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Løsninger for offshore flytende produksjonsinnretninger med minimal bemanning

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Master i energi og miljø

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MASTER THESIS

for

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Minimum manning solutions for offshore floating production systems

Løsninger for offshore flytende produksjonsinnretninger med minimal bemanning

Background and objective

Floating offshore systems are used for production and processing of oil and gas, particularly in deep waters. Reduced offshore manning will give advantages in terms of improved safety and reduced operational expenses (opex), and such solutions may enable field developments in harsh or remote areas which are otherwise difficult to realize. Minimum manning may be achieved by simplification of process and utility systems, selection of equipment with minimal maintenance needs and high regularity (including use of equipment and process solutions originally developed for subsea oil and gas processing), use of redundancy, implementation of condition based or preventive maintenance schemes, use of advanced data analysis capabilities (condition monitoring), and in general by simplifying and minimizing all installations topside. Maintenance models can play a key role, especially considering reliability-centred maintenance and use of remote monitoring.

In the specialization project of Rysst (2015) low manning process and equipment solutions for FPSOs and FLNGs were introduced and briefly evaluated. The potential was found to be quite good, and a number of potential solutions were identified. Based on this initial high-level evaluation, more detailed work can be done using actual system designs and FMEA[1] and/or RAM[2] analyses as well as design reviews to identify promising configurations and their potential for low-manned operation. Analyses of process system configuration and performance may be carried out using flowsheet models, e.g. Hysys. In order to cover a wide range of system complexity, FPSO and FLNG solutions can be studied in specific case analyses. The evaluations may also consider enabling technologies such as robotics and advanced sensor and remote control systems. If cost data can be established, simple capex and opex comparisons could also be included.

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[1] Failure Mode and Effect Analysis

[2] Reliability, Availability and Maintainability

The main objective of the master thesis is to further develop and evaluate minimum manning solutions for offshore floating oil and gas production systems with varying complexity.

The following tasks are to be considered:

1. Brief update on low manning solutions for offshore oil and gas production, establishing key principles and definitions, technology options, and future outlook based on current literature.

2. Establishment of study basis, including base case system definitions, framework and methodology of analysis, and case definitions for low manned design/operation studies.

3. Analysis of base case ("standard") FPSO/FLNG systems and potential low-manned systems using process models, reliability, failure, and maintenance analyses to quantify process performance, system regularity and maintenance needs based on alternative system configurations and technology solutions. If cost data are available, simple capex and opex comparisons could be included.

4. Discussion and comparison of results, and final evaluation of the expected potential of minimum manning solutions for offshore floating oil and gas production. The evaluation need to consider technology development needs, special risk factors, and should also give recommendations for further direction of this work.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14 January 2016

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Minimum manning solutions for offshore floating production systems

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Master Thesis

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Preface and acknowledgement

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I would like to give a big thanks to my supervisor Jostein Pettersen, adjunct professor at NTNU and employee at Statoil, for his valuable feedback on my master thesis and for enlightening conversations helping me to take the next step when needed in this process.

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Lars Rysst

Abstract

Floating offshore systems are used for production and processing of oil and gas, particularly in deep waters. Reduced offshore manning will give advantages in terms of improved safety and reduced operational expenses (OPEX), and such solutions may enable field developments in harsh or remote areas which are otherwise difficult to realize.

The main objective of this report is therefore to explore and evaluate solutions that may enable minimized offshore manning in complex operations of floating offshore systems with a focus on process and facility design. The report also explores how remote operations with condition and performance monitoring, and the use of robotics can reduce the required presence of offshore personnel.

A given "standard" base case FPSO is analysed in order to identify the most critical systems with regard to low manned operations. Inputs to the analysis are the "standard" system configurations, maintenance and manning data, reliability data from OREDA and the results of RAM analysis performed on a similar processing facility to the base case FPSO.

The results show that the gas compression for reinjection, the main power generation and the gas dehydration system are the most critical systems in terms of reliability and maintenance requirements. Further the analysis concludes that a failure in any of the marine systems in case of entirely unmanned operations may take too long to repair to avoid a catastrophic incident. It is therefore recommended that a small crew is present to operate and maintain/repair the marine systems to ensure the safety of the vessel.

The results from the analysis of the base case FPSO have been used to develop and analyse a low manned FPSO concept. New equipment/system solutions for the three most critical systems on the base case FPSO is evaluated and analyzed. The results show that the implementation of integrated compressor solutions and power from shore/host have the ability to greatly increase the availability and decrease the maintenance requirements of the compressor systems and the main power generation system compared to the base case FPSO. No new solution has been found for the gas dehydration system, but current unmanned platforms have shown that it is possible. Further an evaluation of the implementation of remote operations with condition and performance monitoring, maintenance and inspection robots, and a design

that has immense focus on achieving high maintainability has been made. It shows that the required presence on the facility can be reduced through decreased maintenance and inspection requirements.

Based on the development and analysis of solutions for the low manned FPSO concept, it is the author's opinion that a FPSO with a crew of up to 20 people and 30000 yearly maintenance man hours is a possibility, and a proposal to what such FPSO may look like in terms of process, utility and marine systems, and operational philosophy is presented.

In conclusion, the technology needed to design a low manned floating production facility is already available or could be in the near future. The work presented in this report does not have the ability to conclude that low manned operations is beneficial for every FPSO development project, but the result indicates that it will be possible for some projects. Hence it will be beneficial to perform project related feasibility studies to conclude if it is possible or not for each individual project.

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Chapter 1

Introduction

1.1 Background

Floating offshore systems are used for production and processing of oil and gas, particularly in deep waters. Reduced offshore manning will give advantages in terms of improved safety and reduced operational expenses (OPEX), and such solutions may enable field developments in harsh or remote areas which are otherwise difficult to realize. The current low oil prize is forcing oil and gas companies to reduce costs, and reduced offshore manning have the ability to make be a big contributor in achieving this. Especially on the Norwegian Continental Shelf where the cost of manning is very high.

Technologies and solutions such as IT/ instrumentation solutions, and Integrated Operations principles may enable reduced offshore manning, but the present work focuses on how process and facilities design, process system configuration and equipment solutions can contribute to reducing offshore manning needs for operation and maintenance.

Low manned operations may be achieved by simplification of process and utility systems, selection of equipment with minimal maintenance needs and high regularity (including use of equipment and process solutions originally developed for subsea oil and gas processing), use of redundancy, implementation of condition and performance monitoring, and in general by simplifying and minimizing all installations topside. The implementation of remote operations, robotics and a suitable maintenance strategy are also key factors when it comes to achieving low manned operations.

1.2 Floating offshore systems

1.2.1 FPSO

Oil has been produced offshore since the 1950s. Original oil processing facilities sat on the seabed as the conventional platforms we see today, but as exploration moved to deeper and more remote locations floating production systems became an option to make production a economically viable option. The first oil FPSO was the Shell Castellon and was installed on the Castellon field in the Mediterranean Sea in 1977. It was a 60000 dwt converted tanker that produced oil from a single well and was designed for a 10-year field life (Oil&GasJournal (1996)).

Figure 1.1: A typical FPSO (Modec (2015))

In 2012 there were 156 FPSOs in operation. 63% of these are tanker conversions and 37% are newbuilds (OffshoreMagazine (2012)). The reasons for the popularity of the FPSOs are many. They have large deck areas for placement of the processing facilities and plenty of vertical load bearing capability in order to resist mooring and riser loads. FPSOs also provide storage capacity for the produced oil and export of the hydrocarbons can therefore be made by offloading to a shuttle tanker and thereby eliminate the need of installing a pipeline export network. This last factor is very relevant of the coast of West Africa where the pipeline infrastructure is very limited and restricted to shallow waters. Another example is off the coast of Brazil where the offshore infrastructure is working close to capacity and the large depths of new fields allow for shuttle tanker offloading to be a cost beneficial alternative to installing additional export pipelines.

Early FPSOs had quite simple processing facilities, but with the evolution of technology over the years FPSOs today have very complex processing facilities with gas processing, gas export or reinjection, water injection and chemical treatment.

1.2.2 FLNG

Studies into LNG production have been carried out since the 1970s, but it was only in the 1990s that significant research began. Moving the LNG production to a offshore floating facility faces several challenges. For one, every element of a conventional LNG facility would need to fit into an area much smaller than typically used, while maintaining levels of safety and operation. A floating offshore LNG facility will also meet the major challenge of wave motion. The LNG containment system must be able to withstand damages that can occur caused by the waves and motions can cause sloshing in partly filled tanks.

Figure 1.2: Shell's FLNG vessel Prelude (Astor (2015))

The FLNG facility will be moored and gas from the field will enter the FLNG through risers from the seabed. Having reached the facility the gas will be treated to produce natural gas, LPG and natural gas condensate. The processed natural gas will be treated by removing impurities such as CO_2, H_20, H_2S etc., before entering the liquefaction process where the gas will be liquefied and stored in the hull until offloaded to an LNG carrier. The conventional alternative would be to process the gas before exporting it through a pipeline for distribution or liquefaction onshore.

As of today there are no FLNGs in operation, but there are several projects set to be ready for operation within a couple of years. The future of FLNGs is very optimistic, but relies on if the current projects are able to deliver as promised.

1.3 Objectives

The main objective of this master thesis is to develop and evaluate minimum manning solutions for offshore floating oil and gas production systems with varying complexity based on a given "standard" base case FPSO. The following tasks are considered:

1. Brief update on low manning solutions for offshore oil and gas production, establishing key principles and definitions, technology options, and future outlook based on current literature.
2. Establishment of study basis, including base case system definitions, framework and methodology of analysis, and case definitions for low manned design/operation studies.
3. Analysis of base case “standard” FPSO/FLNG systems and potential low-manned systems using process models, reliability, failure, and maintenance analyses to quantify process performance, system regularity and maintenance needs based on alternative system configurations and technology solutions. If cost data are available, simple CAPEX and OPEX comparisons could be included.
4. Discussion and comparison of results, and final evaluation of the expected potential of minimum manning solutions for offshore floating oil and gas production. The evaluation need to consider technology development needs, special risk factors, and should also give recommendations for further direction of this work.

1.4 Approach

In order to highlight the challenges with regard to low manned operations of FPSOs, the chosen approach is to analyse a given "standard" base case FPSOs. The most critical process and utility systems in terms of reliability and maintenance requirements is identified, and other operational challenges is discussed.

The results are used to develop and analyse a low manned FPSO concept where potential low manned systems for the three most critical systems on the base case FPSO is presented and analyzed. The new solutions are compared to solutions used on the base case FPSO in terms of reliability and maintenance requirements. Also considered is the implementation of remote operations, condition and performance monitoring, inspection and maintenance robots, and potential maintenance strategies for the low manned concept.

1.5 Limitations

- To date, no FLNG facilities are in operation and no real operational experience is yet available. To consider FLNGs for unmanned operations is therefore a difficult task as compared to FPSOs where reliability data, maintenance data and extensive experience is available. For this reason, and due to time constraints only some general remarks is therefore made with regard to the challenges of minimum manned operations of FLNG facilities.
- Further cost data has not been available, and is therefore not included in this report.
- In the pursuit of low manned solutions several assumptions have been made based on statements from manufacturers, and not real operational data due to being new technology. The results must therefore be used with caution.

1.6 Structure of the Report

In this thesis, the following tasks are performed and structured as below.

Chapter 2 gives an update on low manning solutions. The chapter includes a presentation of current literature around low manned solutions presenting key principles and definitions. The chapter also presents unmanned facilities operating today and subsea equipment that has the potential to be used for low manned operations topside.

Chapter 3 presents the framework and methodology of analysis that will be used in the analysis of a "standard" base case FPSO and in the pursuit of solutions that have the potential to allow for low manned operations.

Chapter 4 presents the "standard" base case FPSO with a description of the main processing systems, utilities, marine systems, location, maintenance data and manning requirements that will be used as a basis for the work conducted in the following chapters.

Chapter 5 consists of the analysis of the "standard" base case FPSO where the most critical systems in terms of reliability and maintenance requirement are identified. The analysis focuses on the main processing systems, but also mentions potential challenges with regard to the utility, marine and offloading systems. The analysis also consists of a manning assessment in order to consider which positions and services it is possible to reduce when the goal is low manned operations.

Chapter 6 consists of the development and analysis of a low manned FPSO concept based the results from the analysis of the "standard" base case FPSO. A precondition for the development of the low manned concept is that the low manned FPSO is designed as a new build, and is not an approach to the de-manning of existing facilities.

Chapter 7 presents a proposal of a low manned FPSO concept based on what was found in Chapter 6 and proposes technology development needs.

Chapter 8 consists of a brief evaluation of the potential for low manned operations of FLNG facilities in light of the results of the low manned FPSO concept.

Chapter 9 sums up the report with discussion, conclusions and recommendations for further work.

Chapter 2

Update on low manning solutions

2.1 Unmanned and minimum manning definitions

The definitions for unmanned or minimum manned installations are not consistent from one region to another, and Table 2.1 shows a proposal to different classification categories presented by Edwards and Gordon (2015). Norwegian definitions may vary in terms of facility definition and operational manning criteria, but the definitions in Table 2.1 are though to give a good picture of the different types of definitions.

Table 2.1: Definitions for unmanned or minimum manned installations. Edwards and Gordon (2015)

Facility Definition	**Operational Manning Criteria**	**Operational control**	**Maintenance requirements (man hours/year)**
Minimum Manned Installation(MMI)	Manned full time with a crew less than 20. Typically day shift only.	Remote control from host platform or shore	15000-30000
Not Normally Manned Installation(NNMI)	Not manned continuously. Have accommodation for up to 20 people. Visited for 5-7 days every 1-4 months by a crew up to 20 people.	Remote control from host platform or shore	5000-15000
Normally Unattended Installation(NUI)	Not manned continuously, and has no accommodation for overnight stays. Visited for 5 days every 2-6 months.	Remote control from host platform or shore	2000-5000

2.2 What is remote operations?

Cramer et al. (2011) defines remote operations as: "The ability to operate a remote facility from a central control room(CCR), which may be just outside the "blast zone", or hundreds of miles away from the production site". The main objective is to operate the remote production facility unattended, with no staff required for routine operating tasks. The remote production facility can have different degrees of complexity as the examples presented by Cramer et al. (2011) below shows by increasing complexity:

- Subsea wells, manifolds, chemical injection and multiphase transport lines, which are inherently unattended.
- Offshore or onshore surface wells, chemical injection and multiphase transport lines.
- Offshore or onshore surface wells, chemical injection, multiphase transport lines and a test separator.
- Offshore or onshore surface wells, chemical injection, test separator, gravity separation (two or three phase), oil and gas export.
- Offshore or onshore surface wells, chemical injection, test separator, gravity separation (two or three phase), gas/oil dehydration, gas compression, gas injection, and oil and gas export.

2.3 Three main remote operations categories/types

Both brown fields and green fields can be subjects to changes on the facility that can allow for reduced staffing or even unmanned operations. With brown fields that are already manned it is not necessarily justified to spend the CAPEX required to allow for unmanned operations, or it may be impractical to change the existing infrastructure. Even so, there are enablers that have the potential to allow for reduced manning of brown fields. Cramer et al. (2011) defines three main remote operations categories/types; brown field "as is", brown field simplified and/or refurbished and Green Field- Unattended operations designed-in from the start. Cramer et al.

(2011) presents each category with a number of enablers that will allow for reduced manning or unmanned operations entirely as can be seen below.

1. Brown fields "as is" - applicable to all existing assets,excluding those that are already unattended or refurbished.

   Reduce staffing(operational and/or support) at existing facilities in which it is considered impractical to modify/simplify the existing infrastructure. Enablers that allows for reducing staffing of such a facility are:

   - Remote surveillance of wells and processes to predict and manage failures using intervention by exception.
   - Remote surveillance of equipment to identify changes in equipment performance and condition.
   - Minor infrastructure modifications, e.g. addition of video cameras to the remote operating facility.
   - "Campaigns" to execute preventive maintenance to reduce the number of visits to the site.
   - Reduction of on-asset support activities to as low as reasonably possible.

2. Brown fields simplified and/or refurbished- applicable to all existing assets,excluding those that are already unattended or refurbished.

   Identify operations where it is justified to spend CAPEX in pursuit of remote operations. Enablers that allows for reducing of such a facility include the points described above for the Brown field "as is", in addition to the following:

   - As far as possible design-out maintenance by choosing equipment with low maintenance requirements and the use of smart instrumentation to reduce inspection requirements.
   - Critically review the impact on safety and availability of adopting unattended concepts - often reduced staffing concepts can give overall safety improvements with less safety related hardware installed.

  - Install instrumentation to facilitate remote control, e.g actuated control valves, DCS.
  - Amend process equipment to achieve zero or minimal maintenance.
  - "Mothball" living quarters and associated support/logistics equipment.

3. Green fields- Unattended operations designed-in from the start.
   - Designed with no living quarters or with "emergency" facilities only to be used in a case of absolute necessity.
   - Minimum maintenance systems and equipment.
   - Routine maintenance such as inspections are eliminated in the design by the use of smart instrumentation.
   - ESD and F&G: no need to cater for the safety of people in the unattended facility.
   - No local switches/panels, instrument readings, sample points or manual valves.
   - Local operator equipment, integrity checks/ abnormal situation detection replaced by sensors, e.g F&G and video surveillance.
   - Incorporation of appropriate new technology.
   - Personnel access either by helicopter or "walk to work" bridge from a boat.

The focus in this report is on low manned operations for green fields, and the information provided for all categories are guidelines to how this could be accomplished. The big advantage of applying a low manned concept to a green field is that the process starts with a clean sheet, and the best available technology and solutions can be selected without having to deal with the challenges of a facility that intentionally was designed for fully manned operations.

2.4 Current unmanned process facilities

Most of the unmanned platforms today are wellhead platforms with little or no process equipment, but there are some more advanced unmanned processing facilities in operation today, both subsea and topside. Some of them are presented in the follow subsections.

2.4.1 Woodside Angel

The Woodside Angel platform is known to be one of the most advanced not normally manned process facilities to date. The platform is situated 120 km off the coast of Australia in about 80m of water and produces 22.65 million Sm^3 of gas and 50000 barrels of condensate a day. The platform is remotely controlled and monitored from the North Rankin complex. A maintenance crew is deployed every 8 weeks for a period of 7 days to conduct inspections, preventive maintenance and repairs(Edwards and Gordon (2015))

The processes on the Angel platform include separation, a glycol gas dehydration system, condensate dewatering facilities and produced water treatment. The produced water is discharged to the sea(Woodside (2012)). A carbon steel export pipeline transports the dehydrated hydrocarbon gas and liquids to the North Rankin complex for further processing(FMCTechnologies (2015)). Further the selected cooling solution on the platform is air cooling as can be seen highlighted in Figure 2.1.

Figure 2.1: The Woodside Angel Platform (Woodside (2012))

Angel gets its power delivered from the North Rankin complex, and is therefore without the need of gas turbines which is often associated with significant maintenance. During the project process the number of maintenance man hours was reduced to below 5000 hours per year which was an 80% reduction compared to a traditional concept, and the platform has had an exceptionally high availability over the last five year of over 98% (Edwards and Gordon (2015)).

2.4.2 The Solan Platform

The Solan field covers 7 km^2 in the North Sea west of the Shetland Islands in 135m of water. Premier oil is currently in the final phases of completing the commissioning of a normally unmanned platform, and first oil was achieved in April of 2016. There are two horizontal production wells and two horizontal water injection wells to help maintain pressure in the reservoir. Expected production is 24000 b/d of oil, 35000 b/d of liquids and 85000 Sm^3/d of gas, and total production over the projected 20 year lifetime is estimated to be 44 MMbbl (Serna and Goddard (2014)).

The platform has equipment for separating oil, gas and produced water, oil dewatering and produced water treatment. The produced water is reinjected and the associated gas is used in gas turbines that powers the equipment on the platform. Excess gas is flared. The crude oil is stored in a 300000 bbl subsea tank that can hold 10-14 days of production and the oil is offloaded to a shuttle tanker via a flexible hose (Serna and Goddard (2014)).

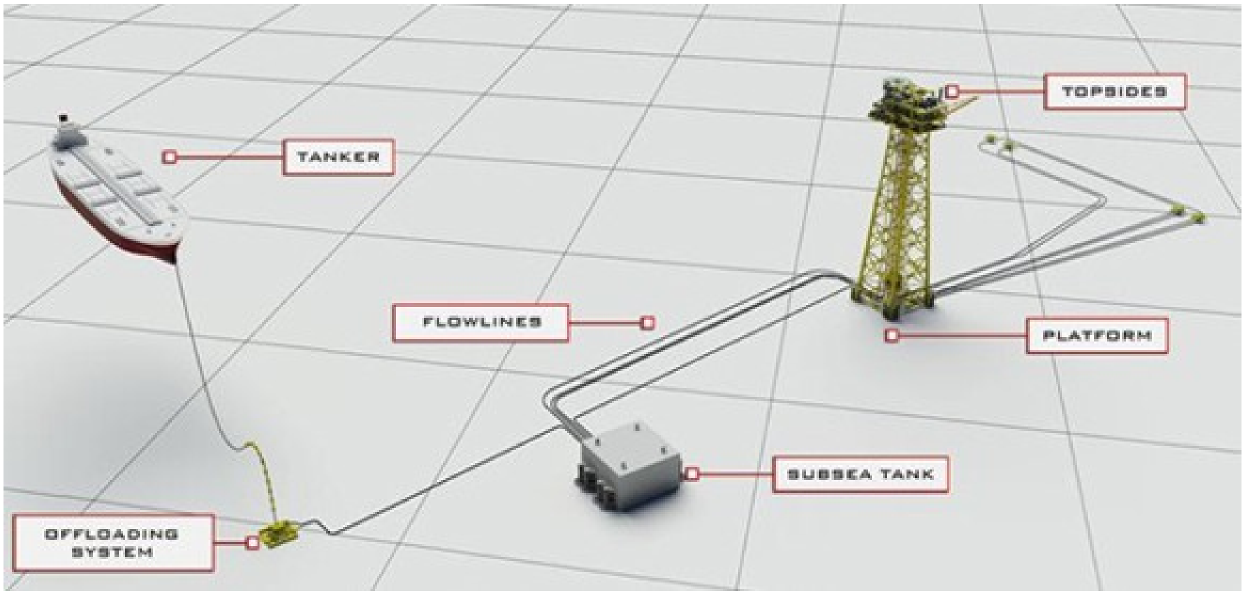


Figure 2.2: The Solan Platform (OffshoreTechnology.com (2015))

The platform has accommodations for a staff of 30, but is planned to only be manned the first year in order to make sure that everything is working as it should. After the first year, the platform will be controlled via satellite link from Aberdeen, and the platform will be visited on a monthly basis for inspection and maintenance(Serna and Goddard (2014). The platform has a helicopter deck for access to the platform.

In order for operators to control the platform remotely, a integrated control and safety system is being installed. The system consists of a digital automation system, a process safety system and a machinery health monitor with a predictive maintenance software that is able to perform instant health checks via the satellite link.

2.4.3 Subsea processing equipment and solutions

For low manned operations of a FPSO the use of subsea technology can have the following two applications:

1. Processing equipment placed on the seabed can help reduce the topside processing requirements, and thus lead to a simpler topside facility with reduced manning levels.

2. The use of subsea solutions/equipment developed for unmanned operations may be introduced topside due to its low maintenance requirements and high reliability in order to reduce the manning level.

Through the design of subsea systems extensive experience has been gained in how to design equipment for unmanned operations with minimum maintenance and interventions allowed throughout the lifetime of the equipment. Due to high intervention costs and the potential loss of production, subsea processing equipment must have very high reliability and availability. The key to a successful subsea system is to keep it simple and to have as few moving parts as possible.

By utilizing the experience gained in the development of subsea technology it should possible to design the same equipment made for unmanned operations topside to a much lower cost as topside equipment does not have to withstand the strains of the subsea environment and is easier to access. Topside equipment can also be easier to standardize, further lowering costs.

Åsgard subsea gas compression and the Troll-Pilot are two examples of subsea installations with process equipment that can be installed topside to allow for reduced manning of the facility, and they are presented below.

Åsgard subsea gas compression

In 2015 the world's first subsea gas compression facility was installed at the Åsgard field offshore Norway. The installation boosts the falling gas pressures of the reservoirs and allows stable production to continue. It is estimated that an additional 280 million boe will be recovered from the Mikkel and Midgard fields (Hedne et al. (2014)).

The traditional topside application is to compress the gas on the platform, but the closer the compression is placed to the well, the more gas can be extracted. The subsea compression system increases the production, has a reduced environmental footprint and is safer to operate due to unmanned operation.

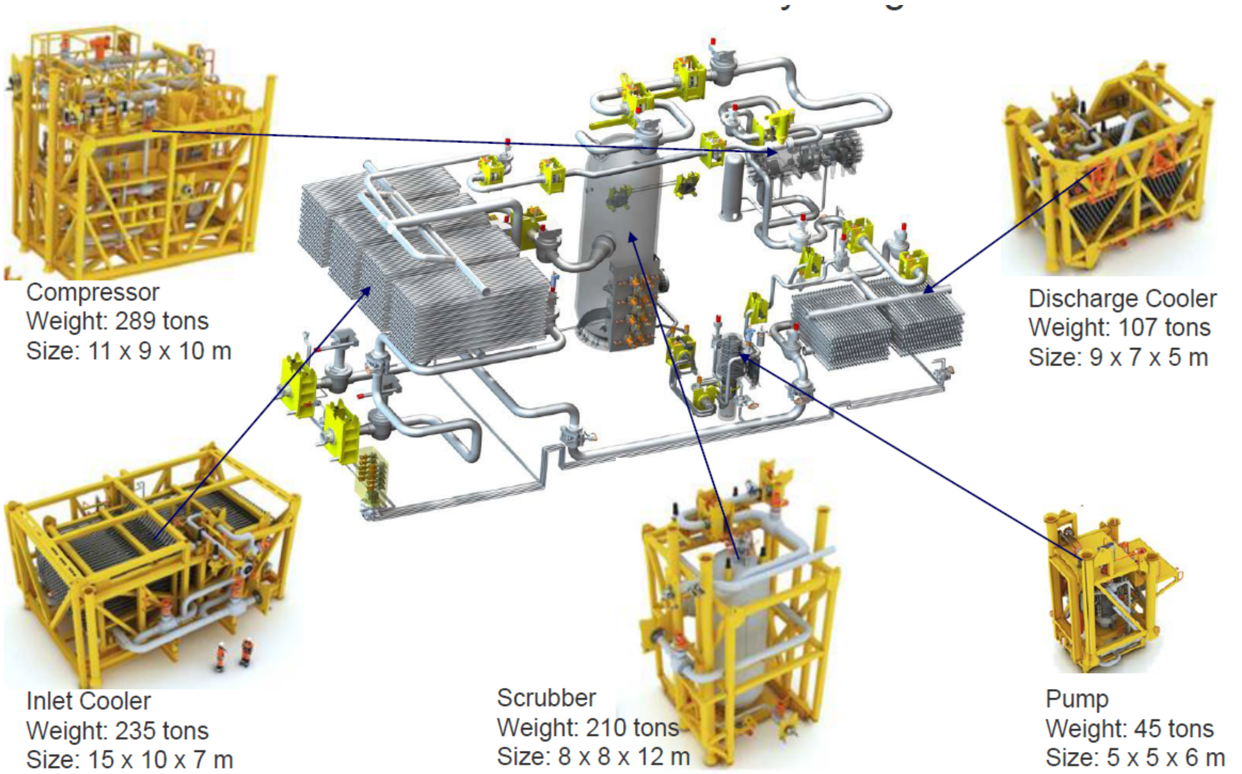


Figure 2.3: Process modules on the compression station (Hedne et al. (2014))

The Åsgard subsea compression system consists of two parallel compression trains with a 11.5 MW compressor each. Both trains also consists of a inlet and anti-surge cooler module, a separator module, a pump module, a discharge cooler module, a subsea control system, a subsea power system and a MEG distribution system. The electric power and control will is delivered from Åsgard A trough about 40 km of high voltage cables and combined power and control umbilicals.

The subsea gas compression module cools the incoming components before it separates the liquid and gas. The gas is then compressed and cooled again before being mixed back with the fluids. The mixture is then pushed to the receiving facility at Åsgard B.

As the subsea system was just put into use last year no operational data has yet been released about how the system performs, but having in mind the costs of such a project it is the author's opinion that the operators would not install the system on the seabed unless they were certain that it would perform according to the requirements. The development of subsea compression technology have already seen manufactures such as Dresser-Rand and GE Oil&Gas develop integrated compressor solutions made for topside applications utilizing the same design principles as subsea compressors. Figure 2.4 shows a comparison of a old compressor system and a new integrated compressor system based on the same design principles as subsea compressors. It is evident that the new solution with no gear box, seal gas system and lube oil system is far less complex, and has a significantly reduced footprint. Why the new compressor solutions can be suitable for low manned operations is further discussed in Chapter 6.

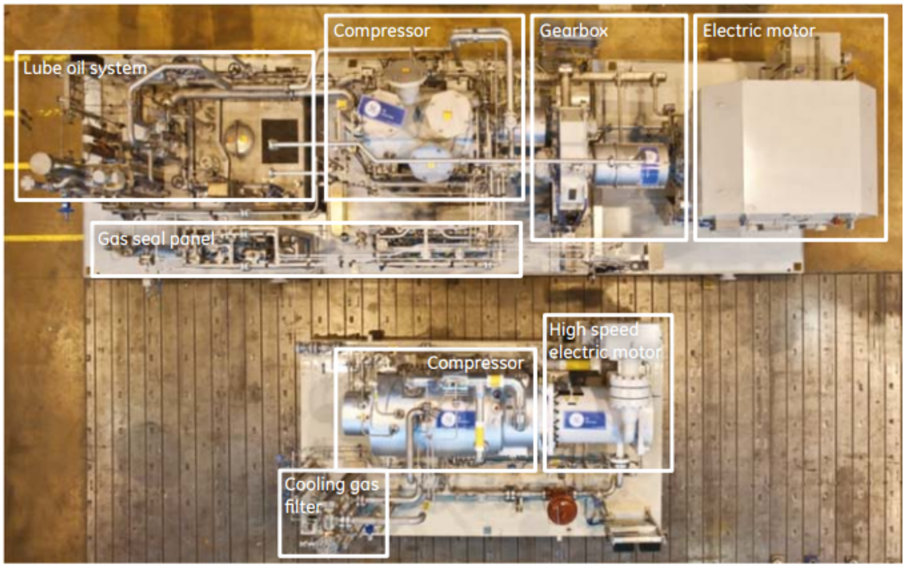


Figure 2.4: A old(top) and a new(bottom) compressor system. (GEOil&Gas (2016a))

Troll-Pilot

The Troll pilot was put into operation in 2000, and was the world's first subsea separation and water injection system put into operation. The main objectives of the Troll pilot development as presented by Horn et al. (2003) were:

1. To improve the water treatment capacity of the Troll C platform and its environment and thus maximize throughput.
2. To demonstrate commercial viability of subsea separation and boosting with a view to other applications, i.e. to be a competitor to separator stations installed on a platform.

The purpose of the subsea process is to isolate the water phase for re-injection into a well. The result is that less water is directed to the topside facility at Troll C. The separation of oil and water was a major consideration when developing the project due to the high oil viscosity. It was therefore decided that the use of a horizontal gravity separator, allowing maximum oil/water interface, would offer the best performance for this particular system. The cylindrical separator vessel is 11.8 m long with a diameter of 2.8 meters. The vessel is thermally insulated from the ambient seawater (Horn et al. (2003)).

For the separator, a patented inlet arrangement was selected and is of great importance in order to achieve the water quality required for injection. The goal was to separate gas from the 3-phase inlet stream by means of multi-G effect, so that the gas separation occupies as little space as possible in the separator. In addition, the inlet arrangement reduces the fluid momentum so that laminar flow conditions is achieved in order to facilitate a gravity based separation process. The inlet device can not be serviced for the design life of 25 years, and is therefore designed to tolerate some failure modes and has a high degree of mechanical integrity in order to withstand erosion, corrosion, vibrations and flow forces((Horn et al. (2003))). The outlet arrangement is designed so that the gas and oil phase is recombined without the occurrence of slugging in the output line. The solution provides a volume of stored oil in the outlet section, so that periods of only gas output is prevented.

The Troll pilot has now been in operation for 13 years, and has experienced stable operation and a near 100% availability since 2008(Statoil (2014)). The Troll pilot has proven that the subsea technology used to design both the separator and the water injection pump has been successful, and similar technology can potentially be used for topside applications.

2.4.4 Overview of systems/equipment used in unmanned operations

Whether the equipment is placed subsea or on unmanned platforms this chapter shows that most of the equipment needed on a FPSO is already remotely controlled on unmanned facilities. An overview of equipment or process systems existing on unmanned facilities today can be found in Table 2.2.

Table 2.2: Equipment or process systems on unmanned facilities

Equipment/System	**Subsea**	**Normally unmanned installation**
Compressors	Yes	Unknown
Pumps	Yes	Yes
Gas turbines	No	Yes
Separators	Yes	Yes
Produced water treatment system	No	Yes
Glycol dehydration system	No	Yes
Condensate/oil dewatering system	No	Yes
Offloading	No	Yes

2.5 Regulations

Laws and regulations related to offshore activities has to be followed when opting to achieve low manned or unmanned operations of offshore facilities. The laws and regulations differ from country to country, and what is required will to a large degree be decided by the shelf state where the facility is placed. Norwegian laws and regulations have immense focus on the safety and health of people, and protection of the environment, and has been known to setting a very high standard with regard to the themes mentioned above.

The Petroleum Safety Authority(PSA) has few references to unmanned or low manned facilities, and recommends following the same principles to manage risk towards health, safety, environment and the assets, regardless of whether the facility is manned or unmanned according to Rambøll (2016). For simpler facilities without accommodation, the facility regulation section 6 states that simpler solutions may be chosen provided that these solutions can be proven satisfactory through special assessment. It is the author's opinion that this regulation is mainly meant for very simple facilities not meant to be manned for periods of time as it could be expected that a large processing facility such as an FPSO will have to be.

The guidelines for the PSA regulations provide references to NORSOK and international standards. The standards are meant to be used as guidelines for design methods in order to meet the requirements in the regulations. Present NORSOK standards have limited references with regard to the design of unmanned platforms according to Rambøll (2016). The NORSOK S-001 standard has some specific requirements to the safety systems of simple not normally manned installations(NNMI) that is only manned during daytime, and does not have accommodation for overnight stays. It is the author's opinion that these guidelines were not made with complex facilities such as an FPSO in mind as the standard states that the process equipment only includes simple equipment such as production manifolds and Xmas trees.

The summary report presented by Rambøll (2016) concludes that current regulations and standards were made to support safe operations of fully manned platforms, and that attempts to develop low manned and minimum manned installations in Norway will quickly get entangled in the requirements and standards made with fully manned installations in mind. Rambøll (2016) recommends that the best short-term solution is to develop a guideline or a NORSOK standard providing an approach to the design of unmanned installations for the Norwegian Continental Shelf. If such a guideline was available the development of a low manned or unmanned FPSO could become a lot easier.

The laws and regulations also has requirements to the competence required to be present on the facility, but the regulations do not refer to a specific number of people required. A floating facility will also have to meet the competence requirements for marine operations such as stability and dynamic positioning. The PSA regulations refers to the regulations for qualifications and certificates for seafarers on these matters. The requirements will have to be decided on a case to case basis depending on what tasks the marine crew is required to perform and on if the FPSO is classified as having its own propulsion system. An FPSO is classified as having its own propulsion system if it is able to maintain a speed of 5 knots in quiet weather and with no current or if it is able to maintain its position in winds up to 20 m/s, currents of 0.5m/s and significant wave heights of 5m.

To summarize, the laws and regulations were not made to support the development of low manned or unmanned operations, and such a development many quickly get entangled in the requirements set upon fully manned installations. On the other hand, simpler solutions may be allowed proven that they are sufficient with regards to the safety and operation of simple NNMI facilities. It is therefore the author's belief that this may also be applied to more complex facilities such as an FPSO. In terms of the required competencies required present on the facility, the goal of these regulations is to ensure that there is enough knowledge present at the facility in order to ensure that operations are performed to the required safety level. If these tasks are proven to be efficiently completed from a remote facility, the crew inhabiting this knowledge may be relocated to the remote facility.

The further work in this report will not focus on following the guidelines of the PSA regulations, as it is not within the initial scope of this report. As a concluding remark the exploration of processing systems and other measures that have the potential to reduce the manning requirements on offshore installations will in itself increase the safety level of the installation as there are fewer people present that could be hurt. It is of course important that the safety of people that remains or have to visit the facility is upheld, but how this could be achieved is not further considered in this report.

2.6 Experience from the design of unmanned installations

When designing a facility for low manned operations the goal is to achieve a sustainable operational availability while minimizing the need for personnel to be present on the facility. In order to achieve this, the equipment has to be reliable and the total maintenance requirements of the facility has to be as low as possible. Some important factors that have to be taken in account when designing for unmanned operations is described below.

- The reliability of equipment including any necessary redundancy. Edwards and Gordon (2015) states that: "Is it not good enough to select equipment with a known poor track record of reliability just because that is what was bought last time. Buying the lowest cost, technically acceptable piece of equipment, is a recipe for a failed unmanned operation. It is far better to buy one good pump than buying three bad ones in an attempt to ensure high availability. Three pumps cost most in CAPEX, more to maintain and it not might even give the availability that one can imagine." For unmanned operations it will always be better to buy 1 expensive pump with a MTBF of 6 years, than buying 3 cheap pumps with a MTBF of 2 years.

- The amount of equipment on the installation. One of the key factors when designing a unmanned/low manned facility according to Edwards and Gordon (2015) is to remove all unnecessary equipment. With a lower equipment count the number of potential causes of shutdown and their effects will also be lower, and thus lead to a higher MTBF for the facility. Where equipment is required it should be high reliability, high integrity and low maintenance.
- Rambøll (2016) states that it is beneficial to reduce the F&G and fire water systems to an absolute minimum. The reason is that these systems will require certification, testing and maintenance, and therefore initiates higher manning frequencies.
- Rambøll (2016) also state that in many unmanned development projects there is a tendency to add "nice to have" equipment and systems because this is done in conventional development projects, and that this must be avoided. Examples of this is personnel related safety systems/equipment that does not add any real value, but do require regular checks that leads to higher manning frequencies. For unmanned operations it is better to bring what is needed when the facility is visited.
- For unmanned operations remote identification of the fault and predetermination of the necessary actions is important to reduce the accumulated downtime. For this reason remote condition and performance monitoring should be present for all critical equipment in the case of unmanned operations according to Edwards and Gordon (2015).
- To minimize the maintenance requirements, and time spent during repair/maintenance the following factors are important to take into account during the design.
  - Ease of access to the equipment on the installation e.g the need for scaffolding and ability to gain access to/lift/move equipment.

  - The modularity of the design meaning how easy or difficult it is to replace a component in the system without dismantling the rest of the system.
  - Rambøll (2016) states that the use of noble materials and special surface treatment systems have the ability to reduce the need for surface treatment to about zero during the lifetime.

As the overall goal is to achieve a sustainable operational availability Edwards and Gordon (2015) states that: "It is important that reliability and availability modelling is carried out at the concept phase and trough the entire project, so that any design and equipment selection decision can be judged on whether they are likely to increase or decrease availability." The typical design availability of 95% normally used for manned offshore facilities is not good enough when the goal is to sustain a viable unmanned operation according to Edwards and Gordon (2015) as this would result in to many unplanned shutdowns of the facility, and lead to an increased number of unplanned visits and costs.

It should be noted that a design availability of 95% does not result in a operational availability of 95%. This is because unless there is a remote reset and restart capability, the time it takes to mobilize a team to the platform has to be added into the downtime which reduces the operational availability. This means that a 95% design availability can result in a 90% operational availability or less depending on the mobilization time of a repair crew. For this reason, the design availabilities of low manned or unmanned operations should always be above 97% and where possible higher according to Edwards and Gordon (2015). The most successful unmanned operations that Edwards and Gordon (2015) are aware of have had continuous operational availabilities of greater than 98% for more than 5 years in a row. The key to achieve this is to select a safe, simple, reliable design and the selection of high quality equipment. One example of this is the use of gas turbines compared to the use of remote power generation and umbilicals from shore or another manned facility. The latter is a simpler and more reliable solution that requires less maintenance. Table 2.3 shows a comparison of technical solutions for Minimum Manned Facilities(MMF) to that of traditionally fully manned platforms, and Edwards and Gordon (2015) states that fundamentally all equipment required has been developed some time ago.

Table 2.3: Comparison of technical solutions for MMF versus traditionally fully manned platforms Edwards and Gordon (2015)

System/Equipment	Traditional Platform Design	MMF Platform Design
Power generation	Local	Remote and cable
Back-up power generation	Yes	No
Emergency power generation	Yes	Limited
Control room	Yes Local	Yes Remote
Utilities	Air, Water - Yes Local	Air, Water - Temporary
Accommodation	Full	Limited(day room)
Topside pipework	CC steel + CI	Stainless steel
Valves	Hydraulic actuation	Electric actuation
Isolation	Two valves + bleed	Integral Double Block and bleed valve
Well heads	Hydraulic actuation	Electric actuation
Emergency systems	Deluge	None
Control system	PLC	Field bus
Compressors	Skid based	Integral design lift on lift off
Main oil line pumps	Skid based	Integral design lift on lift off
Fire and Gas Detectors	Gas Head	Beam and ultrasonic
Life boats + secondary escape	Yes	Yes

2.7 Advantages of unmanned operations

There are several advantages with employing unmanned operations, and some of them is described below.

- Using the right design approach can lead to CAPEX reductions in the range of 10-35% according to Edwards and Gordon (2015). The removal or reduction in size of accommodation blocks, equipment and facilities associated with the long term presence of large personnel on board can by itself lead to a significant CAPEX saving. This is also emphasised by Metcalf et al. (1993) and Cramer et al. (2011).

- According to Edwards and Gordon (2015) estimates that are based on previous studies show that OPEX can be reduced by between 30% and 80% when moving from a traditional manning strategy to an MMF with 10 to no persons on board. Cramer et al. (2011) points out that with a lower manning level costs associated with travel by helicopter and boats, and logistics due to food, catering and cleaning will be lower. Also the removal or reduction of accommodation blocks, equipment and facilities, that lead to a lower CAPEX, will lead to a lower total maintenance requirement for the facility and with that also the operating costs of performing the maintenance will be reduced.

- Lower overall complexity, and therefore theoretically higher platform availability from the point of view of producing hydrocarbons according to Metcalf et al. (1993)

- Cramer et al. (2011) presents the higher safety level as one of the most important aspects of remote operations as it eliminates staff from hazards of travel in helicopters, boats, trucks and planes. It also eliminates staff from on-site process hazards associated with activities like opening/closing of valves subjected to high pressure and exposure to toxic gases, e.g H_2S.

2.8 Approach to developing a low manned concept

The present chapter has shown that most the equipment/systems needed on a FPSO is already in use at unmanned facilities either topside or subsea. The challenge is to use them together to form a complex FPSO facility. Going forward some of the most important factors when the goal is to achieve low manned operations is therefore:

- Set a design availability of 97% or higher. Any design and equipment selection decision have to be judged on whether they are likely to increase or decrease availability.

- Remove all unnecessary equipment from the design in order to achieve minimal maintenance. Chosen equipment should be high reliability, high integrity and low maintenance.

- Remote surveillance and diagnostics should be present for all critical equipment in order to achieve rapid and efficient fault finding and reduce the amount of required routine maintenance.

- The design of the facility must have immense focus on minimizing the need for maintenance and the time spent performing it e.g minimize need for scaffolding and surface treatment.

- Incorporation of appropriate new technology e.g. subsea style equipment.

Chapter 3

Framework and methodology of analysis

A traditional manned FPSO or any other offshore facility will have a basic requirement for marine personnel, production operators, maintenance personnel and safety related systems in order to ensure the production of hydrocarbons. With these people in place a number of support positions such as chefs, maids, medic, administrator etc. will also be needed, driving the total POB up. If the basic crew requirement is decreased, the number of support positions may also be decreased and thus driving the total required POB down. The challenge is to find the best procedure in order to achieve this while at the same time achieving the required production availability.

This chapter will present the framework and methodology of analysis that will be used in the coming chapters to say something about how it could be possible to reduce the manning on an "standard" base case FPSO (presented in Chapter 4) if it were to be designed as new. The focus will be on the processing of hydrocarbons and the equipment used to do so, but will also highlight other important measures that could allow for lower manning of the standard base case FPSO.

3.1 Production availability

The ultimate goal of any hydrocarbon producing facility, manned or unmanned, is to achieve the highest possible production availability to the lowest cost while meeting the safety requirements set upon them from e.g. classification societies and governments. ISO 20815 defines production availability as: "The ratio of production to a reference level(e.g the design or contracted rate, over a specified period of time."

There is a number of events that may happen that require the shut down of production, and leads to a lower production availability. Reasons for production losses can be bad weather, accidents, authority restrictions, modification of facility etc. This report focuses on production losses caused by the process and utility equipment on the FPSO, as it is the production assurance of the equipment that requires the initial presence of a crew. ISO 20815 defines production assurance as: "The activities implemented to achieve and maintain a performance that is at its optimum in terms of economy and at the same time consistent with applicable framework conditions."

Figure 3.1 shows the relationship between some production assurance terms. As can be seen, an input to the production availability is the availability of a system such as oil stabilization, gas compression for reinjection or produced water treatment and the consequences unavailability of the system will have on the production. On a lower level Figure 3.1 also shows that the availability of equipment items can affect the availability of its designated system depending on e.g. the items configuration.

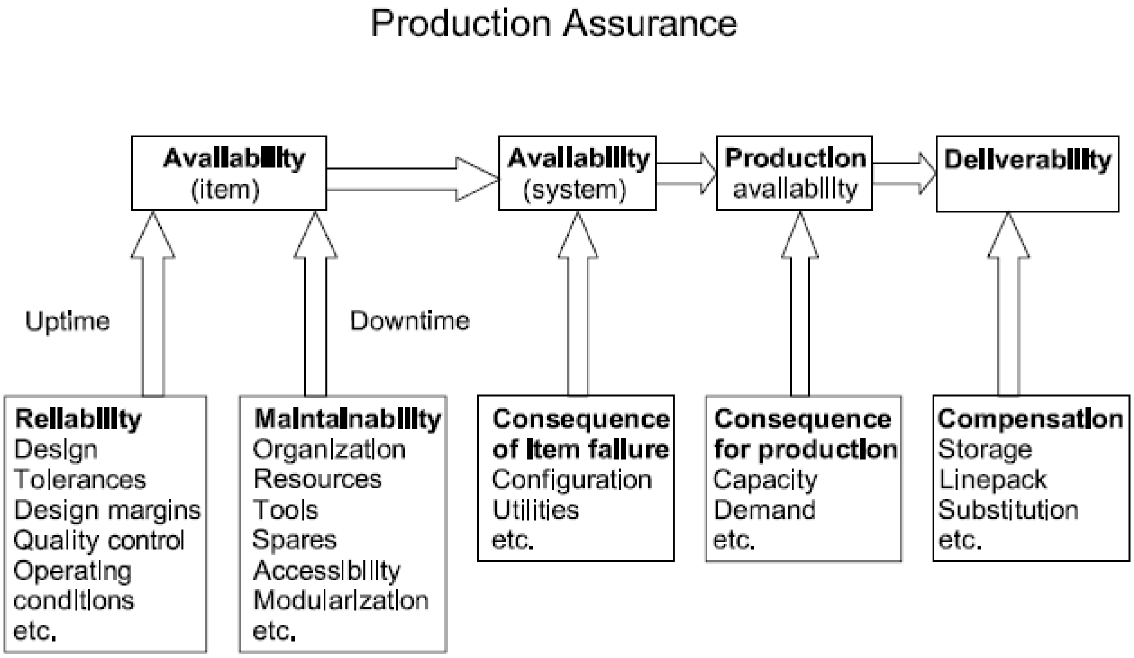


Figure 3.1: Illustration of the relationship between some production assurance terms (ISO20815 (2008))

As the availability of equipment items and in turn the availability of systems has an impact on the production availability, it would be beneficial to study the processing systems of the base case FPSO, and identify critical equipment and systems that will have a big impact on the production availability. The most critical systems are the systems in need of the most supervision during production and maintenance, and hence increases the requirement for presence of personnel on the facility.

3.2 Reliability, availability and maintainability(RAM)

As can be seen from Figure 3.1 it is the reliability and the maintainability of equipment items that will determine the items availability. Reliability, availability and maintainability of equipment are performance measures that can be used to form a picture of how critical the equipment is to the production availability, and can be used when evaluating the different systems on the base case FPSO.

3.2.1 Reliability

Reliability is defined by ISO 20815 as: "The ability of an item to perform a required function under given conditions for a given time interval."

Mean time between failure

The mean time between failure(MTBF) can be used as a measure of how reliable the equipment is. The failure rate(λ) of equipment is typically expressed as the number of failures per unit time, and is connected to the MTBF by the following equation:

$$\lambda = \frac{1}{MTBF} Calixto\ (2012) \tag{3.1}$$

If the MTBF of a equipment item is low, it will tell us that it is most likely in need of more maintenance and supervision. When opting to achieve unmanned or minimum manned operations it is therefore important to reduce the number of equipment items that frequently requires the attention of personnel. The MTBF between failure of the equipment on the base case FPSO is therefore an important measure to identify when the goal is to achieve a lower manning level.

3.2.2 Maintainability

Maintainability is defined by ISO 20815 as: "The ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions, and using stated procedures and resources." The maintainability of equipment items are determined by several factors such as the design of the equipment, the accessibility of the item, the resources needed for repair, the tools needed for repair, potential spares needed and the time it takes to aquire it, and the complexity of potential repair jobs. The maintainability of the equipment is therefore very dependant of the design of the facility and the organization that uses it in addition to the actual design of the equipment itself. The higher the maintainability of the item is, the more likely it is that fewer resources are needed in order to retain or restore the equipment to a state where it can perform its required function.

Mean time to repair(MTTR)

The mean time to repair(MTTR) is defined by ISO 20815 as: "The expectation of time to restoration." The MTTR will in this report be used as a measure of the mean downtime that is related to failures, and interpreted as the time it takes from a failure occurs to when it is back in operation. The maintainability of the equipment will to a large degree determine the MTTR as can be seen in Figure 3.2 that shows the equipment performance in the event of a failure where it has to be shut down. The total downtime related to the repair of failed equipment can be divided into several phases, and includes:

- A pre-repair phase including run down, mobilization of resources, spares, troubleshooting, isolation, depressurization, gas-freeing, potential scaffolding etc.
- The active repair time meaning the time spent actually fixing the failure.
- A post-repair phase that includes mechanical post-work, preparation for production and start up of the equipment.

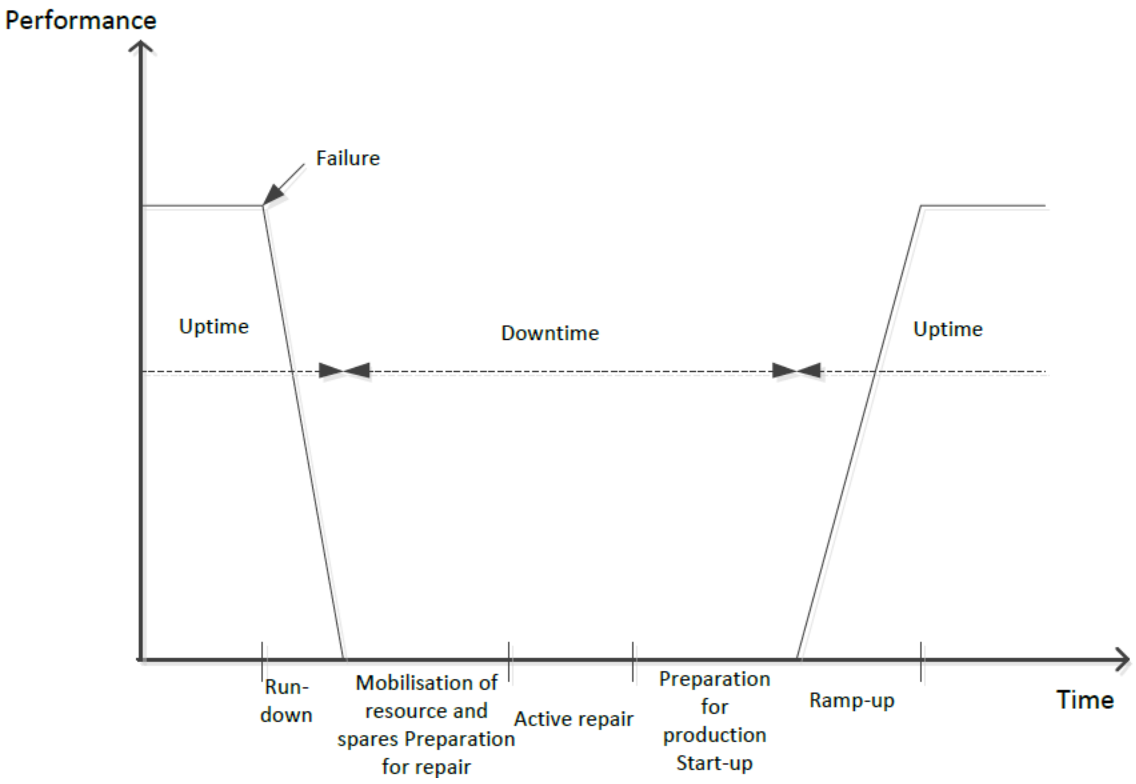


Figure 3.2: Illustration of the downtime associated with a failure event (ISO20815 (2008))

How much time that is spent in the different phases is very dependent on the type of failure and component, and as mentioned the maintainability of the item. It is therefore difficult to quantify measures that will give the item a higher degree of maintainability, and in turn potentially lead to less resources needed for the repair and a shorter MTBF. On the other hand it is possible to discuss such measures, and their potential consequences to the required resources and downtime. Such measures will be discussed in Chapter 6 and includes:

- The need for scaffolding when a repair is required. If the facility is designed in such a way that it allows for unrestricted access to the equipment time can be saved in the pre-repair phase. It will also result in less resources needed for the repair job, and could increase the potential of reduced manning.

- Measures that allows for diagnosis of failures without the presence of personnel. Such measures could be sensors, cameras and robots that allows for the identification of the failure from a remote facility, and will reduce the need for personnel being present at the facility. It also has the potential to reduce the time of the pre-repair phase.

- The term maintainability includes the ability of an item to be retained in a state which it can perform a required function. In order to do so inspections are typically performed on a regular basis. Measures such as cameras, sensors and robots also have the potential to reduce the need for inspections performed by personnel.

3.2.3 Availability

Availability is defined by ISO 20815 as: "The ability of an item to perform a required function under given conditions at a given instant of time, or in average over a given time interval, assuming that the required external sources are provided." The MTBF and the MTTR will determine the availability of an item as expressed by Equation 3.2.

$$Availability = \frac{MTBF}{MTBF + MTTR} Calixto\ (2012) \tag{3.2}$$

To calculate the availability of components placed in series Equation 3.3 can be used. The availability of a system in series will only be as high as the item with the lowest availability showing that all the components must have an high availability in order for the system to achieve the desired system availability.

$$Series\ Availability = Av_a * Av_b .... * Av_n RohaniandRoosta \tag{3.3}$$

To calculate the availability of two components placed in parallel to account for redundancy Equation 3.4 can be used.

$$Parallel\ Availability = 1 - (1 - Av_a) * (1 - Av_b) RohaniandRoosta \tag{3.4}$$

If there is a situation where k out of n components must be available in order for the system to be available equation 3.5 can be used:

$$K\ out\ of\ N\ availability = \sum_{i=k}^{n} \binom{n}{i} Av^i * (1 - Av)^{n-1} Misra\ (2008) \tag{3.5}$$

Equation 3.5 is based on the assumption that the components are identical, and that the non failed components will continuously operate irrespective of the system state. The latter assumption will not be precise on a offshore facility where components in a redundant system is often in standby mode, and the results of using this equation may not give the exact answer. Never the less it is assumed that using this equation will yield results good enough to use in this report. An example of when Equation 3.5 can be used is when the system has three identical pumps placed in parallel 3x50% configuration, and two of them has to work at all times in order ensure the desired production output.

3.2.4 Failure and repair data

The OREDA handbook is the most commonly used source for reliability data in the oil and gas industry. The OREDA handbook has been published in six editions. The latest edition was published in 2015 and has been used to gather failure and repair data used in this report. The useful data from the OREDA handbook needed in this report are the failure rates and active repair times given for the different types of equipment. The failure rates can easily be used to find the MTBF, and the active repair time will give an indication of how long the repair will take. The reliability data from OREDA is used as an input to the analysis of the base case FPSO in order to determine the reliability of the equipment in the different processing systems.

3.2.5 RAM analysis using computer simulation programs

Reliability, availability and maintainability(RAM) analysis, also referred to as production assurance analysis are used to determine system availability based on inputs such as equipment configuration(1x100% or 2x50%), MTTF, MTTR and production capacity. The RAM analysis could in turn be used to optimize design configuration, maintenance schedule and logistics planning.

Computerized RAM analysis tools are available giving a variety of different outputs with some being the contributors to production unavailability per equipment type, per item and per system. Performing such an analysis on the base case FPSO could help identify the most critical systems with regard to unavailability, but as the main focus of this report is not on performing such an analysis it is the author's opinion that using the results of a RAM analysis performed by

Wang (2012) can be used as an input to the analysis of the base case FPSO. It should be noted that equipment configurations and input data may not be exactly the same as for the base case FPSO studied in this report, but the results are still assumed to give a good picture of the criticality of the different equipment and systems.

Wang (2012) has in the report "Production assurance and Life Cycle Cost Evaluation of Offshore Development Projects in the Conceptual Design Phase" performed a RAM analysis of the processing facility presented in Figure 3.3. Included in the analysis are also utility systems such as flare, heating and cooling systems, water treatment, fuel gas, power and sea water. Wang (2012) has used Miriam Regina, a computerized RAM simulation tool, to simulate the production on the facility over a 20 year period 300 times. Planned maintenance has not been considered in the simulation. The results shows for the base case(1x100% gas lift compressor), a production availability of 93.01% with a standard deviation of 0.2%.

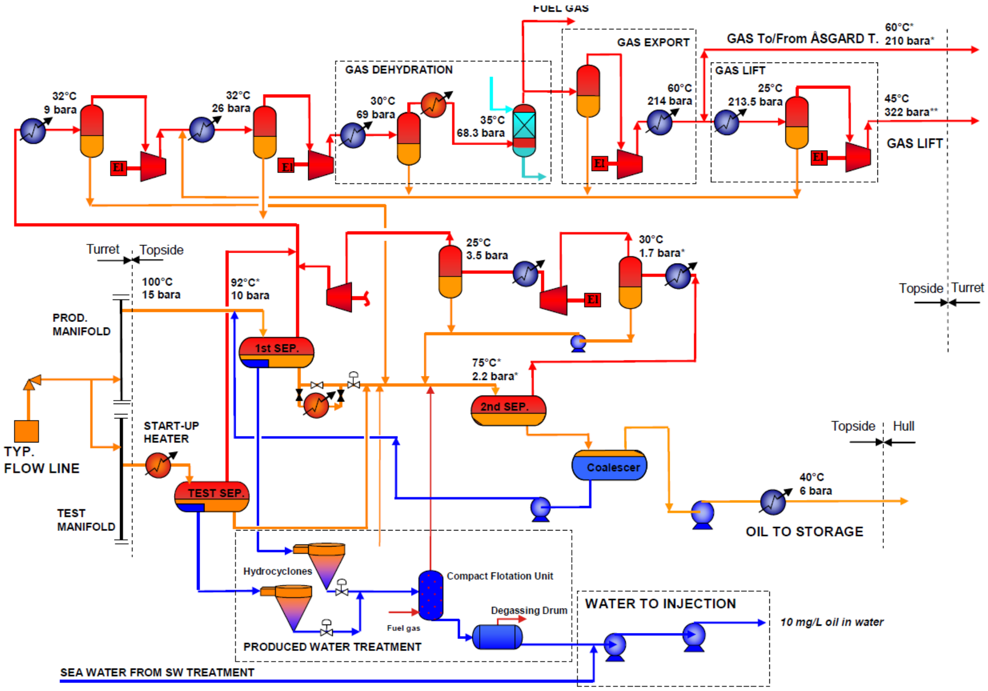


Figure 3.3: Topside process Wang (2012)

Further, Wang (2012) presents the main contributors to production unavailability per equipment type, per item and per system. Figure 3.4 shows the unavailability contributions per equipment type. It can be seen that the centrifugal compressors are contributing to 52.56% of the unavailability, while vessels and electric motors are contributing to 13.63% and 10.26% of the unavailability. It is interesting that the generators/gas turbines are only contributing to 2.33% of the unavailability. Gas turbines are known to be a critical equipment type, and the reason for the low contribution in these results could be that the gas turbines are configured with redundancy so that the contribution to the unavailability becomes lower.

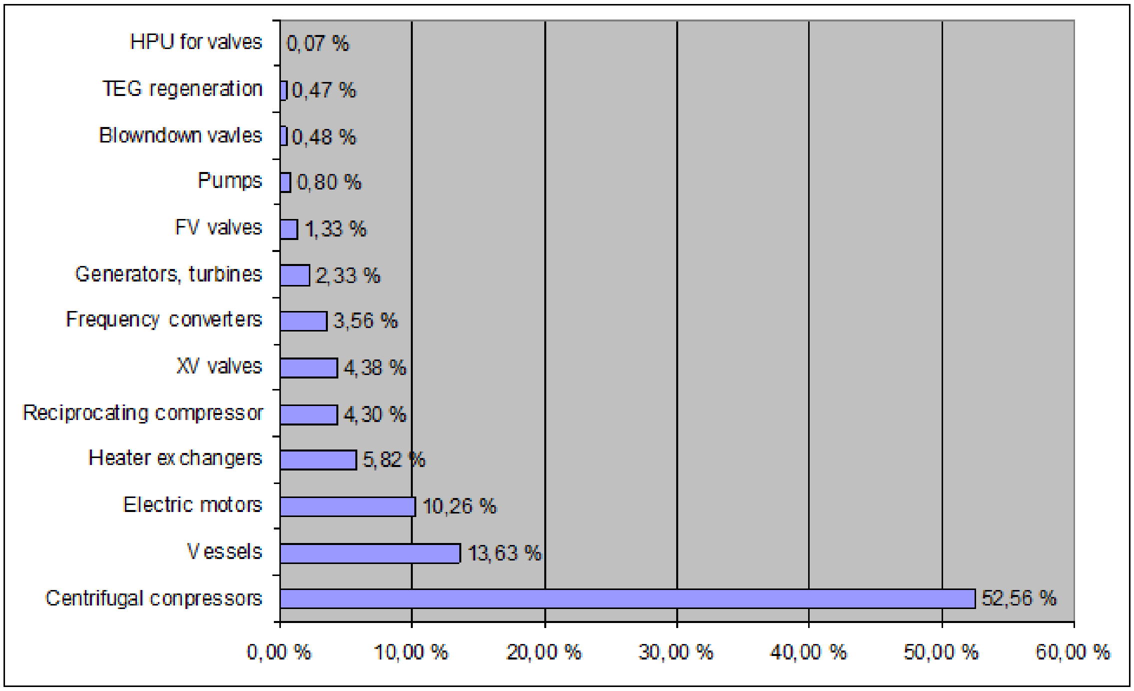


Figure 3.4: Main contributors to unavailability, per equipment type Wang (2012)

Figure 3.5 shows the contribution to the unavailability per item. As would be expected it is the five compressors(including electrical motors and converters) that are the main contributors to the unavailability. Further, Figure 3.6 shows the main contributors to unavailability per system. System 23(Gas compression and re-injection), 27(Gas export including gas lift compressor), 20(Separation and stabilization), 24(Gas treatment) and 80(Main power high voltage) are the main contributors to the unavailability. With nearly 80% of the unavailability contributions coming from systems involving the compression of gas, the results presented by Wang (2012) indicates that systems involving compressors will be the most critical when looking into the possibilities of unmanned operations.

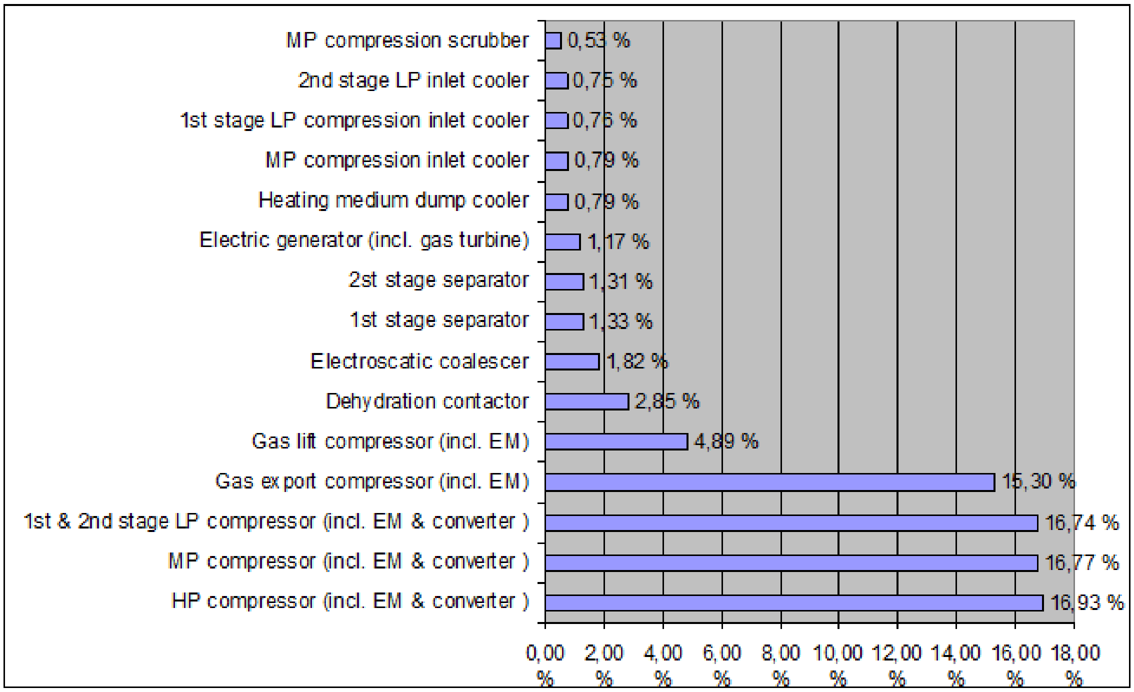


Figure 3.5: Main contributors to unavailability, per item Wang (2012)

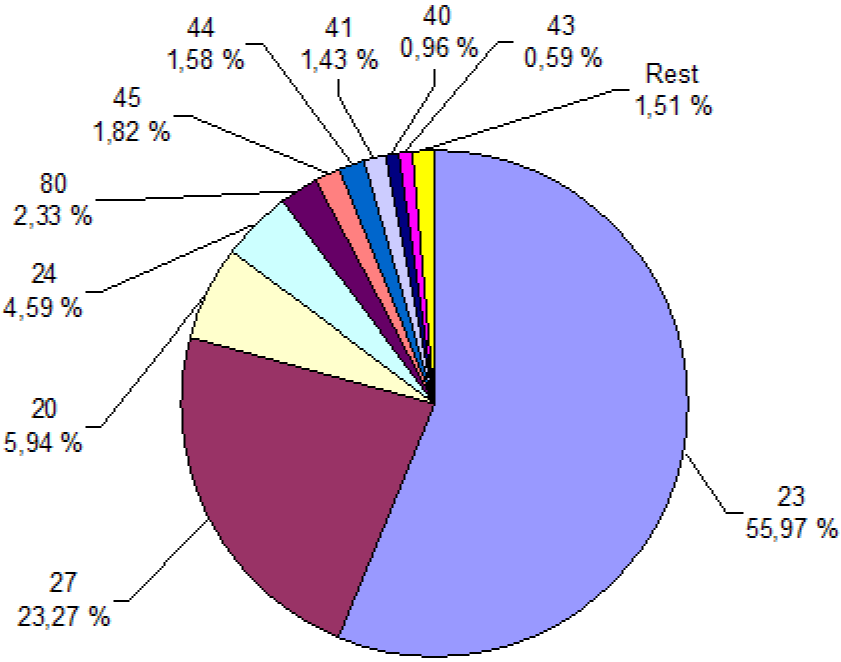


Figure 3.6: Main contributors to unavailability, per system Wang (2012)

3.3 Maintenance

The need for maintenance and repair of process and utility equipment is a big part of what drives the need for personnel to be present on a offshore facility. The amount of equipment together with their MTBF, MTTR and criticality will to a large degree determine the number of maintenance man hours needed on the facility each year, and in turn determine the number of maintenance positions needed on the facility at all times. There are several different ways of performing maintenance, and some are presented in this chapter to give a basis for discussion when analyzing opportunities that may give a potential for lower manning.

3.3.1 Corrective maintenance

Corrective maintenance is performed after the failure has occurred and the equipment item can no longer perform its intended function. The goal of the maintenance action is to restore the equipment to a functional state where it can perform its intended functions. With corrective maintenance there is no time to plan the maintenance action or the logistics needed in terms of spare parts and personnel. It can therefore become a costly affair if the failure is on a critical process or safety equipment item, depending on how much downtime is aggregated until the equipment is functional again. With low manned or unmanned facilities the available resources present at the facility are much lower, and having to respond to failures in need of corrective maintenance will increase the need for personnel to visit the facility at a more frequent basis. Some failures will always occur without a warning. It is therefore not possible to safeguard the facility 100% against the use of corrective maintenance, but it is the author's opinion that in order to successfully implement low manned or unmanned operations of offshore facilities the use of corrective maintenance should be kept to a minimum by introduction of more periodic preventive and condition based preventive maintenance.

3.3.2 Preventive maintenance

Preventive maintenance is performed to reduce the likelihood of the equipment failing, and takes place while the equipment not yet has failed. Preventive maintenance is always planned, and the required spare parts and personnel is always available. The periodic maintenance intervals are normally based on predetermined time intervals or running time, often based on manufacturer recommendations. As the preventive maintenance is planned and all required resources are available it could be a suitable maintenance strategy for low manned or unmanned operations. The preventive maintenance could be planned on a campaign basis where a maintenance crew is sent to the facility for a short period of time each time a campaign is scheduled.

The problem with preventive maintenance is that it is possible to know if you perform enough maintenance, but it is not possible to know if perform maintenance to often. It has also been shown that some systems tend to fail more often after a periodic inspection, and suggests that the "opening" of the systems tend to induce failures that would otherwise not occur.

Condition based maintenance

The downsides of the preventive maintenance can be reduced by increasing the knowledge of when the preventive maintenance action is actually needed, and thus optimize the time period between preventive maintenance actions and the number of times the system is "opened". Condition based maintenance(CBM) is a preventive maintenance strategy that is based on the condition of the equipment, and not a predetermined time interval based on the age of the equipment or the elapsed time since the last maintenance action. The technical condition of the equipment is determined by monitoring different parameters such as vibration, temperature, corrosion, performance and flow. Monitoring these parameters over time will reveal the current health of the asset. In a perfect world, the CBM strategy allows for the detection of every failure long enough before the failure actually occurs, so that the maintenance action can be scheduled when it is actually needed, and not beforehand. The problem is that not all failures are detectable with the monitoring techniques available today. Also the time interval from a possible failure is detected until it actually occurs is not always long enough to allow for the required planning and logistics to have taken place before the failure occurs, and may cause unwanted downtime. With that said any warning beforehand will allow for a safe rundown of the equipment that may save it from further damage. Table 3.1 presents some of the benefits of implementing condition based maintenance as presented by Thorstensen (2008).

Table 3.1: Benefits of implementing condition based maintenance(Thorstensen (2008))

Benefit	**Comments**
Reduced repair time and costs	A planned maintenance action reduces the costs with respect to acquiring necessary labour resource, spare parts and tools. Use of CM gives detailed knowledge of failures and repair requirements.
Avoided revenue loss	An impending failure is detected well in advance, thus the availability can be increased by planning actions at convenient times with respect to known outage periods or periods with lower production requirements.
Maintenance cost savings	Unnecessary maintenance work is avoided and savings can be achieved through reduction in maintenance induced failures, reduction in scheduled maintenance, reduced spares inventory and reduced planned outage.
Increased equipment lifetime	The CM allows longer service time, because the life of each individual equipment item is utilized at a maximum level without increase in damage severity. An incipient failure is stopped.
Higher efficiency	Performance monitoring is useful in scheduling maintenance actions such as e.g. cleaning of heat exchangers and washing of rotor blades of a gas turbine.
Sound basis for continuous improvement	The CM suits procedures for an efficient evaluation to improve maintenance actions. By monitoring the condition both before and after a maintenance action, means of improvement can easily be detected.
Improved safety assurance	Increased equipment knowledge reduces consequences for personnel and environment due to primary and secondary damage caused by machine failure.

Opportunity maintenance

Opportunity maintenance is another form of preventive maintenance that takes advantage of unplanned or planned shutdowns. Shutdowns of a system may require parts or the rest of the process facility to shutdown in addition to the failed system. This will lead to a window of opportunity where preventive maintenance may also be performed on other systems determined on a pre-defined decision rule. This would result in less accumulated downtime for the facility since the process facility only would have to shut down once, instead of potentially two and could lead to substantial cost savings. The use of CBM have the ability to increase the value of incorporating opportunity maintenance as more information is available with regard to the "health" of the different systems, and thus making it easier to determine if it is beneficial to take advantage of the window of opportunity.

Both CBM and opportunity maintenance have the potential to be enablers when in comes to achieving lower offshore manning on FPSOs, and is discussed further in Chapter 6

3.4 Implications for this work

The present chapter has presented some important measures when it comes to allow for lower manning on a FPSO. The reliability, availability and maintainability of equipment and processing systems will have a big impact on the production availability and the maintenance requirements. Chapter 4 presents the base case FPSO that will be analysed in Capter 5 where the most critical systems with respect to reliability and maintenance requirements is identified and other potential challenges with regard to low manned operations are highlighted.

In the development of a low manned FPSO concept in Chapter 6, new or different equipment solutions that have the potential to increase the reliability and decrease the maintenance requirements of the most critical systems is presented and analysed. The results are compared to that of the base case FPSO. Further the maintenance strategy and the monitoring of equipment have the potential to reduce the need for permanent manning of the facility and increase the production availability by minimizing the accumulated downtime, and how this can be utilized is also explored in the development of a low manned concept. The findings in Chapter 6 are used to present a proposal to a low manned FPSO concept in Chapter 7. Figure 3.7 shows an overview of how the rest of this report is structured.

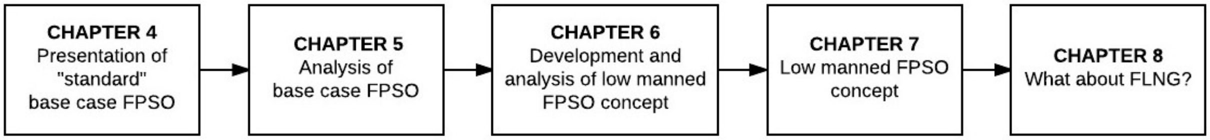


Figure 3.7: Overview showing how the rest of the report is structured

Chapter 4

The base case FPSO

The following chapter consists of the presentation of a "standard" base case FPSO based on information provided by Pettersen (2016). The chapter includes a presentation of the process and utility systems including configurations and type of equipment, proposed location, maintenance data and proposed manning requirements. The information presented in this chapter is used as a basis in the analysis of the base case FPSO in Chapter 5 where critical systems are identified and other potential challenges when it comes to low manned operations are discussed.

Figure 4.1: Norne FPSO Inrigo (2014)

4.1 System description

Figure 4.2 shows a simplified process flow diagram of the base case FPSO. From the swivel on the turret the well stream is transferred to the inlet separator operating at 15-20 bar. The oil from the inlet separator is stabilized in the second stage separator operating at 1.5-2 bar. The water content is reduced to a specified requirement in the coalescer before the crude oil is transferred to the storage tanks. The oil is heated between the inlet separator and the second separator, and cooled after the coalescer. The produced water from the inlet separator and the coalescer enters the produced water treatment system to meet specifications before being reinjected into the reservoir.

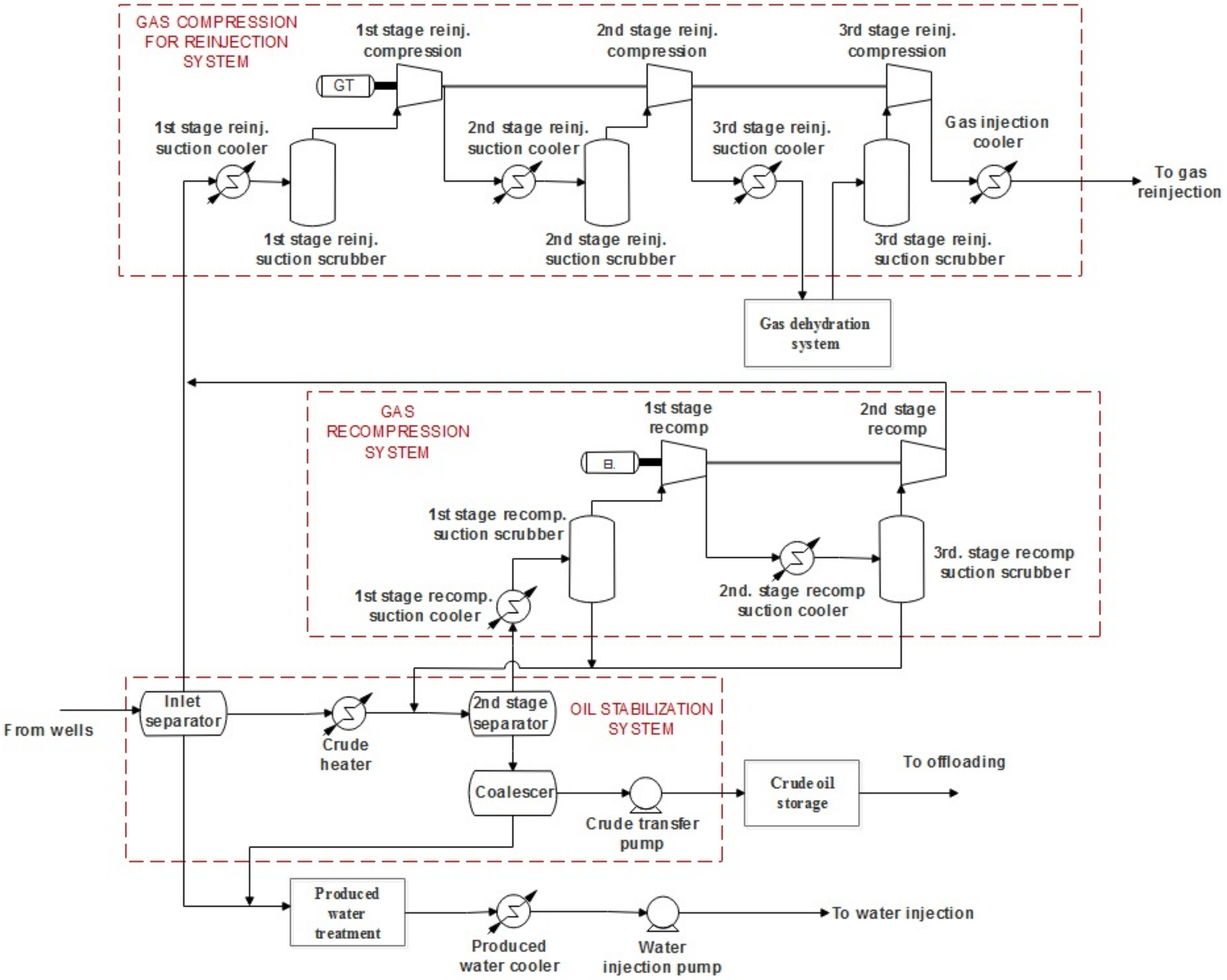


Figure 4.2: Simplified process flow diagram. The different systems are addressed in following subsections.

The gas from the second stage separator is compressed in two stages before it is mixed with the gas from the inlet separator. The compressors used to recompress the gas are driven by electrical motors. Further the gas is compressed up to 280 bars in three stages for reinjection into the reservoir. The gas is dehydrated with the use of TEG absorption before the third stage of the compression for reinjection. In order to achieve a high regularity and flexibility, the system has two compression trains with a capacity of 3.65 MSm^3/d each. Each train is mechanically driven by a LM2500 gas turbine.

The base case FPSO also has utility systems such as heating and cooling systems, a power generation system, a offloading system and marine systems. They are presented in the following subsections together with the main processing systems found in Figure 4.2.

4.1.1 Oil stabilization system

Figure 4.3 shows a reliability block diagram of the oil stabilization process from the FPSO inlet to the storage tank. The processing system includes separators, heat exchangers, a coalescer and pumps driven by electrical motors. The heat exchangers are configured in a 2x50% configuration to ensure that a reduced production can continue should one fail. The crude transfer pumps are configured in a 3x50% for the same reason.

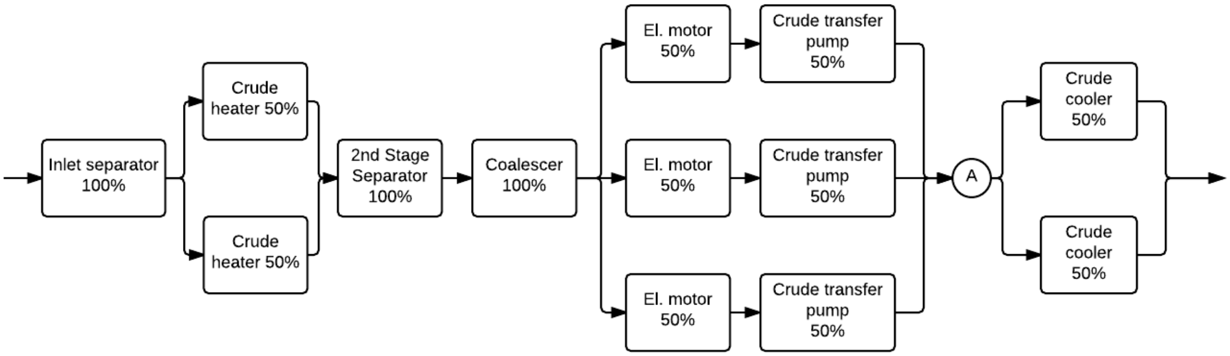


Figure 4.3: Reliability block diagram of oil stabilization process

4.1.2 Gas recompression system

Figure 4.4 shows a reliability block diagram of the gas recompression after the second separator. The process includes heat exchangers, scrubbers and a two stage compressor with a electric motor. All the equipment is set up in a 1x100% configuration, and must be available for the system not to fail.

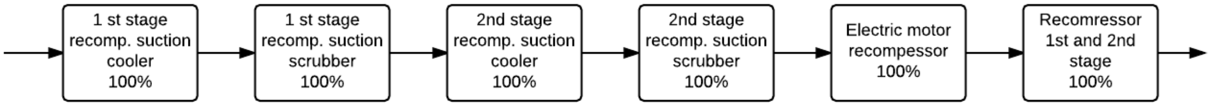


Figure 4.4: Reliability block diagram of gas re-compression after the 2_{nd} separator

4.1.3 Gas compression for reinjection system

Figure 4.5 shows a reliability block diagram of the two gas compression trains used for reinjecting the gas into the reservoir. The two compression trains are installed in a 2x50% configuration, and consists of heat exchangers to cool the gas, scrubbers to remove any excess liquid, and a gas turbine driven three stage compressor. Should one of the compression trains fail, the other will ensure that production can continue at about 50% capacity.

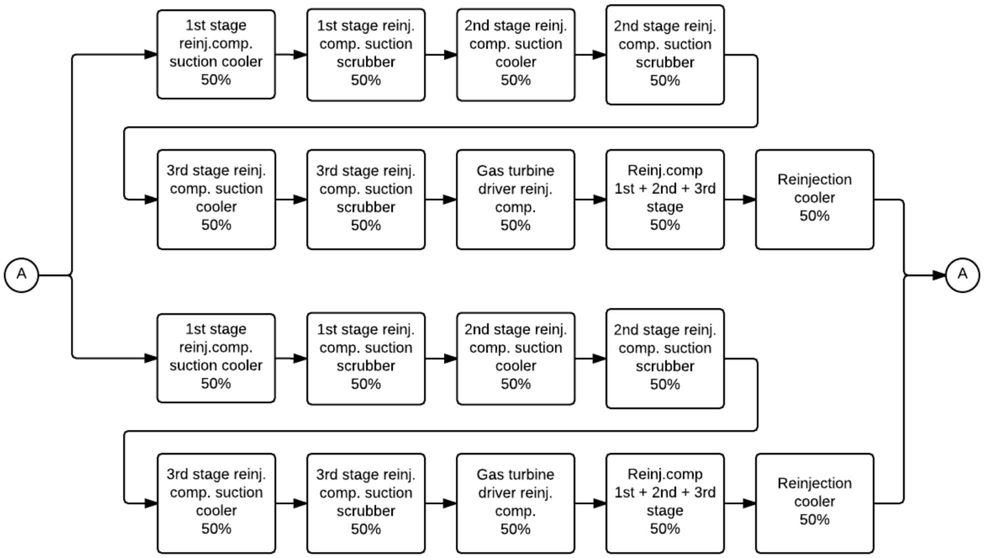


Figure 4.5: Reliability block diagram of the gas compression for reinjection

4.1.4 Gas dehydration system

Figure 4.6 shows a reliability block diagram of the gas dehydration process. The gas enters the glycol contactor after the second stage compression for reinjection, and dry gas leaves the contactor entering the third stage compression for reinjection. The glycol having absorbed the water in the contactor enters a glycol regeneration process going through the process shown in Figure 4.6. All equipment is installed in a 1x100% configuration, except for the glycol pumps that have a 3x50% configuration and the glycol contactors that are installed in a 2x100% configuration. 2 out of the 3 glycol pumps, one of the glycol contactors and all other equipment items must be available at all times in order to ensure the desired production output.

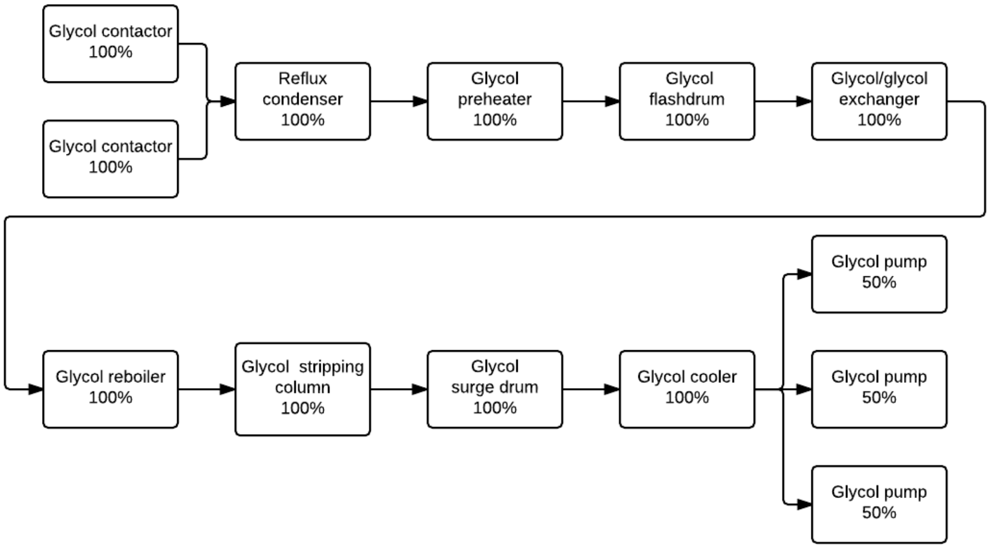


Figure 4.6: Reliability block diagram of the gas dehydration process

4.1.5 Produced water treatment and injection

Due to limited information available about the configuration of the produced water treatment and injection system, a simplified consideration is made with regard to the system. The system consists of the following equipment components:

- Sand cyclones that remove sand and other solids from the produced water.
- Hydrocyclones that separates oil from the water to produce a clean water outlet stream. The separated oil enters the second stage separator.
- A water degassing drum where gas floats to the top of the vessel. Clean water exits the bottom of the drum ready for injection or disposal to the sea. Gas is sent to the low pressure flare.
- Heat exchangers that cool the clean produced water.
- Produced water injection pumps transferring the produced water back into the reservoir. The pumps are driven by electrical motors.

4.1.6 Main power generation system

The main power generation is gas turbine driven and has a capacity of 44 MW using two LM2500. During normal operation the power consumption is about 35 MW, and both gas turbines are required in order to deliver this load. Essential emergency power is supplied from diesel generators with a capacity of 8MW. The main power generation system also consists of electrical transformers and other electrical components in order to manage the produced electricity. Only the electrical transformer is included in this report in addition to the gas turbines. Table 4.1 shows the main power consumers on the FPSO.

Table 4.1: Main power consumers

Description	**Power demand**
Base load	18-23 MW
Water injection	10-15 MW
Offloading(intermittent)	5 MW
Thrusters	5 MW

4.1.7 Utilities

Waste heat recovery units are installed in the exhaust of gas turbines used in the main power generation system, and are used in the glycol/water based heating medium system.

Indirect cooling is provided by a glycol/water based cooling medium system, and was chosen to prevent hydrate formation on the gas side and bio fouling on the seawater side. The crude oil and produced water is directly seawater cooled.

Nitrogen, compressed air, seawater, firewater, potable water(not generated on the vessel), diesel and glycol are supplied from systems placed in the hull to consumers topside.

4.1.8 Offloading

The base case FPSO has a tandem offloading solution where a hose is supplied to the tanker from the stern of the FPSO. When securely connected the offloading pump ensures the transfer of oil from the FPSO to the tanker. The distance between the two vessels is around 120 m during normal offloading conditions.

4.1.9 Marine systems

As a floating facility, the FPSO is in need of the following marine systems:

- A ballast system is needed to ensure the stability of the vessel. Tanks in the hull are filled or emptied with seawater by pumps. During offloading, oil is transferred from the FPSO to a tanker, and the ballast tanks must be filled accordingly to keep the vessel in a stable condition. During production the oil storage tanks are gradually filled, and the ballast tanks must be emptied accordingly.

- A bilge system is used to remove water and oily water from machinery spaces, pump rooms, void spaces and other compartments. The system is used either in case of an emergency such as flooding or for removal of smaller amounts due to e.g. smaller leaks from pumps or valves.

- Propulsion and/or dynamic positioning(DP) system. The DP system consists of machinery and thrusters allowing the vessel to move in all directions. An FPSO is in need of a DP system for two main reasons. One is to reduce the loads on the mooring system during harsh weather conditions. The other is to keep a static position during offloading operations to a tanker. An FPSO may also have a propulsion system in order to move in case of emergency situations. In order to do so it would also need a disconnectable turret mooring system.

4.2 Location

The FPSO is assumed to be located in remote and harsh environments such as Newfoundland or the Barents Sea, where unmanned operations may be a good solution. Oilfields in these locations may be situated several hundred kilometers from shore, and the use of helicopters may be limited due to the very large distance. Such a case would drastically increase the reaction time of maintenance personnel should a critical failure occur, and will again have a big impact on the availability of the facility. Today's limit for helicopters are around 200 nautical miles, and can be reached in approx. 1.5 hours while carrying up to 19 people. The same trip can take up to 15 hours with the use of a ship, depending on the vessels cruising speed. It is assumed that the FPSO is within this 200 nautical mile helicopter limit so that critical failures can be attended to quickly if needed.

4.3 Maintenance data

Table 4.2 shows the systems on the base case FPSO with the highest maintenance load, and is based on maintenance data reported from the FPSO over a 5 year period. It includes both preventive and corrective maintenance. It is noticeable that systems not directly affecting the production of hydrocarbons, such as structures topsides and marine systems, also bring high contributions to the maintenance load. The focus of this report is mainly on the processing systems. The maintenance load from other systems will therefore not be considered to the same extent, but is important to take into account when developing a low manned concept.

Table 4.2: Systems with highest maintenance load (Pettersen (2016)

Description	System	Percentage
Structures topsides	92	9.2%
Main power generation and distribution high/low voltage	80/82	8.4%
Compression for reinjection to reservoir	26	7.3%
Marine systems	58	4.8%
Crude handling and storage systems	21	4.4%
Topside well systems (production)	13	4.3%
Oily water systems	44	4.2%
F&G detection systems	70	3.7%
Telecommunications systems	86	3.5%

4.4 Manning

To get a picture of the maintenance man hours and personnel needed on the base case FPSO, information has been gathered from a FPSO with similar characteristics. The average POB is 75 people, and includes all personnel present on the FPSO.

Table 4.3 shows the average number of reported maintenance man hours and the number of positions based on a work load of 4350 hours/year amongst different disciplines(each position is manned 12 hours/day for 365 days/year). The maintenance man hours with regard to inspection, insulation, scaffolding and surface are reported man hours from contractors. The reported hours include both corrective and preventive maintenance, and is the average of reported hours over a 5 year period. The total reported yearly man hours, divided between the different disciplines, is 63944, and constitutes to a total of 15 maintenance personnel being present at the FPSO at all times.

Table 4.3: Average man hrs.(Pettersen (2016))

Description	Av. reported man hrs.	Positions
Automation	13622	3.1
Electro	6186	1.4
Mechanical	10357	2.4
Inspection(contractor)	754	0.2
Insulation(contractor)	4829	1.1
Scaffolding(contractor)	10454	2.4
Surface(contractor)	3885	0.9
Total	63944	15

In addition to the maintenance personnel there is also a number of positions needed in order to facilitate the management and safety of the FPSO. The minimum positions needed at any time on a floating production facility can be seen in Table 4.4 showing the offshore management work load with a minimum of 13 persons needed on the installation at all times. 6 production operators works in two shifts of 12 hours, with 2 operators in the control room and 1 in the process area. It is assumed that the production operators also are in charge of operating the marine systems.

Table 4.4: Average man hrs. Pettersen (2016)

Description	**Positions**	**Man hrs./ year/ position**	**Total man hrs.**
Offshore installation manager(OIM)	1	4380	4380
Operation supervisor(OSM)	2	4380	8760
Admin/medic	1	4380	4380
Crane operator	2	4380	8740
Lift & Safety	1	4380	4380
Production operators	6	4380	26280
Total	13		56940

The personnel presented above only amounts to 28 people of the 75 average POB. Based on information from Hepsø (2016) it is assumed that about 10 people will make up the catering staff in charge of cleaning, food and the general welfare on the vessel. Other positions and services that will make up the personnel on the vessel are painters, equipment isolators, drillers & well technicians, service technicians from equipment suppliers, and visitors. It has not been possible to obtain the number of people for the positions and services mentioned above, and they will therefore not be accounted for in this report. This will therefore be a limiting factor in the analysis of the base case FPSO.

Chapter 5

Analysis of base case

As presented in Chapter 3 the main goal of any hydrocarbon producing facility is to achieve the highest possible production availability. In order to do so the processing equipment is in need of supervision, inspections and maintenance that requires the presence of operations and maintenance personnel, and the manning requirements will to a large degree be decided by the reliability and maintenance requiremens of the equipment. The analysis of the standard base case FPSO therefore analyses the processing systems to identify the systems/equipment most likely to be in need of frequent supervision and maintenance. The study focuses on the main processing systems, but also evaluates other systems such as marine, heating, cooling and main power generation system. The results are used in the development of a low manned concept as implementing changes or new solutions to the most critical systems will potentially have the biggest impact on the manning requirements with regard to maintenance man hours and inspections. The analysis also includes an assessment of the manning data presented in Chapter 4.4 where the goal is to determine what positions are a necessity and can not be removed, and which positions can possibly be reduced.

5.1 Process and utility systems

The base case FPSO has process and utility equipment designed to be operated by a fully manned crew. As a basis for the development of a low manned concept it is therefore important to highlight the processing equipment and systems which is most likely to affect the production availability in terms of failure rates, downtime and maintenance loads in order to evaluate if other solutions and configurations should be considered for the low manned concept developed in Chapter 6. Normally performing a full RAM analysis of the standard base case FPSO using advanced computer analysis would yield these answers, but as the focus in this report is not on performing a full RAM analysis it is the author's opinion that the following inputs to the analysis is sufficient to identify the most critical systems when the goal is to achieve lower manning levels:

1. Reliability data from OREDA including failure rates and active repair times. The reliability data has been used to perform simple calculations with regard to the different systems availability using the equations presented in Chapter 3.2.3.
2. Maintenance data from the standard base case FPSO presented in Chapter 4.3. The maintenance data will identify maintenance intensive systems driving the required maintenance man hours up, and may also reflect the maintainability and reliability of these systems.
3. RAM analysis of a similar processing facility presented in Chapter 3.2.5 showing the equipment and processing systems leading to the most downtime. The results of the analysis will aid in identifying the most critical systems on the base case FPSO.

5.1.1 Assumptions

In order to calculate the availability of the different systems on the base case FPSO some general assumptions presented in Table 5.1 has been made. Assumption 3 in Table 5.1 is set to account for the pre and post repair phase, and is only a number chosen by the author. It may therefore not be accurate, but will not make a very big impact on the results of the calculations.

Table 5.1: General Assumptions

ID	Assumptions
1	Reliability data from OREDA 2015 is used to gather failure rates and active repair time for the different equipment.
2	Only failure modes classified as critical are considered in the analysis. It is assumed that degraded and incipient failures are repaired at first opportunity and will not affect the production availability. Where critical failures rates are not listed, degraded failure rates are used first and then incipient failure rates.
3	A total of 13 hours has been added to the MTTR in addition to the active repair time from OREDA to account for additional downtime in the pre and post repair phase.
4	The potential unavailability contribution from process transmitters, valves and flanges is assumed to have a negligible impact on the production, and is therefore not regarded in this study.
5	It is assumed that all equipment is classified as "as good as new" after a maintenance activity.
6	Constant failure rates are assumed for all the equipment included in the analysis.
7	Planned shutdowns, revision shutdowns and preventive maintenance are not included in the availability calculations.
8	The total average reported maintenance man hours on the base case FPSO is 63944 in Table 4.3, and it is assumed that the maintenance load percentages in Table 4.2 is a percentage of those man hours.

5.1.2 Oil stabilization system

The oil stabilization process must be operational for the FPSO to produce hydrocarbons, and a critical failure in any of the separators or the coalescer will require the production to shut down as they are all configured in a 1x100% configuration. Table 5.2 shows failure and repair data for the equipment included and the item and system availability in the oil stabilization process. It can be seen that the separators and the coalescer have the lowest MTBF in the system, and must therefore surprisingly be classified as the least reliable components of the system as a critical failure on these components are most likely to occur. Reasons for the low MTBF could be due to problems with level sensors and control, clogging of internals or loosening of internal equipment. Their active repair times are on the other hand the lowest in the system, and failures could be fixed quickly compared to the other equipment components in the system.

The heat exchangers have the highest MTBF of around 7 years in the system, and are the equipment items in the system least likely to fail. When also set up in a 2x50% configuration the likelihood that the system will have to shut down entirely due to a critical failure in the heat

Table 5.2: Oil stabilization

Equipment	**Config.**	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Active rep. time (hours)**	**Item Avail.**
Inlet separator	1x100%	72.93	1.57	6.4	99.86%
Crude heater	2x50%	16.36	6.98	47	99.90%
2_{nd} stage separator	1x100%	72.93	1.57	6.4	99.86%
Coalescer	1x100%	72.93	13712	6.4	99.86%
Crude transfer pump	3x50%	62.28	1.83	25	99.76%
El motor	3x50%	16.25	7.02	22	99.94%
Crude cooler	2x50%	16.36	6.98	47	99.90%
System					99.18%

exchangers is not very high.

The crude transfer pump and the electric motor as a pump driver has a 3x50% configuration. The electric motor has a MTBF of around 7 years and the pump has a MTBF of about 1.8 years. The pump must therefore be classified as the most critical component of the two.

The availability calculations of the total system yields a result of 99.18%, which is the highest availability of the systems considered in this report. Also the oil stabilisation system is not one of the systems with highest maintenance load as can be seen in Table 4.2, and indicates that the maintenance man hours required to maintain the system is not amongst the highest. As these numbers are from real operations of the base case FPSO it could indicate that the system does not have a lot of failures in real operations, and that the system have the potential to function well for a low manned scenario.

On the other hand, the results of the RAM analysis presented in Chapter 3.2.5 showed that the oil stabilization system is the third biggest contributor to production unavailability with 5.94%, and is an indication that the system could lead to a higher level of unplanned visits than preferred in the case of low manned operations. With the separators, coalescer and the crude transfer pumps being the least reliable components in the system special emphasis should be put on finding equipment that has a proven record of reliability when designing the system for a low manned concept. As an example the subsea separator and injection pump installed at the Troll pilot has proven to be very reliable, and proves that it is possible to design separators and pumps with sufficient reliability for unmanned operations.

5.1.3 Gas recompression

The gas recompression system consists of a two stage compression with all equipment items in a 1x100% configuration, and all items must be available for the system to be operational. Table 5.3 shows failure and repair data for the equipment included in the system and the item and system availability in the gas recompression system. The suction scrubbers have the lowest MTBF in the system with about 1.3 years, and the compressor follows with a MTBF of about 1.5 years. With a 1x100% configuration, the MTBF of the components is assumed to be too low in the case of low manned operations as a failure will cause the production to shut down, and hence must be given special consideration in an attempt to ensure sustainable availability. The other equipment items all have a MTBF of 4.5 years or more, and is assumed to be high enough in for low manned operations.

Table 5.3: Gas re-compression

Equipment	**Config.**	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Active rep. time (hours)**	**Item Avail.**
1_{st} stage suction cooler	1x100%	16.36	6.98	47	99.90%
2_{nd} stage suction cooler	1x100%	16.36	6.98	47	99.90%
1_{st} stage suction suction scrubber	1x100%	86.19	1.32	10	99.80%
2_{nd} stage suction scrubber	1x100%	86.19	1.32	10	99.80%
1_{st} & 2_{nd} stage re-compressor	1x100%	77.34	1.48	17	99.77%
Electric motor	1x100%	25.37	4.5	33	99.88%
System					99.06%

The availability calculations for the total system yields a result of 99.06%, and is second highest amongst the systems considered in this report. In addition, the gas re-compression system is not one of the systems with the highest maintenance load as can be seen in Table 4.2, and supports the availability calculations as frequent failures in the system would lead to a higher maintenance load. The system could therefore have the potential function well for low manned operations, but the results of Wang (2012) in Chapter 3.2.5 showed that over 50% of the unavailability contributions per equipment type came from centrifugal compressors. Special emphasis should therefore be put on procuring a highly reliable compressor for the system when designing the system for low manned operations.

5.1.4 Gas compression for reinjection

Table 5.4 shows failure and repair data for the equipment included in the system and the item and system availability in the gas compression for reinjection system. The gas turbine driver and reinjection compressor has a MTBF of about 0.25 years and 0.5 years. Both very low, and by far the least reliable item components in the system. In addition the suction scrubbers only have a MTBF of 1.32 years. With so many items having such a low reliability, low manned operations may prove to be a challenge as the frequency of unplanned failures in the system will most likely be high.

Table 5.4: Gas compression for re-injection

Equipment	**Config.**	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Active rep. time (hours)**	**Item Avail.**
1_{st} stage suction cooler	2x50%	16.36	6.98	47	99.90%
2_{nd} stage suction cooler	2x50%	16.36	6.98	47	99.90%
3_{rd} stage suction cooler	2x50%	16.36	6.98	47	99.90%
1_{st} stage suction scrubber	2x50%	86.19	1.32	10	99.80%
2_{nd} stage suction scrubber	2x50%	86.19	1.32	10	99.80%
3_{rd} stage suction scrubber	2x50%	86.19	1.32	10	99.80%
1_{st} & 2_{nd} & 3_{rd} stage reinj. comp.	2x50%	220.34	0.52	18	99.32%
Gas turbine driver	2x50%	499.17	0.23	27	98.04%
Reinjection cooler	2x50%	16.36	6.98	47	99.90%
System					92.97%

The availability calculations for the total system yields a result of 92.97%, and is by far the lowest system availability amongst the system considered in this report. The gas reinjection system also has one of the highest maintenance loads with 7.3% as can be seen in Table 4.2, and indicates that the system requires a lot of both unplanned and planned maintenance. The system is therefore considered to be very critical when it comes to low manned operations as the maintenance load is high and frequent unplanned shutdowns is very likely. This is supported by the results of Wang (2012) in Chapter 3.2.5 with the gas compression and re-injection system contributing to 55.97% of the unavailability. Those results are calculated using electrical motors as drivers for the compressors, and using gas turbines as drivers would most likely give an even higher contribution to the unavailability due to low MTBF of gas turbines compared to electrical motors.

5.1.5 Gas dehydration

The gas dehydration system consists of many equipment items in order to dehydrate the glycol having absorbed water from the gas in the glycol contactor. Table 5.5 shows failure and repair data for the equipment included in the system and the item and system availability in the gas dehydration system. Both the glycol contactor and glycol reboiler have a very low MTBF with 0.46 and 0.56 years respectively. The MTBF of the glycol contactors are based on degraded failure rates, and may not cause the contactor to shut down entirely. On the other hand, degraded failures have to be repaired as they can develop into a critical failure. The same applies to the glycol stripping column that has a MTBF of 4.25 years, but a failure takes about 600 hours to repair accumulating a lot of downtime to the system. Both the glycol contactor and the glycol reboiler will be the most critical components due to their low MTBF, and will be the most challenging in the pursuit of low manned operations.

Table 5.5: Gas dehydration

Equipment	**Config.**	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Active rep. time (hours)**	**Item Avail.**
Glycol contactor	2x100%	246.71(degraded)	0.46	7.6	99.49%
Reflux condenser	1x100%	16.36	6.98	47	99.90%
Glycol preheater	1x100%	16.36	6.98	47	99.90%
Glycol flash drum	1x100%	40.27	2.83	4.7	99.93%
Glycol/glycol exchanger	1x100%	16.36	6.98	47	99.90%
Glycol reboiler	1x100%	205.2	0.56	14	99.45%
Glycol stripping column	1x100%	26.85(degraded)	4.25	601	98.38%
Glycol surge drum	1x100%	53.69	2.13	4.8	99.90%
Glycol cooler	1x100%	16.36	6.98	47	99.90%
Glycol pump	3x50%	51.66	2.21	27	99.79%
El. motor for pump	3x50%	16.25	7.02	22	99.94%
System					97.28%

The availability calculations for the total system yields a result of 97.28%, and is the third lowest amongst the systems considered in this report. The gas dehydration system is also one of the main contributors to unavailability with 4.59% according to the results presented in Chapter 3.2.5, and supports the availability calculations made in this report. On the other hand, the gas dehydration system is not amongst the systems with the highest contribution to the maintenance load on the base case FPSO in Table 4.2. As for the oil stabilisation system this could indicate that the system has little need for maintenance and repairs in real operations, but when designing a gas dehydration system for low manned operations the very low MTBF of the glycol contactor and glycol reboiler will have to be drastically increased.

5.1.6 Produced water treatment and water injection

Table 5.6 shows failure and repair data for the equipment included in the produced water treatment and water injection system. As can be seen, the sandcyclones and hydrocyclones are only listed in the ORDEA handbook with a low incipient failure rate, and is therefore regarded as reliable equipment with regard to unmanned operations. Further as no reliability data for the degassing drum is listed in OREDA it is assumed that, due to its simplicity, the degassing drum is a reliable equipment item with low maintenance requirements. The MTBF of the produced water coolers and the electric motors for the water injection pumps are above 4 years, and will not be regarded as critical equipment with regards to unmanned operations. The water injection pumps have a MTBF of 3 years which is quite good, and as the produced water is assumed to be treated to a quality where it can be disposed to the sea it is not likely that production have to shut down due to a failure in either the produced water coolers or in the water injection pumps.

Table 5.6: Produced water treatment and water injection

Equipment	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Actual rep. time (hours)**
Sandcyclone	16.30(incipient value)	61350	3.30
Hydrocyclone	16.30(incipent value)	61350	3.30
Degassing drum	NA	NA	NA
Produced water coolers	16.36	6.98	39
Water injection pumps	38.01	3	69
Electric motor injection pump	6.55	17.43	9.8

When also considering that the system is not one of the main contributors to the maintenance load as can be seen Table 3.3 or one of the main contributors to the unavailability per system as presented in Chapter 3.2.5 it is assumed that the produced water treatment and water injection system will not be one of the most critical systems when it comes to unmanned operations.

5.1.7 Main Power generation

The main power generation is driven by two gas turbines(LM2500), and has a capacity of 44MW in total. During normal operation the consumption is about 35MW, and both gas turbines must be available to have a 100% production output. Should one gas turbine fail, the other one can produce about 60% of the power needed during normal operation. Table 5.7 shows failure data, repair data, and item and system availability of the equipment included in the main power generation process. The gas turbine and the electric generator only have a MTBF of 0.23 and 1.19 years, and the reliability of the equipment must be classified as very critical considering that both gas turbines must be available to cover the power demand during normal operation.

Table 5.7: Main power generation

Equipment	**Config.**	**Failure rate (per 10^6 hours)**	**MTBF (years)**	**Active rep. time (hours)**	**Item Avail.**
Gas turbines	2x60%	499.17	0.23	40	98.04%
Electric generators	2x60%	95.94	1.19	122	98.72%
System					93.68%

The availability calculation for the total system yields a result of 93.68%, and is the second lowest amongst the systems considered in this report. The main power generation and distribution high/low voltage also contributes to 8.4% of the total maintenance load which is the second highest contribution. With main power high voltage also being the fifth biggest contributor to the unavailability per system in the results presented by Wang (2012), it is safe to say that a main power generation system using gas turbines could prove to be a challenge when it comes to unmanned operations. Especially considereding the very low MTBF of the gas turbine, and a configuration where both gas turbines and electrical generators have to be available in order to deliver the normal power demand. Having a more redundant system could prove to be a useful option, and will be considered in the development of a low manned concept.

5.1.8 Utilities

Both the heating and the cooling systems are required to be available so that all the other systems can function properly. The systems are made up of small pumps, valves, piping and heat exchangers that will require regular maintenance and repair, and may impose a challenge with regards to unmanned operations as a critical failure in either system may require production shutdown. On the other hand, none of the systems are listed as one of the main contributors to the maintenance load on the base case FPSO or as one of the main contributors to the unavailability in the results presented by Wang (2012). The current system solutions may therefore have the potential to be sufficient for unmanned operations provided that reliable equipment with low maintenance requirements is selected.

5.1.9 Offloading

The offloading system itself is regarded to be simple as the only processing equipment is the offloading pump, and a hose supplied to the tank ship. The availability of the system itself is therefore not regarded as the biggest challenge when it comes to low manned operations. On the other hand there are many safety issues with the use of tandem offloading with the biggest being the small distance between the shuttle tanker and the FPSO during offloading as can be seen in Figure 5.1. A collision between these two massive structures may have catastrophic consequences. Though having no people on the FPSO will reduce the risk of personnel during offloading, it is believed that performing the required procedures, communicating with the shuttle tanker and overseeing the use of tandem offloading may be a challenge if the FPSO is unmanned. Other solutions, such as buoy systems, may therefore prove to be a better option for entirely unmanned operations.

Figure 5.1: Ships during tandem offloading (SOFEC (2016))

5.1.10 Marine systems

While the processing systems on the FPSO are there to ensure the production of hydrocarbons, the marine systems are needed on the FPSO to ensure the safety of the vessel during production. A failure in/or in the use of the ballast system may jeopardize the stability of the vessel, and a worst case scenario would be that the FPSO capsizes. A failure in the bilge system in the case of flooding can in the worst case lead to the ship sinking. A failure in the DP system may put to much strain on the mooring system causing the anchor chains to break, which again will lead to the risers going through the turret breaking. All these events are quite unlikely to happen, but are on the other hand catastrophic in nature. While a critical failure in the processing systems could be handled by shutting down production to prevent further escalation of the situation, a critical failure in the marine systems have a bigger potential to escalate quickly into a catastrophic event. Ensuring that marine systems are functioning at all times is therefore of utmost importance.

Table 4.2 shows that the marine systems contribute to 4.8% of the total maintenance load which is the fourth biggest contribution. This is assumed to only account for the maintenance load from the ballast and bilge system, as the NORSOK standards coding systems does not include the DP system under marine systems. An additional contribution to the maintenance load should therefore be expected from the DP system.

Due to the high maintenance load of the marine systems, and the criticality of the systems with regard to the safety of the vessel, unmanned operations of the FPSO is regarded to be a challenge due to these systems alone. If the remote control facility loses the ability to control the systems or a critical failure occurs to equipment in the systems, a catastrophic event can escalate quicker than the response time of a repair crew. So even in the case of achieving unmanned operations of all systems related to the processing of hydrocarbons, it is the author's opinion that a small crew is required with the ability to control and maintain the marine systems.

5.1.11 Summary and conclusions

Table 5.8 shows an overview of the availability calculations performed in this chapter. A total availability of 83.24% would never be accepted for neither manned or unmanned operations, and typical production availability goals are around 95%. It should be noted that these the availability numbers are based on numbers from OREDA and simple calculations. The results may therefore not be exact and is only used to indicate the critical systems.

Table 5.8: Summary of system availability for the base case FPSO

System	**Availability**
Oil stabilization	99.18%
Gas re-compression	99.06%
Gas compression for re-injection	92.97%
Gas dehydration	97.28%
Main power generation	93.68%
Total availability	83.24%

The three systems with the lowest availability are the gas compression for reinjection, gas dehydration, and main power generation system. As presented in Chapter 3.2.5, the study performed by Wang (2012) showed the gas compression for reinjection, gas treatment/dehydration and main power high voltage systems to be amongst the highest contributing systems to the unavailability of the facility. These results compare well to the availability calculations made in this report. Also examining the maintenance data of the base case FPSO presented in Chapter 4.3, it can be seen that main power generation and distribution high/low voltage and the gas compression for reinjection systems are amongst the main contributors to the maintenance load on the base case FPSO. Although the gas dehydration system is not amongst the highest contributors to the maintenance load on the base case FPSO, the system includes many equipment items and has several equipment items with a low MTBF. Based on this the gas dehydration system is viewed as a more critical system in the pursuit of low manned operations compared to e.g. the oil stabilization system.

When developing a low manned concept in Chapter 6 the focus will therefore be on developing a low manned design for the three most critical systems on the base case FPSO, namely the gas compression for re-injection, the gas dehydration and the main power generation, as these systems are considered to have the biggest potential in terms of increasing the reliability and reducing the maintenance requirements.

In addition the tandem offloading system and the marine systems have been considered to be challenging when it comes to entirely unmanned operations, mainly due to safety issues that could arise during operations. A small crew may be required to be present at all times in order to maintain and operate these systems to sustain a required safety level.

5.2 Manning assessment

As presented in Chapter 4.4 the average POB is 75 people, and consists of all the different positions and services required to run the base case FPSO. The following section will discuss within what trades it is possible to reduce the number of people, and what positions it is more unlikely to remove.

5.2.1 Maintenance personnel

Maintenance personnel may be the easiest trade to see that a reduction in the number of personnel is achievable, and instead go towards a maintenance philosophy where maintenance is carried out in campaigns by a crew visiting the facility having planned the maintenance actions ahead of the visit. Corrective maintenance could possibly be attended to by a fast reacting team that responds to a failure by flying out to the FPSO. In order to achieve this, the number of yearly maintenance man hours must be managed down to a level where such a philosophy becomes a possibility through selection of less complex system solutions, highly reliable equipment with low maintenance requirements and a design with high maintainability. As discussed in Chapter 5.1.10 it is assumed that a small maintenance crew will be required to maintain and repair critical failures to all marine systems to ensure the safety of the vessel.

5.2.2 Production operators

There is a total of 6 production operators on the base case FPSO. They work in two shifts of 12 hours, with typically 2 operators in the control room and 1 in the process area inspecting equipment and processing areas. These positions have the possibility to be moved to an onshore location or another facility with the implementation of remote operations. Subsea installations, wellhead platforms and more advanced facilities such as the Angel platform is remotely operated, and has proven that the technology is available. Doing so with a large complex facility such as an FPSO is of course more challenging, but it is the author's opinion that such a solution could be reached. A problem with removing the operators will be that there is no one to perform the required inspections of equipment and the processing areas. Solving this problem is discussed in Chapter 6, and include measures such as condition and performance monitoring, and inspection robots.

5.2.3 Marine personnel

The offshore installation manager(OIM) has the ultimate authority on the vessel, and will be required to be present on the facility as long as there also are other people permanently placed on the facility. The OIM on a FPSO will typically have the same competence as a captain on a ship and has the knowledge to perform and oversee all the required marine operations on the vessel including offloading operations. As discussed in Chapter 5.1.10 it is believed that for an FPSO, people with competencies to operate the marine systems will be required to be present at all times in order to ensure the safety of the vessel. The OIM will be one of those people, but it is assumed that the OIM will need assistance from a minimum of two people with competencies in operations of the marine systems. All marine personnel should also have extensive knowledge and experience in how to operate the processing systems.

5.2.4 Other positions

It is more difficult to determine how other trades could possibly be reduced, but some comments are made below:

- With people present on the facility an medic/admin is most likely required on the facility.
- With the possible removal of the production operators the two operation supervisors, who is in charge of the production operators, may also potentially be placed at the remote central control room provided that they are able to perform all their required tasks from this location.

- Crane operators are needed on the facility in case crane operations are necessary. As lifting operations is not always performed this is a position that as the option to be combined with e.g a maintenance position where for example 40% of the time is spent as a crane operator, and 60% is spent as a maintenance technician.
- The number of catering people in charge of food, cleaning and the general welfare on the facility is decided by the total number of POB, and will be scaled accordingly.

5.2.5 Overview

Table 5.9 shows a overview of the manning assessment made for the positions and services considered in this report.

Table 5.9: Overview of the manning assessment

Description	**Comments**
Maintenance crew	Reduction achievable through reduction in maintenance requirements and implementation of condition and performance monitoring from remote control center. A small crew is regarded as a requirement to maintain/repair all marine systems. They should also have extensive knowledge in maintaining/repairing process related equipment.
Production operators	Implementation of remote operations have the ability to move these positions to a control room onshore or at another facility.
Marine crew	An OIM and small marine crew is regarded as a requirement to operate the marine and offloading systems to ensure the safety of the vessel. The crew should also have knowledge and experience in operating process related systems.
Admin/Medic	Required with people present on the FPSO
Operation supervisors	Same as for production operators.
Crane operators	May be combined with a maintenance position as lifting operations are not always performed.
Catering crew	The number of catering people is scaled according to total POB.

5.3 Conclusions

The analysis of the base case FPSO has shown that the complexity of the facility is very high, and that moving from current manning levels to a fully unmanned facility is a big challenge. In addition to all process and utility systems required to produce hydrocarbons, the FPSO also has marine and offloading systems further increasing the operational and maintenance requirements of the facility.

As discussed in Chapter 5.1.10 a small crew is assumed to be a requirement in order to have the ability operate and maintain/repair the marine systems to ensure the safety of the vessel. In addition the definitions for Not Normally Manned Installations and The Normally Unattended Installations presented in Chapter 2.1 suggests that the yearly maintenance man hours should be between 5000-15000 and 2000-5000 respectively to achieve a viable operational model. The yearly maintenance man hours for the base case FPSO is 64000 hours, and to reach 15000 yearly maintenance man hours would mean that the maintenance requirements for the FPSO would have to be reduced by over 400%. Achieving unmanned operations of the base case FPSO is therefore regarded to be too challenging of a task.

The definition for a minimum manned installation(MMI) on the other hand suggests a maximum of 30000 yearly maintenance man hours to achieve a viable operational model, and is manned full time with a crew of less than 20. This operational model fits well with the results that a marine crew and some maintenance personnel have to be present on the low manned FPSO, and is only about a 50% reduction in the yearly maintenance man hours. The assumption that a MMI operational model is possible is supported by Edwards and Gordon (2015) who states that using a similar approach as Woodside did in the design of the Angel Platform can be applied to high complexity FPSOs to drive the POB down from over 100 down to 20-30.

Chapter 6

Development and analysis of low manned FPSO concept

The analysis of the base case FPSO concluded that the best option for a low manned operations for an FPSO due to the complexity of the facility is to achieve a MMI operational model with a crew less than 20 and a maximum of 30000 maintenance man hours per year. In order to achieve this the present chapter consists of a development of a low manned concept for an FPSO consisting of the following parts:

- Presentation and analysis of new system design solutions for the three systems highlighted as the most critical with regards to low manned operations. Also discussed are the marine and offloading systems.
- Discussion of how much the maintenance man hours can be reduced by designing the FPSO to have a high degree of maintainability.
- Remote operations with condition and performance monitoring, and the use of robots for inspections and simple maintenance tasks.
- Presentation of a suggested maintenance strategy for a low manned FPSO.

6.1 System and equipment solutions for low manned operations

A prerequisite in order to allow for lower manning is to reduce the number of maintenance man hours required, reduce the number of unplanned shutdowns and introduce measures allowing remote operation and condition monitoring of the facility while meeting the production availability requirements. In order to do so the following factors are important when developing the low manned concept:

1. Simplify processing systems and remove unnecessary equipment. Less equipment will mean less potential failure causes, and at the same time reduce the maintenance requirements.

2. Choose equipment with high reliability. Equipment with high reliability will be less likely to affect the production availability while also requiring less maintenance.

3. Reduce the MTTR by increasing the maintainability of equipment and optimizing the logistics with regards to repair and maintenance.

4. Increase redundancy where deemed necessary. Increasing the redundancy will allow for continued production should the equipment fail, but will also increase the total maintenance requirements. Redundancy should therefore only be introduced where deemed absolutely necessary.

5. Introduction of remote surveillance and diagnostics using equipment monitoring will allow for the possibility of remote operations of the facility, without jeopardizing safety and availability, while removing process operators from the facility. It also has the potential to reduce the number of required inspections and increase maintenance optimization.

The analysis of the base case FPSO in Chapter 5 highlighted the three most critical systems with regard to low manned operations to be the gas compression for re-injection, gas dehydration, and main power generation system. In the development of a low manned FPSO concept these systems will be evaluated on the above factors introducing new solutions, equipment and/or configurations in order to increase the systems potential for low manned operations.

6.1.1 Gas compression for re injection

As presented in the previous chapter the compressors and the gas turbines are the least reliable equipment items in the compression trains, and new solutions and equipment for these should be looked at first. Integrated compressor solutions utilizing the same design principles as subsea compressors are today available from manufacturers such as GE Oil & Gas and Dresser-Rand. These compressor solutions have many of the same characteristics, and Table 6.1 shows the characteristics and benefits of GE Oil & Gas's solution called the Integrated Compressor Line.

Table 6.1: Characteristics and benefits of GE's Integrated Compressor Line GEOil&Gas (2016a)

Characteristic	**Benefits/Comments**
Active magnetic bearings(ACB) that levitates the rotor avoiding contact and friction.	The benefit of ACB technology is that it removes the wear of rotors and convectional ball bearings due to contact and friction. It also removes the need for lubricants(see next point)
No gear box, lube oil system or seal gas system	The removal of these auxiliary systems/equipment simplifies the system and removes potential failure sources. Added benefit of reduced footprint and weight, and no fluids that could leak or the need to dispose of them.
The compressor is driven by a high-speed electric motor fully integrated with the compressor in a single sealed casing.	The use of electric motors removes the need for gas turbines as drivers for the compressors. The failure rate in OREDA of compressors that are driven by electrical motors are 77.34 failures/10^6 hrs. compared to 220 failures/10^6 hrs. for those that are driven by gas turbines. This is not taking into account the failure rates of the electric motors or gas turbines which are 25.37 failures/10^6 hrs. and 499.17 failures /10^6 hrs. respectively. These failure rates are from conventional compressor solutions, and may be even lower for the new integrated compressor solutions due to no lube oil systems or dry gas seals and the use of active magnetic bearings.
No venting/depressurization needed on shutdown	The benefit will be faster start and stops, and a potential reduction in the MTTR.

Implementing such a compressor solution would remove the gas turbines from the compression system, while also give giving the benefits of removing auxiliary systems that requires maintenance and are potential failure sources. The result is according to GEOil&Gas (2016a) that the compressor solution is in need of 40% less requested maintenance compared to conventional compressor solutions. Further the integrated compressor line has maintenance intervals of 5/10 years for minor/major overhauls, and is thus very adapted to low manned operations according to GEOil&Gas (2016b). This includes both the compressor itself and the electrical motor. As a basis for the analysis of the compression system it will therefore be assumed that the integrated compressor solution(electrical motor and compressor) will be able to achieve a MTBF of 5 years, and that the requested maintenance is 40% less than conventional compressor solutions.

The MTBF failure of the suction scrubbers is only 1.32 years as presented in Table 5.4, and is viewed as too low for the low manned concept. Other solutions should therefore be considered. FMC technologies offers a scrubber called CDS Gasuine cyclonic scrubber that uses cyclonic forces to separate liquid/solids and the gas with an efficiency close to 100% according to FMCTechnologies (2016). The benefits of the cyclonic scrubber compared to a conventional scrubber can be seen in Table 6.2

Table 6.2: Benefits of CDS Gasuine cyclonic scrubber over conventional scrubbers. FMCTechnologies (2016)

Smaller size and weight
Liquid/gas ratios up to 10% vol/vol can be handled
No required maintenance due to no moving parts, small channels or downcomer pipes. The cyclonic scrubber has therefore a low fowling tendency.

As this technology is quite new it has not been possible to obtain any reliability data for this type of equipment. Mikkelsen et al. (2013) has made an inventory of the operational and performance status of InLine Separators that is based on the same technology as the cyclonic scrubber, and states that: "In a specific North Sea operating environment collectively 16 InLine units has been in operation uninterruptedly for 781 months until 28.11.2012, thus approximately 65 run years aggregated time in service without failure". By evaluating this information an assumption is made that each InLine unit has operated about 48 months without a failure, and that the minimum MTBF for the cyclonic scrubber is therefore assumed to be 48 months or 4 years. This a 300% increase of the MTBF to that of the old suction scrubber, and as no maintenance is required according to FMCTechnologies (2016) the CDS Gasuine cyclonic scrubber is regarded as a suitable choice for low manned operations.

The suction coolers on the base case FPSO has a MTBF of about 7 years, and is assumed to be suitable for the low manned concept as is.

Table 6.3 shows a comparison of the MTBF of the equipment components in the new and the old gas compression for reinjection system, and shows that the reliability of the most critical components have been drastically increased. As no reliability data has been available with regard to the new equipment assumptions has been made based on information from manufacturers or statements made in the literature. Any results based on the assumptions should therefore be used with caution.

Table 6.3: Comparison of the MTBF of new and old equipment items

Equipment	**MTBF(new)**	**MTBF(old)**
Compressor and driver	5 years	0.16 years
Suction scrubber	4 years	1.32 years
Suction cooler	7 years	7 years

Another benefit of the of the integrated compressor solution is that it requires 40% less maintenance than conventional compressor solution. In addition CDS Gasuine scrubber is in need of little to no maintenance, and the suction cooler is regarded as being maintenance friendly due to the long MTBF.

Analysis of the new compression for re injection system

In order to compare the new compression system to the one found on the base case FPSO the availability of the new system and the yearly required maintenance man hours will be considered. The new compression system will have the same 2x50% configuration as for the base case FPSO presented in Figure 4.5. The following assumptions are made for the new system:

- A critical failure requiring shut down and immediate repair will be handled by a maintenance team visiting the platform by helicopter. The response time of this team will add 10 hours to the MTTR compared to the base case FPSO.
- The total system will require 40% less maintenance compared to the old system. The compression for re injection system on the base case FPSO contributed 7.3% to the total maintenance load of around 64000 hours as presented in Chapter 4.4. A 40% reduction in the

maintenance load would then result in the yearly required maintenance man hours going from 4762 to 2803.

As can be seen in Table 6.4 the availability of the compression system has been greatly increased due to the new equipment components while at the same time reducing the yearly maintenance requirements with about 1400 man hours. The availability calculations assumes that both compression trains have to be available at all times. During real production there will always be periods with lower production requirements, planned shutdowns for audits and maintenance or shutdowns due to other systems failing, and the assumption will therefore not be entirely correct. The system availability of about 98% will therefore be regarded as sufficient for the low manned concept. This new compression system can also be used for the gas recompression system to also increase the reliability of this system, while further decreasing the total maintenance requirements.

Table 6.4: Comparison of new and old compression for reinjection system in a 2x50% configuration

	Low manned FPSO	**Base case FPSO**
Maintenance man hours/year	2803	4672
System Availability	98.28%	92.76%

6.1.2 Main power generation

The main power generation on the base case FPSO is one of the most critical systems on the FPSO mainly due to the low MTBF of the gas turbines. With only two gas turbines, both required to be available in order to cover the power demand during normal operation, a different solution is needed in order to achieve lower manning as the number of unplanned shutdowns will be too high. As the compressors in the reinjection system are now also driven by electrical motors, more power needs to be generated by the main power generation system. The two options for the main power generation systems considered in this report are the use redundant gas turbines and power from shore/nearby facility, and a presentation and analysis of these options is found below. A third option that was considered was the use of fuel cells, but this option was considered to not be a viable option due to being a very large and heavy chemical plant.

Option 1: Installing redundant gas turbines

The first option is to install gas turbines in a 3x50% configuration to ensure that production can continue should one gas turbine fail. This would not solve the issues with frequent failures that has to be attended to, but it is possible to decide when the failures or maintenance will be performed to a larger degree as immediate action does not have to be taken in order to meet the required power demand. If the FPSO's operational and maintenance philosophy is based on a maintenance crew visiting the facility in the case of a critical failure or for larger preventive maintenance campaigns, the crew now has more headroom to plan and perform other maintenance actions when deciding to repair the failed gas turbine. The introduction of redundancy will also allow the maintenance crew to perform preventive maintenance on one gas turbines while still delivering the required power demand.

By assuming that the total power requirement for the FPSO is 80 MW, and that a manufacturer offers a suitable gas turbine with a 40MW output it is possible to look at the availability of the main power generation system for low manned operations in a 3x50% configuration. The same failure rates and repair times as presented in Table 5.7 has been used for the calculations, and the results show that with a 3x50% configuration it is possible to obtain a system availability of 99.70% as listed in Table 6.5. Obtaining a system availability of 99.70% is considered to be sufficient for the low manned concept, but introducing one additional turbine will increase the maintenance requirements of the system. By assuming that the total maintenance requirements for the system will increase by 50% with the introduction of another gas turbine and electric generator, the total maintenance man hours per year will increase with over 2500 hours as can be seen in Table 6.5.

Table 6.5: Comparison of new and old main power generation system using gas turbines

	Low manned FPSO	**Base case FPSO**
Configuration	3x50%	2x50%
Maintenance man hours/year	7872	5248
System Availability	99.7%	93.68%

As one of the main prerequisites of achieving lower manning levels is to reduce the number of yearly maintenance man hours, increasing the number of maintenance extensive equipment items such as gas turbines should be avoided. It is therefore the author's opinion that other solutions should be considered first, but that the use of redundant gas turbines have the potential to be used as main power generators on a low manned FPSO. If the option is selected, special emphasis must be put on procuring the most reliable, robust and easily maintainable gas turbines available as this will have a big impact on reaching a viable solution.

Option 2: Import electricity from nearby facility or shore

The second option is to import power/electricity from a nearby facility or shore, and will remove the need for gas turbines and electrical generators on the facility. Such a solution will simplify the system and remove the maintenance load associated with the gas turbines and the electrical generators on the FPSO. The big downside of this option is that it is very expensive due to the cost of the umbilical itself and installing it subsea, but in the recent years part or full electrification of several offshore installations on the Norwegian Continental Shelf has been chosen due to being environmentally friendly and in some cases also cost efficient.

One of these installations is the Vallhall platform that is supplied with up to 78MW of power through a 292km high voltage direct current subsea cable which is enough to power the entire installation. Westman et al. (2010) states that the reasons for choosing this solution was that power from shore for the Vallhall installation is cost efficient, saves space and weight on the facility, and requires less offshore maintenance compared to the conventional gas turbine solution. The solution also has the added benefits of being friendlier to the environment by reducing emissions and contributing to a safer work environment on the platform according to Westman et al. (2010). These benefits are backed up by ABB (2014) who states that some of the benefits when electrifying petroleum installations are:

- Increased reliability due to less mechanical parts on the facility resulting in lower costs associated with production stops, maintenance, repair and transport of service personnel to the facility. Higher regularity and fewer production stops will also increase the earnings.
- From a health, environmental and safety aspect electrified installations are safer to people due to less noise, vibrations and fewer sources of ignition. Lower maintenance requirements will also reduce the risks associated with transporting people from shore in order to perform maintenance and repair.

Another benefit with electrifying the low manned FPSO is that it is possible to integrate a fiber optic cable into the umbilical, and provide a secure connection in the implementation of remote operations.

It is evident that with the benefits of electrifying petroleum installations, it is the best option for the development of a low manned concept in terms of reliability and maintenance requirements. But the solution will not be chosen unless it is calculated to be cost effective. ABB (2014) states that electrification is typically more profitable in new fields compared to old fields as the solution of power from land can be taken into account right from the design and construction phase. Typically new fields will also have more years to divide the investment costs and an increased number of years with lower operating costs. The low manned FPSO concept is thought to be used in the development of new fields, and will have the opportunity to utilize these advantages. The costs will to a large degree be determined by the distance, depth and the expected production period, and will have to be considered on a case to case basis. A case where several new fields are developed in the same area have the potential to have a positive impact on the economical aspect of electrification as the costs will be shared among several installations and companies.

In order to compare the option of using power from shore to the option of installing gas turbines an expectation of the availability of this solution must be set. Devold et al. (2012) assumes that electrical power is available from the main grid with 99.9% availability, and that downtime from subsea cables and transformers can be set to 14 days per 10 year period. The average availability over a 10 year period would then be 99.5%. With regard to the expected offshore maintenance man hours such a system can expect Devold (2012) states that the expected maintenance costs can be reduced by 80% compared to the use of gas turbines. It is not possible to know if a 80% reduction in the maintenance costs leads to a 80% reduction in the time spent maintaining the system for a low manned unit, but in the case of a fully manned FPSO the author has assumed that this is reasonable. A low manned FPSO will most likely require mobilization of at least some of the maintenance personnel needed which will add to the maintenance hours, and for the purpose of this report it is assumed that a 60% reduction in the maintenance man hours compared to the base case FPSO is achievable. Whether or not this estimate is accurate has not been possible to determine, and the results must therefore be used with caution.

Summary and conclusions

Table 6.6 shows a comparison of the two options considered for the main power generation system on the low manned FPSO, to that of the base case FPSO. While the use of redundant gas turbines may be able to achieve the desired availability, the introduction of a third gas turbine will drastically increase the yearly maintenance man hours. Devold (2012) states that with the use of gas turbines, 1 unit will be in maintenance over 50% of the time, indicating how much attention the use of gas turbines will need from maintenance personnel.

Table 6.6: Comparison of the main power generation system for the Base Case FPSO, Low manned FPSO Option 1 and Low manned FPSO Option 2

	Base case FPSO	**Low manned Option 1**	**Low manned Option 2**
System selection	Gas turbines(2x50%)	Gas turbines(3x50%)	Power from shore
Maintenance man hours/year	5248	7872	2099
System Availability	93.68%	99.7%	99.5%

The option of choosing power from shore is able to achieve about the same availability as the gas turbine option, while at the same time reducing the required maintenance man hours by 60% compared to the base case FPSO. Power from shore is therefore considered as the best choice for the low manned FPSO, when not considering the costs of choosing this option. The Norwegian government have put immense focus on the emissions of green house gases from the offshore industry the latest years, and often requires oil and gas companies to consider the option of power from shore by performing cost analysis of either using gas turbines or power from shore. For Valhall the use of power from shore proved to be the best choice from a cost perspective, and may also prove to be so for the low manned FPSO as the location is though to be within helicopter range which is about 370km. This is only about 80km longer than Valhall and is assumed to have the same power requirements.

To conclude the following options should be considered for the main power generation system for a low manned FPSO. The best considered solution is listed first:

- Power from shore with electricity delivered from the main grid.
- If the option of power from shore is found to be too costly the possibility of supplying power from a nearby facility should be explored. This will have the same benefits as power

from shore, but the nearby facility will have to install additional gas turbines to cover the power demand of the low manned FPSO. It may also lead to increased man power requirements on the nearby facility.

- The last option to be considered should the use of gas turbines. This option will require extensive maintenance on the low manned FPSO, and will increase the man power requirements.

For the purpose of this report it will be assumed that power from shore is achievable for the low manned FPSO, and that the umbilical will have fiber optic cables for remote control of the facility.

6.1.3 Gas dehydration

The gas dehydration system was identified as the third most challenging system with regards to low manned operations due to the complexity of the glycol regeneration system and the low MTBF of the gas/glycol contactor and the glycol reboiler. Other gas dehydration methods are currently being explored for subsea application, but to the author's knowledge the technology is still in a development phase.

One of the most promising technologies is the use of supersonic separators for subsea gas dehydration due to no need for a glycol regeneration, low equipment count, low maintenance requirements and high reliability. The use of supersonic separators do on the other hand have two major disadvantages. The technology development so far are experiencing pressure drops of 20-35%, and will require additional compression of the gas before being injected into the reservoir. Another big disadvantage is that the technology does not yet achieve the required dew point in order to meet the specifications for reinjection. The technology is therefore in need of further development before it can be considered for the low manned FPSO.

The unmanned Angel platform presented in Chapter 2.4.1 has proven that unmanned operations of a glycol dehydration system is possible, and could therefore also be considered for the low manned FPSO. Special emphasis should be put on the procurement of a gas/glycol contactor and a glycol reboiler with proven reliable track records to achieve a viable solution for a low manned FPSO. Another option if there is a facility nearby is to supply the glycol from this location, and send it back for regeneration. This would simplify the system as all that would be needed on the FPSO is the gas/glycol contactor.

6.1.4 Offloading

The assessment of the tandem offloading solution on the base case FPSO concluded that other solutions should be considered for unmanned operations mainly due to the close proximity of the vessels during offloading. But as the analysis also concluded that due the complexity of the facility a MMI operational model with up to 20 people is the most likely achievable model, the use of a tandem offloading solution is regarded as a viable option for the low manned FPSO. The required marine crew will have the competencies to perform and oversee the offloading procedures to ensure safe operations.

6.1.5 Marine systems

The marine systems on the FPSO are needed to ensure the safety of the vessel during operations. The ballast and bilge system mainly consists of piping, valves, pumps and tanks. The main scope of this report is not on the marine systems, and possible solutions for low manned operations will not be analyzed. But as mentioned in the analysis of the base case FPSO, the marine systems are one of the main contributors to the total maintenance load. As for all systems on the low manned FPSO, emphasis should be put on simplifying the systems and choosing reliable equipment with low maintenance requirements.

The low manned FPSO is also in need of a propulsion system either sufficient to maintain the vessels position(DP system), or with the capability to also sail the vessel away from its position as a normal ship in case of an emergency situation. The latter will require the installation of much more complex machinery in need of testing, inspections and maintenance even though its intended use is very limited.

It is therefore the author's opinion that the best solution for the low manned FPSO will be to only have a DP system in order to minimize the maintenance requirements and the complexity of the facility. Power to the thrusters can be supplied from the main power generation system bu using electric motors, and will not require any additional generation of power on the vessel.

6.2 Reducing maintenance man hours by high maintainability

As presented in Chapter 3.3 high maintainability is a key factor when it comes to low manned operations in order to both reduce the MTTR and to reduce the yearly maintenance man hours. In order to achieve a facility with high maintainability it is not enough to only select equipment with high maintainability. The design and layout of the facility itself will have just as much impact on maintainability, and some important measures that have the ability to increase the maintainability are presented below.

- The low manned FPSO should be designed to avoid the use of scaffolding when performing maintenance and repair to the greatest extent possible. Table 4.3 shows that more than 10000 hours are spent yearly on scaffolding and will have to be greatly decreased in order to achieve a viable low manned concept. A reduction in the need of scaffolding can be achieved by selecting easily accessible equipment solutions or build in permanent access points for maintenance. For inspection work at high elevations, the use of scaffolding can be avoided with the use of drones taking high quality footage that can be evaluated by experts.

- Provide sufficient space around equipment items to provide easy access for personnel and potential removal/replacement of equipment to minimize the time spent during maintenance. If a seawater pump in the hull requires maintenance where it has to be transported to a workshop a bad equipment layout could drastically increase the time it takes to both remove and transport the pump to the workshop. The maintenance crew should not have to battle against narrow spaces when gaining access to, lifting and moving equipment items.

In order to achieve a facility with a high degree of maintainability, operation and maintenance personnel have to take part from the design and construction phase. An engineer designing the facility will most likely only think about how the equipment should be placed in order to perform its intended function, and not how it should be placed to ensure a high degree of maintainability. Input from operation and maintenance personnel will ensure that this is avoided by providing input throughout the entire process, and will have a key role in order to ensure that low manned operations can be achieved. It is difficult to quantify the impact of having immense focus on designing a facility with high maintainability, but as an example a 50% reduction in the scaffolding requirements from the base case FPSO will save 5000 maintenance man hours per year compared to the base case FPSO.

6.3 Remote operations

Remote operations of the low manned FPSO from a central control room enables the removal of production operators and operation supervisors from the facility, and can be a big contributor to reduce the total POB on the FPSO. Extensive experience in remote operations has been gained from subsea installations and simpler topside facilities, and should be utilized when developing a far more complex FPSO. There are several companies that delivers complete solutions for remote operations of oil and gas facilities. The systems includes:

- Complete control and monitoring of all processing equipment. It is the author's opinion that these systems also can have the capability of controlling and monitoring all marine systems on the FPSO.
- Integrated into the process control system is also advanced safety systems and fire and gas detection systems. It is important the system has the capabilities for remote shutdown of the production.

With the implementation of such a system, the process operators will have access to all the required information in order to control the operation of the FPSO from the remote facility. The system also allows for condition and performance monitoring of the equipment so that failures can be detected and maintenance actions can be planned. With all the information available regardless of geographical location the appropriate actions can be determined without having to visit the FPSO. Condition and performance monitoring techniques available for different types of equipment are presented below. In addition, the introduction of inspection and maintenance robots could aid the remotely placed process operators, and reduce the required presence of humans on the low manned FPSO, and is presented in sub section 6.3.2.

6.3.1 Condition and performance monitoring

The use of condition and performance monitoring is vital to ensure low manned operations in order to optimize maintenance intervals and reduce the number of required visits to the facility. The most critical components on the base case FPSO are generally made up rotating machinery(compressors, pumps and electrical motors) and static equipment(separators, scrubbers and heat exchangers), and the two categories will have different needs of condition and performance monitoring.

Monitoring of rotating machinery

Pumps, compressors and electrical motors will have many different failure modes that could lead to a critical failure, but rotating machinery generally follow the degradation curve seen in Figure 6.1. By monitoring vibrations, noise and temperature from the equipment, failures can be detected before a repair is required, and proper maintenance and shutdown can be planned.

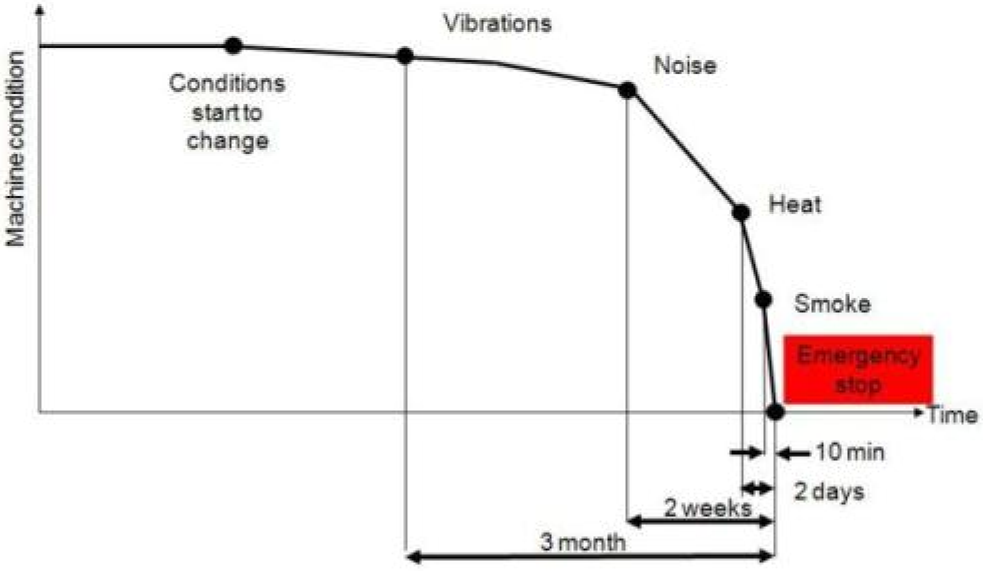


Figure 6.1: The warning signs of developing failures in rotating machinery NI (2016)

In addition a reduction in the equipments performance can be an indicator of a failure. A reduction of delivered pressure, increased power consumption or reduced flowrate from compressors and pumps are examples of deteriorated equipment performance and should be monitored as well. Table 6.7, 6.8 and 6.9 shows different failure modes for compressors, pumps and electrical motors and how the failure symptoms can be monitored to detect a developing failure.

Table 6.7: Failure modes and monitoring techniques for compressor Cherkashina (2013)

Possible failure modes	**Symptoms of failure**	**Monitoring technique**
Bearing failure	Increasing compressor vibration and bearing temperature	Vibration and temperature sensors
Shaft failure	Increasing compressor vibration, friction and wear	Vibration and temperature sensors
Internal corrosion	Increasing compressor vibration	Vibration sensor
Loss of gas output	Drop in outlet temperature and compressor efficiency	Temperature, pressure and flow sensors at compressor inlet and outlet
Surge and cavitation	Low flow rate at compressor inlet and increasing compressor vibration	Pressure and flow sensors at inlet and outlet. Vibration sensors
Overheating	Increasing temperature in compressors rotating parts, high compression ratio, high gas outlet temperature	Temperature and pressure sensors at inlet and outlet

Table 6.8: Failure modes and condition monitoring for pumps Cherkashina (2013)

Possible failure modes	**Symptoms of failure**	**Monitoring technique**
Drop in produced head	Decreased reading of pump pressure sensor and increased pump vibration	Pressure and vibration sensors
Shaft failure	Increasing pump vibration	Vibration sensors
Pump wear	Drop in produced head, increased power consumption	Pressure sensors, flow meter and operating head
Overheating	Increasing temperature in rotating parts	Temperature sensors
Corrosion	Increased vibration	Vibration sensor
Loss of liquid output	Drop in produced head and pump performance	Pressure sensor, flowrate and operating head.

Table 6.9: Failure modes and condition monitoring for electrical motors Cherkashina (2013)

Possible failure modes	**Symptoms of failure**	**Monitoring technique**
Stator faults	Stator Magneto Motive Force(MMF)	Current and voltage sensors
Rotor faults	Unequal rotor bar currents	Rogowski coil measurement
Insulation breakdown	Decreasing electrical resistance and moisture content in windings	Megaohm resistor and moisture sensor
Overheating	Increasing stator and rotor temperature	Stator winding temperature detector
Mechanical imbalance (misalignment or bent shaft)	Increasing vibration	Current, voltage, vibration and temperature sensors

Monitoring of static equipment

Monitoring of static equipment may be more difficult then monitoring rotating machinery as they mainly consist of a vessel with some static internals. It may therefore be difficult to determine the reason for a failure without inspecting the inside of such components, but a developing failure can be detected by monitoring the performance of static equipment such as separators, scrubbers and heat exchangers. There are also condition monitoring techniques available that can detect changes of vessels internals such as infrared cameras and passive acoustic monitoring.

For heat exchangers fouling is one of the main problems leading to reduced performance of the equipment or in the worst case clogging. By monitoring temperature, pressure and flow on all inlets and outlets it is possible to calculate the exchanger's heat duty, heat transfer coefficient and fowling factor in order to determine the overall health of the exchanger. Operator and maintenance personnel can then be alerted when the exchanger is in need of cleaning or an abnormal increase in fouling is detected.

For vessels such as separators and conventional scrubbers, monitoring temperature, pressure and flow on all inlets and outlets may also aid in determining the performance of the equipment. Level sensors inside the vessel are also needed to give a picture of how the vessel operates. Separation vessels also consist of internal equipment such as hydrocylones and demisters that may loosen and fall off due to the harsh environment inside the vessel, and the detection of such a failure without human inspection may reduce the requirements to visit the low manned FPSO. The use of infrared cameras and passive acoustic monitoring(vibration monitoring of higher frequencies) are examples of monitoring techniques that have the ability to detect changes in the internal conditions of the separator(Houmstuen (2010)). For more information about these monitoring techniques it is referred to Houmstuen (2010)

Discussion

Remotely placed operators have to rely on all the information provided by the all the different sensors placed on the equipment in order to ensure safe operations and determine the condition and performance of the equipment. Abnormal instrument readings is one of the main contributors to the critical failure rates of equipment presented in OREDA. Procurement of reliable sensors and implementation of redundancy will therefore be required in order to achieve remote operations of the FPSO.

For the purpose of this report it would have beneficial to quantify the effects of implementing performance and condition monitoring will have on the total number of maintenance man hours, number of necessary inspections and reductions in unplanned shutdowns on the low manned FPSO, but it has not been possible to obtain any data in order to do so. Any further analysis has therefore not been performed.

6.3.2 Robots

Offshore installation operators spend a large amount of time performing inspections and regular maintenance of the equipment on the installation. Having a robot that could perform these routine and often quite simple tasks, either autonomously or remotely controlled, have the potential to remove the personnel performing these tasks from the facility. The benefit would be both a lower manning level and the removal of the safety issues related with humans being present in the processing area. No such robot is yet commercially available, but several prototypes have been tested to confirm the applicability of such robots in the oil and gas industry. The Sensabot can be seen in Figure 6.2, and is presented in this report.

JPT (2012) presents the Sensabot, a mobile inspection robot, developed and launched by Carnegie Mellon University's National Robotics Engineering Center(NREC). The robot is able to

Figure 6.2: Sensabot NREC (2016)

perform the same inspection and reporting tasks as humans do, but without the risk of workers being exposed to potential hazardous conditions.

Sensabot is not able to operate autonomously and is controlled by remotely positioned operators. Some of the robots characteristics are:

- 360 degree cameras giving a view of the surroundings in order to visually inspect process equipment and areas for operating performance and defects such as corrosion. The robot also has a powerful pan/tilt/zoom camera that enables operators to inspect small or distant objects.
- Spotlights that allow for low light inspections.
- Microphones and vibration sensors enabling monitoring of audio and seismic conditions of equipment such as compressors, pumps, motors and bearings.
- Temperature senors that allows for recognition of overheating equipment.
- Gas sensors able to detect H_2S and CO_2, and other flammable gases.

Some other applications not mentioned above includes the inspection of safety equipment, reading of remote gauges, inspection of valve and switch panel positions, and testing of fixed sensor instrumentation.

Tests of the prototype in 2011 proved to be a success and confirmed the potential applications that the robot has according to JPT (2012). Further development is needed before the robot is ready for manufacture and commercialisation, but JPT (2012) states that a complete commercial system could be ready for licensing and manufacture within 2 years. Reaching this goal will be dependent on industry, sponsor and application requirements.

To the knowledge of the author, the Sensabot or any other inspection robots are not yet commercially available to the oil and gas companies. For the purpose of this report it will be assumed that an inspection robot similar to the Sensabot will be available within a 10 year period, and can be applied for use on a low manned FPSO. The robot is assumed to be able to perform all the inspection tasks mentioned above that does not require any initial human consideration autonomously, and the system is able to directly report on any abnormalities. Some examples of such tasks are gas detection, temperature measurements, inspection of valve and switch panel positions, reading of remote gauges and testing of fixed sensor instrumentation. The robot will also have the ability to be remotely controlled in order to perform tasks such as visual inspections.

6.4 Maintenance strategy

The following section presents a proposal to a maintenance strategy for the low manned FPSO based on the precondition that the platform is remotely controlled with the required condition and performance monitoring for all critical equipment components, that the FPSO has inspection and maintenance robots able to do the tasks described in Chapter 6.3.2 and that a small maintenance crew is present to maintain the marine systems. Based on these preconditions it is believed that the implementation of a maintenance strategy with the following main characteristics have the potential to support viable low manned operations of the FPSO:

- Maintenance of all critical equipment will be based on information from the condition and performance monitoring, and planned maintenance should be grouped to the greatest extent based on this information. This will also include implementation of opportunity maintenance where possible as described in Chapter 3.3. The planned maintenance will be performed by a larger crew(e.g 20 people) that visits the FPSO by ship or helicopter depending on what kind of maintenance that will be performed. A ship may be required if large spare parts are needed for the maintenance. It is crucial that the maintenance crew is familiar with the facility and its equipment. A possible scenario for visit frequency can be a 7 day visit every 2 months.

- A small maintenance crew(preferably 5 or less) will be present at the facility at all times in order to perform critical maintenance/repair of the marine systems. The crew will also have extensive knowledge in maintenance and repair of process equipment, and is able to perform simpler repair jobs of the processing equipment.

- Corrective maintenance will be performed by a response crew visiting the FPSO by helicopter to perform all repairs that the in-situ maintenance crew do not have the competence/equipment/time to perform.

- The maintenance and inspection robots presented in Chapter 6.3.2 will be able to perform all inspections that is possible to perform without the "opening" of equipment either autonomously or remotely controlled from shore.

- Visual inspections at high elevations, e.g. flare and storage tanks, can be performed using drones. The use of drones have the potential to both remove the risks of people working at heights, but also induce time and cost savings. As an example, the inspection of storage tanks typically take 3-4 days using rope access while performing the same job took a two man team(Drone pilot and inspection engineer) one day to complete(IUS (2016))

As previously mentioned the total yearly maintenance man hours of the low manned FPSO should preferably be less than 30000 hours, and the maintenance strategy presented above would have to cover this load. The following calculations will show how the maintenance man hours can be divided between the permanent maintenance crew, the crew performing planned maintenance and the response crew performing corrective maintenance.

- 5 permanently manned maintenance positions working 12 hours/day for 365 days/year is able to cover 21900 maintenance man hours.
- A maintenance crew of 20 visiting the platform for 7 days every two months(average of 5.5 visits per year) will be able to cover about 9000 maintenance man hours.
- A onshore response crew consisting of 5 people will have to attend to 3 critical failures each year. Each visit will last on average 2 days and the crew work 12 hours per day. This will amount to 369 maintenance man hours per year.

The above calculations amounts to a total of about 31400 maintenance man hours/year, and is enough to cover the 30000 yearly maintenance man hours/year.

It should be noted that this is only a suggestion to a possible maintenance strategy for the low manned FPSO. A prerequisite for the implementation of such a maintenance strategy is that the process systems are reliable enough to reduce the number of unplanned visits and that the yearly maintenance requirements are low enough.

6.5 Summary

Based on the information presented in this chapter it is the authors opinion that a low manned FPSO with 20 or less POB is achievable. New solutions for the gas compression for reinjection system and the main power generation system have the potential to greatly increase the availability of the systems to a satisfactory level while at the same time drastically decreasing the maintenance requirements with over 5000 hours compared to the base case FPSO. Although no new technology has been found to replace the use of glycol dehydration, the Angel platform has proven that the solution has the ability to function for unmanned operations and is therefore considered as a viable option for the low manned FPSO. By selecting simple and reliable solutions also for the other processing, utility and marine systems on the base case FPSO and designing a FPSO with high maintainability it is the author's opinion that it is possible to reduce the yearly maintenance man hour to below 30000 hours as was set as a prerequisite to achieve low manned operations of the FPSO.

Remote operations of the facility will allow for the removal of the process operators, and the technology is regarded as available today. The introduction of inspection and maintenance robots will enhance the capabilities of the remote operators, and will reduce the need to visit the FPSO for inspections while at the same time reducing the maintenance requirements performed by humans. Remote operations also allows for the incorporation of condition and performance monitoring from the central control room and a condition based maintenance strategy. This will allow for a reduction in the number of maintenance personnel permanently placed on the FPSO and a larger maintenance crew can visit the facility for planned maintenance campaigns based on information from the condition and performance monitoring.

The following chapter presents a low manned FPSO concept based on the development made in this report, and technology development needs that could further enhance the potential for low manned operations of the FPSO is discussed.

Chapter 7

Low manned FPSO concept

Based on the development of a low manned FPSO concept in the previous chapter the present chapter suggests how a low manned FPSO with a crew of less than 20 may look like, and a proposed procurement process for low manned operations is presented. In addition technology development needs with the ability to enhance the potential of low manned operations is discussed.

7.1 Overview

- The FPSO will need accommodation for up to 40 people to acommondate the permanent crew and a maintenance crew up of up 20 people visiting the facility for campaign maintenance.
- The FPSO will be in need of a helideck to ensure fast transportation of personnel to the facility. Regulations require that the helideck has fire water pumps installed.
- With people constantly present on the facility the FPSO will most likely be required to have all safety related systems/equipment that a fully manned FPSO will need. Some simplifications may be allowed as the total POB is drastically reduced e.g number of life boats and life vests.

7.2 Operational philosophy

The low manned FPSO will be remotely controlled from a remote central control room with production operators and maintenance planners to conduct daily operations of the FPSO. They will be able to control and monitor the complete facility including all the marine systems during normal operations. They are assisted by the crew on the FPSO, and the inspection and maintenance robots. Table 7.1 shows a proposal to the permanent manning on the low manned FPSO. The total POB in Table 7.1 only amounts to 14 people, and additional personnel that may be needed could for example be a HSE coordinator, extra maintenance personnel or other personnel based on requirements from regulations.

Table 7.1: Proposed permanent manning on the low manned FPSO

Position	**No. of people**	**Tasks and Competencies**
OIM/Captain	1	Will be the ultimate authority on the vessel. Will need the competencies to control all marine systems and offloading, and have extensive experience as OIM from a "standard" FPSO.
Marine crew	3	All the marine crew will need competencies to control and monitor the marine and offloading systems. Should also have knowledge and understanding of the processing systems in order to assist the operators in the remote control room.
Maintenance crew	5	The maintenance crew on the FPSO will mainly be in charge of maintaining and repairing the marine and offloading systems. The crew should also have the competencies to perform simple maintenance and repair of process related equipment, and at least one person should be certified for crane operations.
Admin/Medic	1	A medic is regarded as a requirement when there is personnel present on the FPSO. The medic will also be in charge of daily administrative tasks.
Catering personnel	4	4 people to be in charge of cleaning, food preparation and general welfare on the facility is regarded as sufficient for a total POB up to 20 poeple.

The following points show how operation and maintenance of the low manned FPSO can be performed:

- During normal operations the FPSO is completely controlled by the remote control room, but the marine crew on the FPSO will take control of the marine and offloading systems during offloading, severe weather conditions or if connection is lost between remote control room and the FPSO in order to ensure the safety of the vessel.
- The inspection and maintenance robots presented in the previous chapter will be the "eyes, ears and hands" present in the processing area during normal operations either operating autonomously or remotely controlled from the remote control room. The crew present on the facility will therefore not be required to be present in the processing areas during normal operations.
- The low manned FPSO will follow a similar maintenance strategy as the one presented in Chapter 6.4 as the assessment of the strategy showed that it can cover over 30000 maintenance man hours per year.

7.3 Process, utility and marine systems

Table 7.2 shows an overview of the systems considered for the low manned FPSO concept. The new solutions for the compression for reinjection and the main power generation system are able to achieve availabilities above 98% and the total calculated reduction in maintenance man hours is about 5000 hours, and it is the author's opinion that the systems now have the potential to be used in low manned operations. The integrated compressor solutions can also be used for the recompression system to enhance the reliability and reduce maintenance requirements also for this system. It has not been possible to perform the same calculations for the glycol dehydration system due to not having specific numbers of the maintenance load, and what procuring more reliable gas/glycol contactors and glycol reboiler may do to the reliability of the system. It would be beneficial to avoid the need for a glycol regeneration system. A possible solution, if there is another facility nearby, could be to regenerate the glycol at this facility.

Table 7.2: Overview of solutions for the low manned FPSO concept

System	**System solution**	**Comments**
Compression for reinjection	Integrated compressor solution with cyclonic scrubbers	The analysis shows that the system in a 2x50% configuration can achieve a 98.3% availability while at the same time reducing the number of maintenance man hours by 1869 hours compared to the base case FPSO.
Gas recompression	Integrated compressor solution with cyclonic scrubbers	The new compressor solution can reduce maintenance requirements and increase the reliability also for the gas recompression system.
Main power generation	Power from shore or nearby facility	The analysis show that power from shore can achieve a availability of 99.5% while reducing the number of yearly maintenance man hours by 3149 hours compared to the base case FPSO.
Gas dehydration	Glycol dehydration	The Angel platform has proven unmanned operations of a glycol dehydration system, and the solution is therefore assumed to be viable for the low manned FPSO as well.
Offloading	Tandem offloading system	With a small crew present on the FPSO, the use of tandem offloading can be applied to the low manned FPSO concept as the competencies to oversee and perform offloading procedures are present on the facility.
Marine system	DP system, ballast and bilge system	To reduce the complexity the FPSO should only have a DP system, and not a full propulsion system. In the design of the ballast and bilge system a focus should be on simplicity and the procurement of reliable and low maintenance equipment.

Only some of the systems have been evaluated for the low manned FPSO concept, and a similar assessment should also be made with regard to the other process and utility systems. This has not be done in this report due to time constraints, but as an example the subsea separator and water injection pump at the Troll pilot presented in Chapter 2.4.3 have shown that it is possible to design both separators and large pumps with very high reliability. Similar equipment have the potential to be used on the low manned FPSO to improve the reliability and reduce the maintenance requirements of e.g. the oil stabilization system. Table 7.3 shows an overview of some considerations made with regard to the other main process and utility systems also needed for the low manned FPSO.

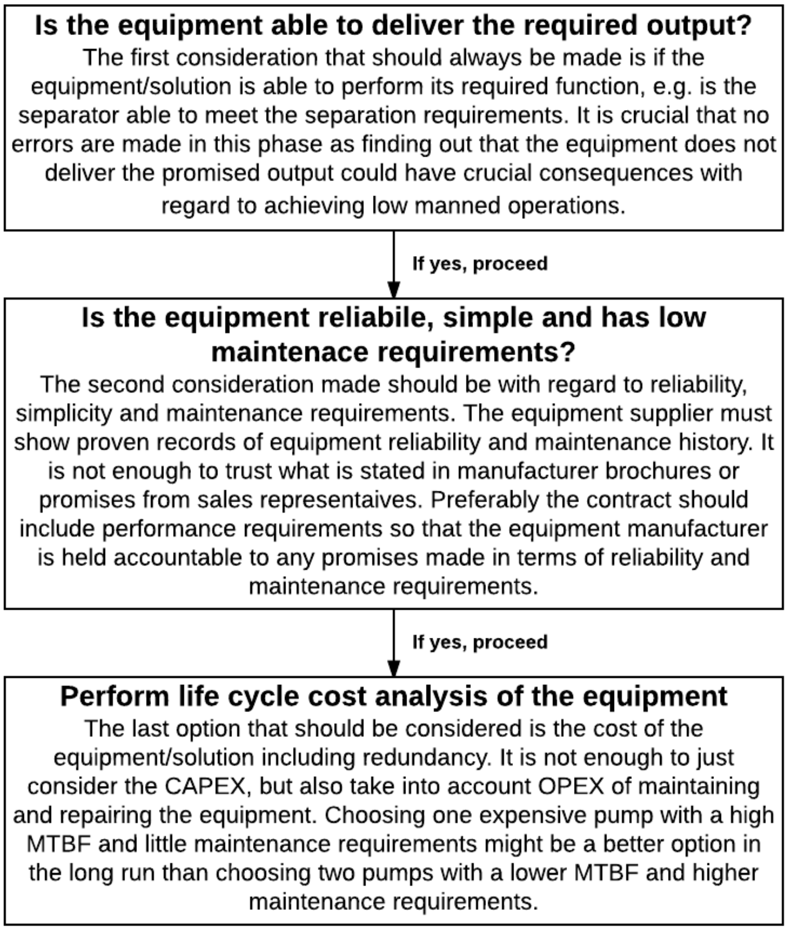
Table 7.3: Considerations for the other process and utility system not covered in Chapter 6.1

System	**System solution**	**Comments**
Oil stabilization	As for base case	The oil stabilization system is not regarded as one of the main challenges in terms of low manned operations, but is a highly important process on the FPSO. The subsea separator at the Troll pilot has proven that it is possible to design separators with high reliability and low maintenance requirements. This experience should be utilized in the design of a system for low manned operations.
Produced water treatment & injection	As for base case	Not regarded as a challenge with regards to low manned operations as the system mainly has equipment with high reliability. The main challenge is to find water injection pumps with high reliability. Troll pilot has proven that this is possible. Water can be disposed to sea in case of injection pump failure provided the water is treated to sufficient quality.
Cooling system	Air cooling or indirect seawater cooling	The use of indirect seawater cooling could be an option for the low manned FPSO, but the system has large seawater lift pumps, extensive piping, valves, strainers and heat exchangers all requiring maintenance. The use of air cooling is far less complex as all that would be needed is heat exchangers and fans to provide air circulation. Air cooling is prone to seasonal variations, and must be designed to always provide sufficient cooling. A combination of the two solutions is a possibility.
Heating system	Hot oil system or electrical heaters	With power from shore utilizing the generated heat from the gas turbines is no longer an option. The use of a hot oil system with a heater or electrical heaters can then be considered. The use of electrical heaters would increase the power demand on the FPSO and has to be accounted for when dimensioning the main power generation system.

It is important to note that these are all just proposals to how it could be possible to design the different systems in order increase reliability and reduce the maintenance requirements to allow for low manned operations. The different solutions will also have to be evaluated with regard to process performance(delivering the required output) and costs in the selection process which has not been the main focus in this report. The different solutions must therefore be considered on a case to case basis to find the best option.

7.4 Procurement process for low manned operations

As mentioned several times in this report the equipment and solutions on a low manned FPSO have to be reliable, simple and have low maintenance requirements. A different approach may therefore be needed in the procurement process for low manned projects compared to fully manned projects where costs often are set as the first main criteria. A proposal for how equipment should be procured for a low manned project is presented in Figure 7.1.



Is the equipment able to deliver the required output?
The first consideration that should always be made is if the equipment/solution is able to perform its required function, e.g. is the separator able to meet the separation requirements. It is crucial that no errors are made in this phase as finding out that the equipment does not deliver the promised output could have crucial consequences with regard to achieving low manned operations.

Is the equipment reliabile, simple and has low maintenace requirements?
The second consideration made should be with regard to reliability, simplicity and maintenance requirements. The equipment supplier must show proven records of equipment reliability and maintenance history. It is not enough to trust what is stated in manufacturer brochures or promises from sales representaives. Preferably the contract should include performance requirements so that the equipment manufacturer is held accountable to any promises made in terms of reliability and maintenance requirements.

Perform life cycle cost analysis of the equipment
The last option that should be considered is the cost of the equipment/solution including redundancy. It is not enough to just consider the CAPEX, but also take into account OPEX of maintaining and repairing the equipment. Choosing one expensive pump with a high MTBF and little maintenance requirements might be a better option in the long run than choosing two pumps with a lower MTBF and higher maintenance requirements.

Figure 7.1: Procurement process for low manned operations

The procurement process for low manned operations will require more resources and considerations during the project phase compared fully manned installations. But in order to reach the goal of low manned operations and avoid any surprises when the facility is put into operation it is essential to know that the selections made performs as expected.

7.5 Technology development needs

Most of the technology needed to achieve low manned operations of a FPSO is regarded as available today, but additional new technology will be needed to reach unmanned operations of an FPSO due to the complexity of the facility. Below are some suggestions to technology developments needed to achieve unmanned operations of a complete FPSO facility:

- The inspection and maintenance robots for the oil and gas industry may soon be a reality, but there are still only prototypes available so far. The robots have a huge potential to perform a large variety of tasks on a oil and gas facility, and have the ability to remove both process operators and maintenance personnel from the facility. It is the authors opinion that the development of such robots may have the largest potential in terms of achieving unmanned operations of complex offshore facilities such as an FPSO.
- The development of a gas dehydration system without the need for glycol and a glycol regeneration system will help simply the system to a great degree. With current developments for subsea gas dehydration, a solution may not be that far away.
- The development of a reliable and low maintenance main power generation solution removing the need for power from shore or gas turbines can help realize unmanned operations at locations further from shore.
- Development of unmanned FPSO offloading solutions where the offloading procedure can be performed in a safe way from a remote location.

Chapter 8

What about FLNG?

The processes included in producing liquefied natural gas is even more complex than the processes found on a FPSO. Unmanned operations of FLNGs may therefore be an even bigger challenge. To date, no FLNG facilities are in operation and no real operational experience is yet available. To consider FLNGs for unmanned operations is therefore a difficult task as compared to FPSOs where reliability data, maintenance data and extensive experience is available. For this reason, and due to time constraints only some general remarks are therefore be made with regard to the potential of unmanned operations of FLNG facilities.

- A FLNG vessel will have the same requirements with regard to marine systems as for an FPSO, and the considerations made with regard to these systems in this report will therefore also apply for a FLNG.
- The use of power from shore have the same potential with regard to availability and maintenance requirements on a FLNG as on a FPSO.
- During the liquefaction process, compressors are needed for the refrigerant being used in the process. The Integrated compressor solutions presented in this report can be utilized with the benefits of high availability and low maintenance requirements compared to conventional compressor solutions.

- In order to liquefy the gas there are stringent requirements to how the gas needs to be treated before entering the liquefaction process in order to prevent freezing. The gas will need treatment to remove acid gases and mercury. In addition the gas dehydration process needs to achieve lower water dew points than what is required in order to reinject the gas into the reservoir on the FPSO. These are all factors that will add to the complexity of a FLNG compared to a FPSO.
- Before the natural gas is liquefied the removal of heavier hydrocarbon components is also required as they may freeze during the liquefaction process. This is also a contributor to increasing the complexity of the FLNG facility.
- Remote operations and the use of robots have the ability to reduce the manning and maintenance requirements of FLNG facilities as for FPSOs.

The coming years several FLNG facilities will go into operation, and with that operational experience will become available in order to perform a more thorough analysis of the possibilities and challenges with regard to low manned operations of FLNG facilities. Based on the above remarks it is the author's opinion that due to the complexity of the facility, low manned operations of FLNG facilities is even more challenging than for FPSOs, but the use of power from shore, integrated compressor solutions, remote operations and robots have the ability to reduce the maintenance and manning requirements.

Chapter 9

Summary and Recommendations for Further Work

9.1 Discussion

Throughout this study a "standard" base case FPSO has been analysed to highlight the challenges of low manned operations and potential solutions that may allow for reduced offshore manning have been explored and evaluated.

The analysis of the "standard" base case FPSO is based on maintenance and manning data provided by Pettersen (2016), reliability data from OREDA and the results of the RAM analysis performed by Wang (2012).

The maintenance and manning data are reported data from a "specific" FPSO, and what lies behind the figures are unknown to the author. It is therefore difficult to evaluate whether the numbers are high or low compared to other similar FPSO's.

The reliability data from OREDA have been used to make simple availability calculations of different systems on the base case FPSO and also to highlight the most critical equipment in the different systems in terms of reliability. As the data from OREDA has been the only available source of reliability data, it is difficult comment on the validity of the failure rates and active repair times. On the other hand, reliability data from OREDA is widely used in the industry to perform RAM analysis. It is assumed that the numbers give a good reflection of the reliability of different equipment.

Further availability calculations made in this report are performed using simple equations and several assumptions. The availability of the different equipment/systems in Chapter 5 may therefore not be exact, but is the author's opinion that the calculations are good enough to give an indication of the systems most likely to have a negative impact on the production availability.

As standalone sources of information, the inputs to the analysis of the base case FPSO may therefore not be enough to conclude on whether a system or equipment will be critical in terms of low manned operations. On the other hand, when used together it is the authors opinion that the inputs form a valid tool for determining the systems that is most likely to be a challenge when the goal is to achieve low manned operations.

The analysis of the base case FPSO recommends that a small marine crew must be present to ensure the safety of the vessel, and that this is the main reason that entirely unmanned operations is too challenging. The main reason for this recommendation is that a failure in the marine systems can lead to a catastrophic incident before a crew is able to repair the failure in case of entirely unmanned operations. It might be possible to argue that by installing extensive redundancy to the marine systems it can be possible to minimize the possibility of such a scenario to a degree where unmanned operations is possible, but this will increase the amount of equipment on the facility and hence the maintenance requirements. The result will thus be increased required presence on the FPSO. When also taking into account all the other systems on the FPSO and the complexity of operations, it is the authors opinion that the best solution is to have a small crew with the capabilities to operate and maintain/repair the marine systems while also contributing to maintaining and repairing process related equipment to reduce the number of visits to the facility.

In the development and analysis of the low manned FPSO concept several assumptions have been made in order to quantify the effects of implementing new system solutions, and thus the validity of the results may be questioned. As an example the MTBF for the integrated compressor solutions is assumed to be 5 years based on a manufacturer statement that the compressor will need a minor overhaul every 5 years. There are a number of factors that may cause the real MTBF to be less than five years such as insufficient scrubber separation leading to erosion in the compressor due to the presence of liquids. It has not been possible to find any sources of information for comparison of the results, and it is therefore difficult to know if the assumptions are valid. The results must therefore be used with caution.

Further it has not been possible to quantify the effects of implementing remote operations with condition and performance monitoring, and inspection and maintenance robots other than assuming that the production operators can be removed to a remote control center and that a maintenance crew can visit the facility for maintenance campaigns based on the information from the monitoring of equipment.

The procurement process presented in Chapter 7.4 presents the author's opinion of the most important aspects that have to be taken into account when procuring equipment/solutions for low manned operations. There may be other inputs to the process that have not been accounted for in this report, and the presented process may therefore be subject to discussion. But the main essence of the process is that extensive considerations have to made when procuring equipment for low manned operations. Just as for subsea installations, the goal should be to install as little equipment as possible to reduce the total maintenance requirements while at the same time achieving the highest possible availability. In order to do so redundancy should be avoided by choosing equipment that has proven to be reliable and has little need for maintenance. A different and more extensive approach than for fully manned installations is therefore needed during the procurement process in order to be certain that the equipment will perform as required.

Based on what has been discussed above the proposed low manned FPSO concept in Chapter 7 must only regarded as what it is. Namely a suggestion to how a low manned FPSO may look like in terms of operational philosophy and system solutions.

9.2 Summary and Conclusions

The main objective of this report is to develop and evaluate minimum manning solutions for offshore oil and gas production systems. Low manned operations give advantages of improved safety and reduced operational expenses, and may enable field developments in harsh and/or remote areas that may otherwise have been difficult to realize. Lower manning requirements can be achieved by simplifying process and utility systems, choosing equipment with high reliability and minimal maintenance requirements, implementing remote control systems with condition and performance monitoring, the use of robotics and in general design a facility with low maintenance requirements.

The study of current unmanned facilities and subsea installations shows that most of the equipment and technology needed on a FPSO is already in use in unmanned operations today, but has not yet been put together to form a facility with same complexity as an FPSO. The study of current literature regarding low manned operations shows that an immense focus must be put on choosing equipment/solutions with high reliability and low maintenance requirements in order to achieve the desired production availability and reduce the need to respond to unplanned shutdowns. Remote surveillance and diagnostics should also be implemented for all critical equipment in order to achieve rapid and efficient fault finding and reduce the amount of required routine maintenance.

A "standard" base case FPSO is presented and analysed in order to identify the most critical systems with regard to low manned operations of a FPSO and to determine if entirely unmanned operations of a FPSO is a possibility. Maintenance and manning data, reliability data from OREDA and the results of a RAM analysis performed by Wang (2012) on a similar processing facility has been used as inputs to the analysis. The results show that the gas compression for reinjection, the main power generation, and the gas dehydration systems are the most critical in terms of reliability and maintenance requirements. Further the analysis concludes that reacting to a failure in any of the marine systems(DP system, ballast and bilge system) in case of entirely unmanned operations may take to long to avoid a catastrophic incident as e.g a failure in the DP system may cause the anchor chains to break before the DP system is repaired. In such a case manual operator interference is needed unless extensive and hence costly redundancy is built into the system. The analysis therefore recommends that a small crew is required present on the FPSO with the capability to operate and maintain/repair the marine systems to ensure the safety of the vessel.

The results from the analysis of the base case FPSO have been used to develop and analyze a low manned FPSO concept. New equipment/system solutions for the three most critical systems on the base case FPSO is evaluated and analyzed. The results show that the implementation of integrated compressor solutions and power from shore/host have the ability to greatly increase the availability and decrease the maintenance requirements of the compressor systems and the main power generation system compared to the base case FPSO. No new solution has been found for the gas dehydration system, but current unmanned platforms have shown that unmanned operations of glycol gas dehydration systems is possible. Further an evaluation of the implementation of remote operations with condition and performance monitoring, maintenance and inspection robots, and a design that has immense focus on achieving high maintainability has been made, and shows that required presence on the facility can be reduced through decreased maintenance and inspection needs.

Based on the development and analysis of solutions for low manned FPSO concept, is the author's opinion that a FPSO with a crew of up to 20 people and 30000 yearly maintenance man hours is a possibility, and a proposal to what such FPSO may look like in terms of process, utility and marine systems, and operational philosophy is presented. Also included are technology development needs that have the potential to further increase the chances of achieving successful low manned operations of low manned FPSOs.

Lastly a short evaluation has been made with regard to low manned operations of FLNG facilities. The implementation of integrated compressor solutions, power from shore and remote operations all have the capability of reducing the need for personnel on the facility just as for FPSOs. The main challenge is that the processes included in order to liquefy gas is regarded as even more complex compared to those found on a FPSO. Achieving low manned operations of an FLNG may therefore be even more challenging than for an FPSO.

In conclusion, the technology needed to design a low manned floating production facility is already available or could be in the near future. The work presented in this report does not have the ability to conclude that low manned operations is beneficial for every FPSO development project, but the result indicates that it will be possible for some projects. Hence it will be beneficial to perform project related feasibility studies to conclude if it is possible or not for each individual project.

9.3 Recommendations for Further Work

This scope of this report is very wide and a more detailed study of the solutions that have the ability to allow for low manned operations can be performed to get a better understanding of their potential. The following recommendations for further work is therefore made.

- The CAPEX of investing in power from shore compared to gas turbines has not been thoroughly addressed in this report. Life cycle cost analysis comparing the two options for different scenarios(depth, length of cable, power demand etc.) can be performed to give a better picture of when the use of power from shore/host will a cost effective alternative.
- It has not been possible to quantify the effect of introducing condition and performance monitoring for the equipment on the low manned FPSO. It would therefore be beneficial to perform an analysis where the goal is to quantify the reduction in maintenance/inspection requirements, and production stops by the implementation of condition and performance monitoring.
- This report has only briefly discussed low manned operations of FLNGs. Several FLNG installations go into operation over the next couple of years. Operational data and experience will then become available, and reveal the most challenging aspects of operating FLNG facilities. A full study compared to what has been made for the FPSO in this report can be performed to help discover solutions that can allow for low manned operations of FLNGs.

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