	589.774	223.620	287.936	10	90	Yes
97	397.219	490.490	563.288	233.397	281.073	11	90	Yes
98	397.219	483.571	582.534	241.903	275.631	12	90	Yes
99	397.219	465.882	605.834	246.647	283.579	14	90	Yes
100	397.219	467.114	603.660	247.130	288.069	16	90	Yes

Case No	**Towline1 End GX-Force Static State (KN)**	**Towline1 Effective Lead Tension-Min (KN)**	**Towline1 Effective Lead Tension-Max (KN)**	**Towline4 Effective Trail Tension-Min (KN)**	**Towline4 Effective Trail Tension - Max (KN)**	**Wave Period (s)**	**Wave Dire-ction (degrees)**	**Current in 90 degrees**
101	397.219	470.481	601.050	248.655	287.131	18	90	Yes
102	397.219	479.149	591.683	251.926	284.277	20	90	Yes
103	397.219	485.884	577.843	255.975	277.757	22	90	Yes
104	397.219	494.123	567.769	257.714	271.508	24	90	Yes
105	397.219	422.132	589.325	64.625	493.747	6	45	Yes
106	397.219	408.639	620.123	120.869	336.479	7	45	Yes
107	397.219	430.766	590.354	214.283	284.721	8	45	Yes
108	397.219	474.382	562.645	237.308	263.195	9	45	Yes
109	397.219	469.757	560.264	221.520	272.439	10	45	Yes
110	397.219	478.979	570.217	215.332	290.115	11	45	Yes
111	397.219	489.797	581.517	217.816	290.595	12	45	Yes
112	397.219	401.899	662.161	232.518	281.138	14	45	Yes
113	397.219	400.485	735.023	240.875	285.176	16	45	Yes
114	397.219	360.713	800.487	232.084	300.454	18	45	Yes
115	397.219	351.969	759.780	248.272	297.665	20	45	Yes
116	397.219	387.627	769.654	248.691	287.112	22	45	Yes
117	397.219	386.016	767.963	247.227	280.406	24	45	Yes
118	397.219	440.023	603.463	141.748	382.130	6	0	Yes
119	397.219	437.068	590.225	147.503	357.983	7	0	Yes
120	397.219	418.576	607.997	183.936	320.909	8	0	Yes

Case No	Towline1 End GX-Force Static State (KN)	Towline1 Effective Lead Tension-Min (KN)	Towline1 Effective Lead Tension-Max (KN)	Towline4 Effective Trail Tension-Min (KN)	Towline4 Effective Trail Tension - Max (KN)	Wave Period (s)	Wave Direction (degrees)	Current in 90 degrees
121	397.219	446.229	601.478	205.062	291.553	9	0	Yes
122	397.219	470.211	578.487	212.651	283.621	10	0	Yes
123	397.219	461.604	594.655	180.448	307.649	11	0	Yes
124	397.219	487.862	560.900	184.132	293.844	12	0	Yes
125	397.219	453.734	626.846	228.997	301.605	14	0	Yes
126	397.219	425.689	679.007	219.155	339.353	16	0	Yes
127	397.219	403.833	725.491	211.081	342.144	18	0	Yes
128	397.219	382.613	702.591	213.748	331.125	20	0	Yes
129	397.219	405.862	729.232	224.395	343.087	22	0	Yes
130	397.219	401.972	717.594	225.033	324.988	24	0	Yes