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Abstract

There is an identified need for mid-level systems for monitoring a large number of subsea wells. To meet this demand Statoil is looking into developing a software program for such monitoring. As a step in this process, this thesis is looking into development of key condition indicators to be used in such a program for the Statoil operated Gullfaks Satellites tied back to Gullfaks C (GFCSAT). The indicators developed in this thesis are aimed at contributing to a good and efficient mid-level monitoring of technical integrity and availability for the GFCSAT subsea production system.

The first step in the development process has been to establish the goals and objectives that will be the pillars for the indicators. These goals are based on the same goals that are used to govern the operations of the GFCSAT; the three chosen goals are within the areas health, safety and environment, operational costs and production. For each of these three goals relevant reports of past events were retrieved from GFCSAT historical records. The reports were categorized into 11 categories based primarily on common failure modes. Categories without indicator detectable failure modes were discarded after the analysis process leaving 8 categories for further analysis. For the indicator detectable failure modes possible indicators were suggested and reviewed using a checklist approach. Based on this review, one indicator was selected for each of the 8 categories. The 8 selected category indicators were in turn compared based on the number and severity of reports, trends and coverage of the failure modes within the respective category.

Based on this the key condition indicators are found to be the indicators within the categories *communication, hydraulics, sensors, downhole gauges* and *multiphase meter*. The hydraulics-indicator is a system indicator aimed at detecting leaks. The other four indicators are well specific and are all aimed at detecting the failure modes *no signal* and *out of range signal* for the equipment within the respective categories.

Acknowledgments

I would like to express my gratitude to Statoil for providing me with the opportunity to write this thesis. Through the work with the thesis, I have learned a great deal about Statoil's subsea operations, the Gullfaks Satellites and the subsea equipment.

I would like to thank the engineers in the subsea operations department in Bergen for their contribution, especially my company supervisor Christian M. Rotter. Additionally I would like to thank Hanne Ravneberg for providing me with input data for the analysis conducted as part of the thesis.

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Stavanger, June 15th

Lars M. Hosaas

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Acronyms and abbreviations

AMV – Annulus Master Valve

AWV – Annulus Wing Valve

BV – Branch Valve

CCR – Central Control Room

CP – Choke position

DHPT – Down Hole Pressure and Temperature (sensor)

FCM – Flow Control Module

GFC – Gullfaks C

GFCSAT – Gullfaks Satellites tied back to Gullfaks C

GFSAT – Gullfaks Satellites

HIPPS – High-Integrity Pressure Protection System

HOST – Hinge Over Subsea Template

HPU - Hydraulic Power Unit

HTP – Hydraulic Test Panel

IMR – Inspection, Maintenance and Repair

IOR- Increased oil recovery

ISEM – Subsea electronics module for downhole equipment

KPI – Key Performance Indicator

LAN – Local area network

MEG – Monoethylene glycol

MFM – Multiphase flow meter

MV – Manifold Valve

MQC – Multi Quick Connect Plates alt. Multi Quick Connector

NCS – Norwegian Continental Shelf

OPEX – Operational Expense

OS - Operator Station

PDO – Plan for Development and Operations

PE – Production Efficiency

PGB – Permanent Guide Base (for installing conductor)

PMV – Production Master Valve

PT – Pressure Transmitter/Pressure Transducer

PWV – Production Wing Valve

ROV – Remote Operated Vehicle

SCM - Subsea Control Module

SCSSV – Surface Controlled Subsurface Safety Valve

SCU – Subsea Control Unit

SEM - Subsea Electronic Module

SPCU – Subsea Power and Communication Unit

SRI – Skinfaks and Rimfaks Increased oil recovery

TH – Tubing Hanger

TT – Temperature Transmitter/Temperature Transducer

UPS – Uninterruptable power supply units

WOV – Workover Valve

XOV – Crossover Valve

XT - Christmas Tree

NORSOK Terminology (Norwegian Technology Centre, 2001):

Failure - termination of the ability of an item to perform a required function

Failure mechanism - physical, chemical or other processes which lead or have led to failure

Failure mode – effect by which a failure is observed on the failed item.

Failure rate – number of failures of an item in a given time interval divided by the time interval

1. Introduction

The petroleum industry has continuously developed new technologies to develop new fields. This development has led the industry from land into shallow water and further into deeper and deeper water. An important enabling factor for this development has been subsea technology. It started with simple X-mas Tree (XT) systems and is now developing towards subsea plants with processing and compression. Today more than 30 years after the first subsea XTs were installed about 800 subsea XTs are installed on the Norwegian continental shelf alone (DNV GL, 2014). The systems currently in operation represent many generations of development. This is particularly evident in the control systems. Where the older XTs have only the most vital sensors, the new systems have a large number of sensors for conditional monitoring (DNV GL, 2014). An important part of this development is software solutions for monitoring all parameters important for monitoring the condition. While the development in conditional monitoring is moving towards monitoring details such as the power consumption of solenoid valves there is a shortage of mid-level systems that can monitor key condition parameters for a large number of wells (Rotter, 2014).

To meet this demand, Statoil is looking into developing a mid-level software program for conditional monitoring and operational management (Rotter, 2014). As a step in this process, this thesis aims to identify key condition indicators for such a program for the Statoil operated Gullfaks Satellites tied back to Gullfaks C.

1.1. Scope and objective

The objective of this thesis is to develop key condition indicators for the Gullfaks Satellite wells tied back to Gullfaks C. These indicators may be included in a prototype of a mid-level conditional monitoring and operational management program for Statoil.

1.2. Limitations

The indicators are to be developed for the L, M and N-template of the Gullfaks Satellite fields. These templates are tied back to Gullfaks C and will hereafter be referred to as "GFCSAT". The thesis is limited to considering these wells with associated systems.

The objective is limited to consider indicators that can be developed with the sensors and systems currently in place, i.e. only sensor signals available from onshore computers. Therefore, it is not considered part of the scope to suggest changes such as adding sensors, improvements to the control system or the signal infrastructure. It is therefore a requirement that the indicators are based on sensor signals that are currently available from excel on onshore Statoil computers.

1.3. Methodology

The purpose of this section is to show the method used in this thesis for development of key condition indicators for the GFCSAT subsea production system.

The methodology used in this thesis consist of the following steps:

- Establish goals
- Acquire available relevant data for achieving each goal
- Analyze and systemize the data
- Combine the data and divide into categories based on common features
- Identify common and critical failure modes that need to be detached
- Review external sources to verify the analyzed data
- Find the indicator that has the best coverage of failure modes within each category
- Select the key indicators that provide the best overall condition monitoring

By applying these steps, the final few key condition indicators shall cover the most important parameters for mid-level conditional monitoring.

1.4. Structure of the report

The report is structured as follows:

Chapter 1 contains the introduction of the thesis with scope and objective. The objective and the rational behind it are demonstrated. The chapter also contains a brief explanation of the methodology used for reaching the objective.

Chapter 2 presents the organization Statoil and the Gullfaks Satellite wells tied back to Gullfaks C. The chapter further contains a detailed description of the most relevant equipment which the indicators are to be developed for.

Next, Chapter 3 presents the goals and objectives that currently applies to the subsea production systems. These are reviewed in order to establish goals to be achieved by the indicators.

In Chapter 4, an analysis of incident reports, malfunction reports and PE-loss reports are reviewed in order to find common failure modes.

In chapter 5, the failure modes are developed into key condition indicators, that in turn are tested based on indication rate of failure modes.

Chapter 6 contains the discussion of the work performed and results achieved.

Chapter 7 contains the conclusion of the thesis.

2. Field and equipment description

This chapter presents the relevant background information for the thesis, including Gullfaks Satellite fields, the organization operating it, and the installed equipment and control systems it consists of. The presentation will focus on the wells tied back to Gullfaks C, referred to as GFCSAT. An overview of GFCSAT is given in figure 1.

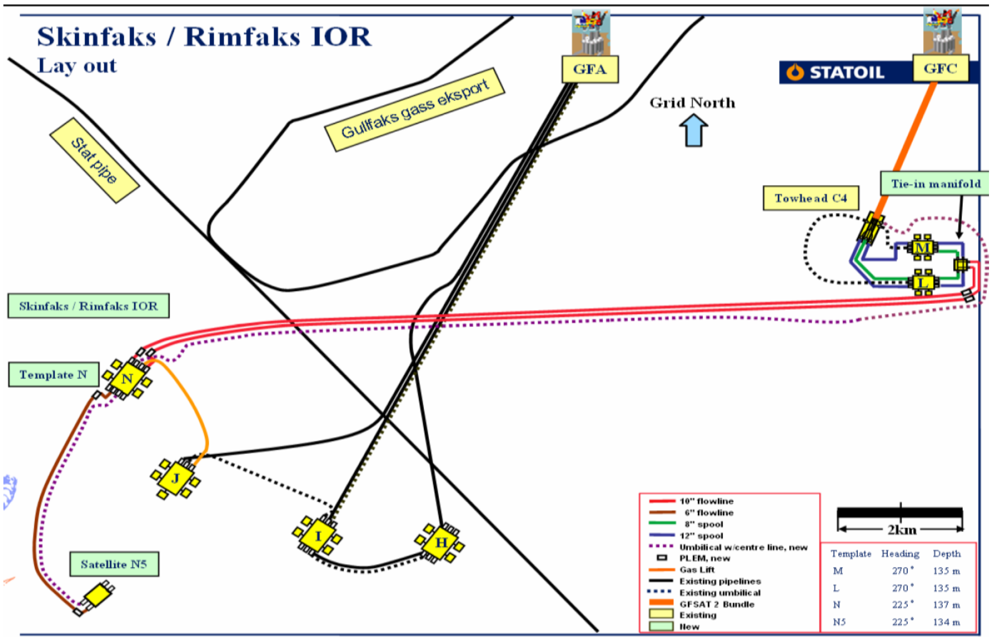

Figure 1: Overview of GFCSAT (FMC Technologies, 2008).

2.1. Field description

The satellite fields Gullfaks South, Skinfaks, Rimfaks and Gullveig in block 34/10 and 33/10 have been developed with subsea solutions. These fields, known as the Gullfaks Satelittes, are all tied back to Gullfaks A or Gullfaks C on the Gullfaks main field (Statoil, 2015A) (Statoil, 2015B).

The first phase of the development, Gullfaks Satellites phase 1, covers the installation of 8 subsea templates (template D-K). The first well delivered by this project came on stream in 1998. It was followed by the second phase, Gullfaks Satellites phase 2, covering installation of 2 templates (template L and M) tied back to Gullfaks C. Production from these wells started in 2001 (Knudsen, Tor W.; Sølvik, Nils A., 2011).

The last of the development projects is the Skinfaks/Rimfaks Increased oil Recovery Project (SRI). This project was an extension of the Gullfaks Satellites phase 2 project and installed one tie-in manifold, one additional template (template N) and a satellite well (N5) (Knudsen, Tor W.; Sølvik, Nils A., 2011). The first SRI-well came on stream in 2007 (Statoil, 2015C).

Two new development projects for Gullfaks Satellites are ongoing, one for installation of a subsea wet gas compressor and one for two additional templates (Knudsen, Tor W.; Sølvik, Nils A., 2011) (Norwegian Petroleum, 2015).

2.2. Organization

The operator of the Gullfaks field and the GFCSAT-templates is the international energy company Statoil (Statoil, 2015A). Statoil has approximately 23 000 employees and operates in 36 countries. The company's headquarters and majority of operations is located in Norway, where the company currently operates 48 fields (Statoil, 2015D). Statoil has a complex organizational structure that is divided into multiple levels. The main department of interest in this thesis is the subsea operations department "Asset Bergen" that is responsible for the technical integrity and availability of the GFCSAT subsea production system (Statoil, 2015E). This department is part of the Subsea division. The operation of the GFCSAT also involves several other departments, of which the well integrity department, IMR department, the production technology department and the Gullfaks C organization both onshore and offshore are of most importance (Rotter, 2014). In the following section, a brief presentation of these departments will be given, focusing on tasks that are of importance for GFCSAT and the interface with the subsea operations department.

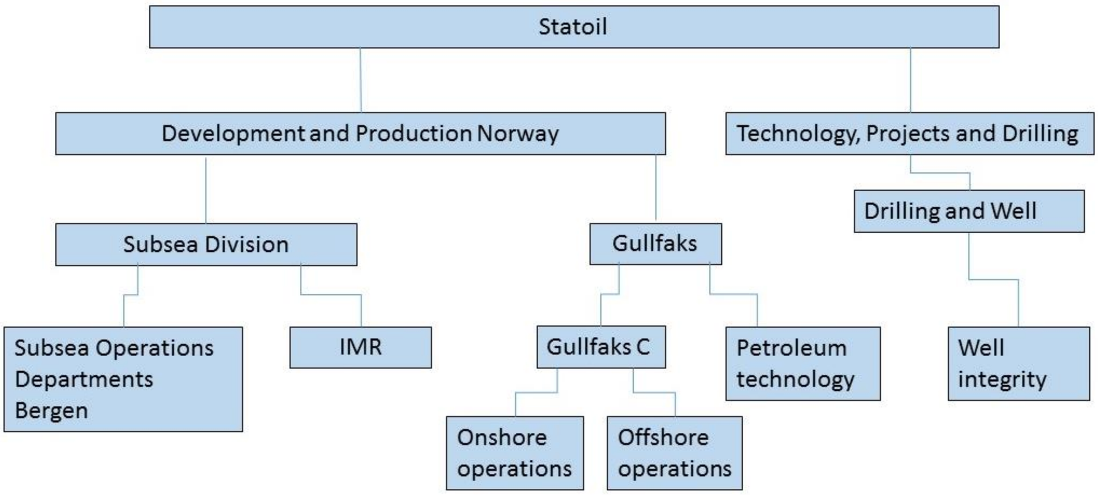

Figure 2: Simplified organizational chart, based on Statoil (2015E).

Subsea operations department

The subsea operations department is responsible for the technical integrity and availability of the subsea production systems on GFCSAT. As a part of this responsibility, the department provides operational and technical support. All maintenance activities on the subsea systems both preventive and corrective are initiated and followed up by the department (Statoil, 2015E).

Well integrity department

The well integrity department is responsible for the technical integrity of the well, including the XT. This department provides operational and technical support (Statoil, 2015F), much like the subsea department.

Inspection, maintenance and repair department

The inspection, maintenance and repair department (IMR) is responsible for conducting all interventions on the subsea production system, with the exception of well related interventions. This department is part of the subsea division. In most cases the subsea operations department will initiate the intervention and the IMR-department will physically perform the operation. (Statoil, 2015E)

Petroleum technology department

The petroleum technology department's responsibilities are reservoir and well management. The department covers the disciplines geology, reservoir technology and production technology. Its main responsibility is to manage the reservoir efficiently, in order to ensure that as much as possible of the resources in place are produced. (Statoil, 2015E)

Offshore organization

Gullfaks C has an offshore organization that carries out the day-to-day operations of the installation, including all satellite wells. The operation of the satellite wells is primarily conducted by the central control room (CCR) operators. (Statoil, 2011)

Operations group

There is an operations group for each installation. This group is the main point of contact, whose main tasks are to plan, prepare and facilitate operations conducted on or for the installation. (Statoil, 2015E)

2.3. The Gullfaks subsea operational philosophy

The subsea production systems on GFCSAT have a design lifespan of 20 years. For operations within the defined lifespan the philosophy is primarily focused on operating the subsea production system in a cost efficient way that at the same time ensures integrity and production (Statoil, 2011). The philosophy covers the areas monitoring, inspection, maintenance and repair, which will be introduced in the following sections.

Monitoring

The control room operators on the host platform Gullfaks C conduct the daily operations and monitoring of the subsea facilities. To assist in operations, the control systems' predefined alarms are automatically activated if the sensor readings indicate abnormal values. There is also a system for automatic shutdown should the sensor readings indicate potentially dangerous situations like leaks or process values approaching the operational or design limits. (Statoil, 2011)

Inspection

The planned inspection activities for the GFCSAT subsea production system are conducted according to a plan that is to be prepared each year. The inspection is designed to uncover the general condition of the subsea production system with focus on detecting leaks, mechanical damages and assessing the condition of the anode protection systems. All damages are registered. The further measures taken depend on the seriousness of the condition, ranging from immediate action to further inspection for tracking development. In addition to the planned inspection activities, the subsea department can mobilize additional inspections should irregularities or abnormal situations call for it. (Statoil, 2011)

Maintenance

Some components have shorter lifespan than the 20 years, and faults and damages can occur. To best account for this, different maintenance activities are conducted for the different components. Preventive maintenance activities on the subsea production system is mainly limited to testing the integrity of the barriers, i.e. mostly testing of internal leak rate of valves. The corrective maintenance activities are divided into planned and unplanned corrective maintenance. The planned corrective maintenance relates to replacement of retrievable modules that contain components with a shorter lifespan than the system design life of 20 years. (Statoil, 2011)

Examples of such components are the choke valve and the subsea electronics modules. For the choke valves, it is important to know the condition in order to plan a replacement of the FCM-module before the choke valve is worn out. For the SEM, redundancy ensure that production can continue even if one unit fails. There are usually large variations in time from one failure to the next. These two factors make planned maintenance in defined time intervals less economically than planned corrective maintenance. If failures occur in other components than the ones pre-defined to be replaced or fixed according to the planned corrective maintenance program, this is defined as unplanned corrective maintenance. For the planned maintenance condition monitoring, redundancy and replacement modules should ensure continuous production until replacement could be conducted. For unplanned corrective maintenance this may not be the case. (Statoil, 2011)

Repair

All interventions, including inspections, are conducted by the IMR department and are preferably conducted as planned campaigns. The planned campaigns are typically initiated when there is a sufficient number of needed repairs and replacements of the planned corrective maintenance type. The planned campaigns help minimize the time spent and costs related to maintenance. They are also preferably conducted simultaneously with other production reducing activities topside, such as turnaround or compressor maintenance, to reduce lost production.

If immediate repair is needed the IMR department has to prioritize the intervention up against other interventions. If the repair is not HSE-related it will normally be prioritized by which intervention gives or saves the most production. (Statoil, 2011)

There will also be some interventions where a needed immediate repair initiates a campaign, and other planned repair, replacements or inspections are conducted by the same vessel when it is on site (Rotter, 2014).

2.4. Equipment

The templates installed in Gullfaks satellites projects phase 1, 2 and the SRI project are all based on the FMC hinge-over template solution (HOST) (Knudsen, Tor W.; Sølvik, Nils A., 2011). There are few differences between the equipment installed in GFSAT 1 and 2 (Knudsen, Tor W., 1999). For the SRI-project the difference is more extensive. In this presentation, the GFSAT 2-consept is described and the differences to the SRI project are described where it is of importance.

The basic concept for HOST-templates was to minimize foundation of the template by folding in wing element to allow for installation through the moonpool of a drilling rig. The rough weather and seabed conditions proved the initial installation method to be difficult and time consuming. The concept was therefore changed to larger foundations installed by vessel in the GFSAT 2 and SRI projects. (Knudsen, Tor W., 1999) (FMC Technologies B, 2006)

The HOST-configuration used L and M templates have four wing elements for well slots, two and two on opposing sides and triple porches for two flowline and one umbilical connection elements on to two other sides, as shown on figure 2. This configuration allow for a daisy-chain configuration of the templates. The N-template is similar but with an additional flowline connection on both sides. (FMC Technologies B, 2006)

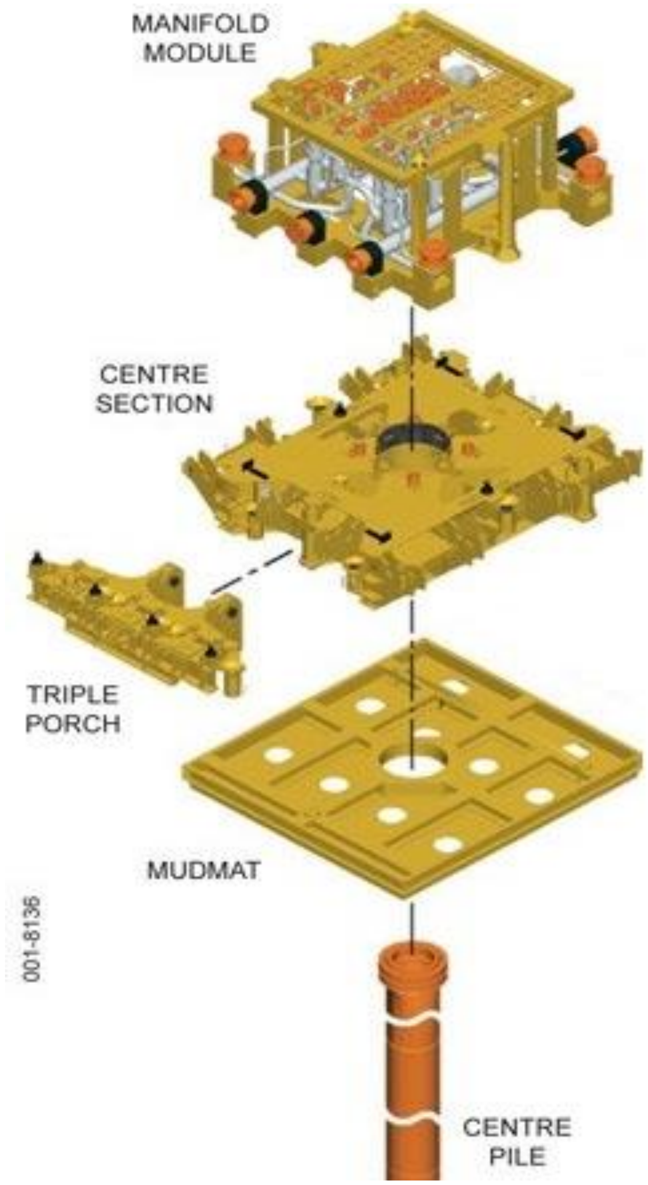

Figure 3: Manifold module with foundation, retrieved from (FMC Technologies B, 2006, s. 15).

2.4.1. Manifold module

The central element of the template is the manifold module, placed on top of the center section, shown in figure 3. The main function is to provide a connection from the flow control module (FCM) for each individual well to one or more manifolds for commingling the different wellflows and connecting it to the seabed flowlines. The manifold modules on the L and M-templates have connections for four wells and two flowlines. The M-template also holds a HIPPS-module, to protect the manifold from initial high well pressure in the M-2 well (FMC Kongsberg Subsea, 2001A). As there is no longer need for the system it as be permanently taken out of operation (Rotter, 2014).

On the N-template the center hub was enlarged to accommodate the complex manifold module. The module holds two production headers, one gas lift header and connection for the satellite well. To provide connections for all the headers the N-template has quadruple porches (FMC Technologies B, 2006).

Another important function of the manifold module is to connect the utility lines, electric- and signal cables in the umbilical to the individual wells. The module holds manifolds for distribution of chemical, hydraulics and service lines (annulus bleed) to the FCM of each well. The lines are connected to the FCM through the same connector that connects the wellflow. Electrical and signal cables are connected to each well though jumpers. (FMC Technologies B, 2006)

2.4.2. Protective structure

A protective structure is placed directly on top of the template to protect the equipment from dropped objects and fishing gear. The roof of the protective structure is made of several hatches allowing operations that require access to the template equipment and at the same time providing maximum protection for the rest of the equipment. The structure should also allow for ROV inspection and operations without opening the roof hatches. (FMC Kongsberg Subsea, 2001B)

2.4.3. Tubing hanger and X-mas tree

The GFCSAT well uses 18 ¾" wellhead connected to horizontal X-mas tree (FMC Kongsberg Subsea, 2001A). Inside the XT 7" tubing and tubing hanger are installed. The tubing hanger has side connection to the production bore of the XT and wireline retrievable plugs act as barriers in the top section. The tubing hanger also holds several electrical and hydraulic connections for downhole equipment, such as the surface controlled subsurface safety valve (SCSSV) and down hole pressure and temperature gauges (DHPT). Since there were plans early on for intelligent completions the tubing hanger in all GFCSAT-wells have additional connections for intelligent completion. (Knudsen, Tor W., 1999) (FMC Technologies B, 2006)

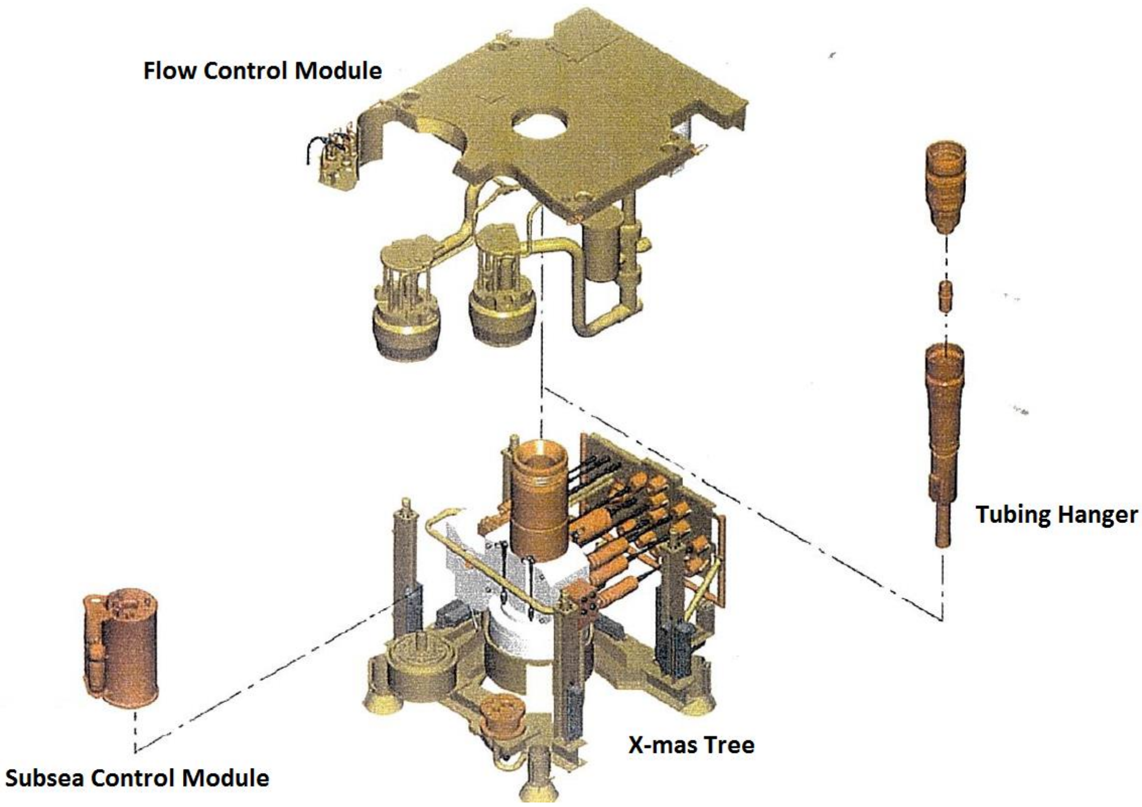

Figure 4: FCM, SCM, Horizontal XT, and Tubing Hanger. Retrieved from (Statoil, 2001)

In the tubing hanger the production fluid is diverted 90 degrees into the production bore of the XT. The production bore has two 5 1/8" gate valves, the production master and wing valves that make up the barriers. Between the two valves there are ports with associated valves for injection of MEG, scale inhibitor, wax inhibitor in addition to a crossover line connection to the annulus bleed system. On the opposite side there is an annulus bore with an annulus master valve for connection to the production annulus, and a workover valve for connection to the sealed compartment above the tree cap. These two bores connect to the crossover line upsteam of the annulus wing valve that again connects to the annulus bleed system (FMC Technologies B, 2006). As the name implies the primary function of the system is to bleed down excess pressure in the annulus, but the system is also used for service and maintenance operations (Rotter, 2014).

The XT is made of three valve blocks, where the tubing hanger is positioned inside the main central block. This block also contains the workover valve, production master valve and annulus master valves. On opposing sides the production and annulus wing blocks are bolted on. The annulus wing block contains the annulus wing valve and dual pressure transmitters. The production wing block contains the production wing valve, temperature and pressure transmitters in addition to all other valves for chemical injection and crossover lines. All lines are connected to the XT wing hub that in turn connects to the manifold module via the flow control module. (FMC Kongsberg Subsea, 2001A)

The XT's used in the SRI-project are somewhat different. The most significant differences are caused by the gas lift system that uses the production annulus. The annulus wing block has an additional 2" connection with associated valves and flowloop for connection to the gas lift system via the XT-wing hub. (FMC Technologies, 2008)

The XT has several connection points. The XT wing hub connect all fluid lines from the production line to the hydraulics to the flow control module. The subsea control module (SCM) mounting base provide connection to the SCM that controls and monitors all XT and FCM functions. All valves also have the possibility for ROV override from the side mounted ROV panel. The MQC plate is an integrated part of the ROV-panel, this is used for ROV-operations during installation or retrieval of the XT. (FMC Technologies B, 2006) (FMC Kongsberg Subsea, 2001B)

All the XT components are fitted within a rigid frame structure for protection. The frame holds four guide funnels, four pillars and anodes. The guide funnels used for guiding the XT in place on top of the PGB during installation. The four pillars are used to support and lock the FCM in place. (FMC Technologies B, 2006)

2.4.4. Flow Control Module

The FCM connects the XT-wing hub to a similar manifold wing hub on the manifold module. Two 12" downward facing connectors that lock on to the wing hubs provide the connections. The FCM has a 6" flowloop for controlling and measuring the wellsteam passing through. Within the flowloop is a hydraulically-operated choke valve, temperature and pressure transmitters both up- and downstream, and sand detectors. The choke valve can be mechanically operated from the side mounted ROV-panel. The FCM equipment is mounted to a protective frame that forms a protective roof over the XT (Knudsen, Tor W., 1999). Mounted to the roof structure is a hydrocarbon leak detector for detecting leaks from the XT. The FCM can be installed and retrieved as a part of the XT or independently by a FCM running tool. The SCM on the XT controls the choke through hydraulic lines incorporated in the XT-connector. Choke position and sensor signals are connected to the SCM via ROV-operated electrical conductive connectors. (FMC Kongsberg Subsea, 2001A)

The FCMs on the SRI project are similar but with more equipment. The most significant differences are a multiphase flow meter for measuring the wellstream and a 2”flowloop with choke and instrumentation for controlling the gas lift. (FMC Technologies, 2008)

2.5. Production control system

The production control system as a topside and a subsea part as illustrated in figure 5. This illustration and the following text in this chapter is based on the L and M-templates. There are certain differences to the N-template, but these are not of significant importance for this thesis and are therefore not described in detail.

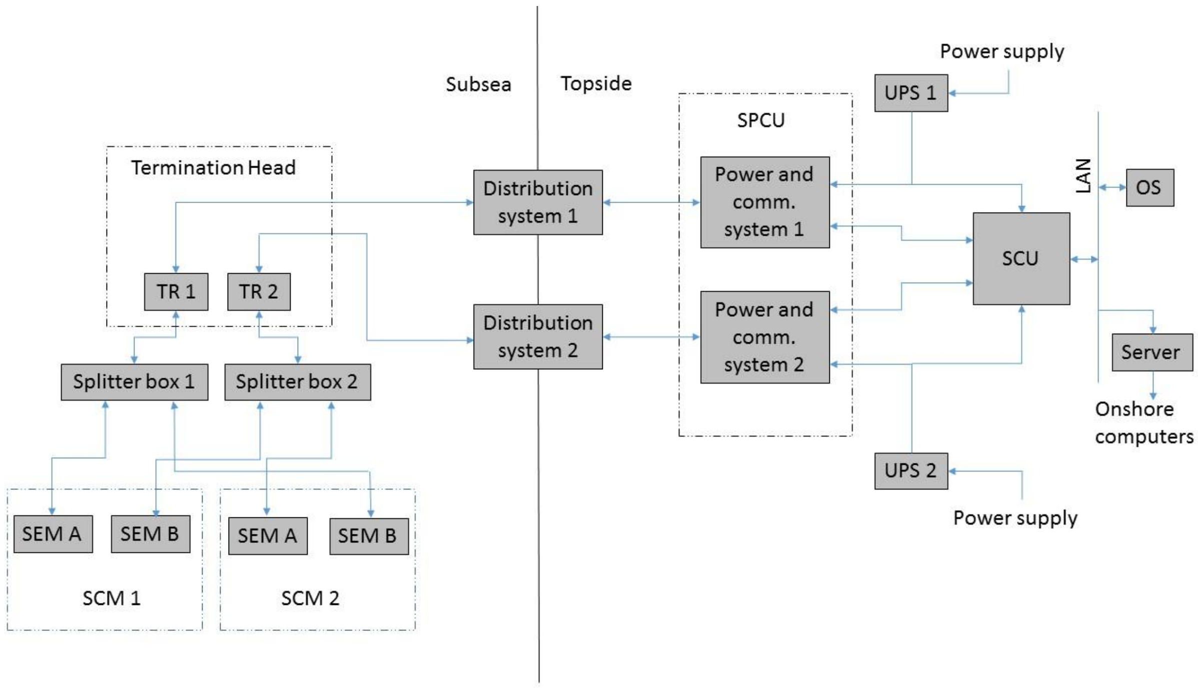

Figure 5: Simplified overview of control system based on (Statoil, 2001).

The signals from the SCU are also available for onshore computers. These signals are accessed by excel for development of the indicators.

2.5.1. Top side equipment

The major parts of the topside production control system are the Subsea Control Unit (SCU), Subsea Power and Communication Unit (SPCU), Uninterruptable power supply units (UPS), Hydraulic Power Unit (HPU) and the Hydraulic Test Panel (HTP). (FMC Kongsberg Subsea, 2001A)

The SCU is a single cabinet containing a computer system that monitors and controls the other parts of the production control system. The SCU also interfaces with the OS in the CCR and with the process and emergency shutdown systems. Sensor signals are collected in the SCU for monitoring the operational state of all the related systems both topside and subsea. The data is relayed to the OS that displays the system status to the operator. If any action is needed the commands are sent from the OS via the SCU to the correct component. (FMC Kongsberg Subsea, 2001A)

Signals from the SCU to all the SCMs and back, are sent via the SPCU. The SPCU is a cabinet containing dual electric power systems, filters and modems. The two identical power systems both have sufficient capacity to supply power to all the SCMs via the umbilicals. The filters and modems enable transmitting the signals to the SCMs via the same cables that supply the electrical power. (FMC Kongsberg Subsea, 2001A)

The electric power for the SPCU is supplied from the platforms system via dual UPS units to ensure uninterrupted supply for at least 30 minutes after platform supply fails. (FMC Kongsberg Subsea, 2001A)

The hydraulic power for the subsea facilities are generated in a HPU topside and distributed by umbilicals. The HPU is composed of reservoirs, pumps and accumulators capable of providing a continuous supply of high-pressure (HP) and low-pressure (LP) hydraulics. One line of HP and one of LP hydraulics are supplied to each of the two hydraulic test panels. (FMC Kongsberg Subsea, 2001A)

The hydraulic test panels provide connection and testing facilities for all hydraulic and most of the utility lines in the umbilicals. The utility lines are; MEG, scale inhibitor, wax inhibitor, emulsion breaker supply, and the annulus bleed lines. Each of the two test panels supplies one of the two umbilicals. (FMC Kongsberg Subsea, 2001A)

2.5.2. Subsea Control Module

The main component subsea is the electro-hydraulic subsea control module (SCM) that is connected to the SCM mounting base on each XT. The topside production control system communicates with the SCM through electrical cables in the umbilical. Commands for operation of all valves from the SCSSV to the branch valves on the manifold module are processed and effectuated by the control and hydraulics system in the SCM (FMC Technologies B, 2006). Similarly, all sensor signals are collected and sent back to the topside production control system. (Knudsen, Tor W., 1999)

Seen from the outside the SCM consists of a protective canister with a hydraulic accumulator and a hydraulic compensator mounted to the side. The bottom of the canister has 3 wire conductive connectors and a total of 27 hydraulic couplers connecting to the SCM mounting base. The top has an additional 5 wire conductive ROV connectors. The SCM also holds locking mechanisms for locking or unlocking it from the mounting base. Should any failure occur the SCM can be retrieved and reinstalled by ROV and a Module Running Tool. (FMC Technologies, 2007)

All the finer electric and hydraulic equipment are mounted inside the pressure compensated and silicon-oil filled canister. Electrical power supply and communication is provided by two electric cables connected to the top connectors. Each cable is independent of the other and connected to an independent power supply, modem and subsea electronic module (SEM) (FMC Technologies, 2007). The commands processed in the SEMs are effectuated by two valve solenoids that in turn control one hydraulic directional valve that supplies a valve actuator on the XT, FCM or manifold module with hydraulic power. The system is made with dual components that make up two independent systems from cable via SEM to solenoid. Only one system can be active at the time. (FMC Kongsberg Subsea, 2001B)

The hydraulic system is divided into a HP- and a LP part. Both parts have two independent supply lines with individual filter elements, and a directional valve to connect one of them to the supply manifold. The LP-supply manifold supplies 14 different valve actuators, while the HP-manifold only supplies the SCSSV and two lines for other downhole functions, if installed. To ensure a sufficient supply without large pressure changes an accumulator is connected to each of the supply manifolds. (FMC Technologies, 2007)

The return hydraulic fluid is collected in a HP and a LP return manifold and expelled into the sea through check valves. A compensator is installed on the LP-return line to prevent possible vacuum during bleed down. (FMC Technologies, 2007)

3. Goals and objectives

In this chapter, established national and company specific requirements and strategies are reviewed in order to establish the goals for the development of indicators.

How the operator of a subsea field chooses to operate varies from field to field. The operator or partnership usually have a set of goals that govern the operation. Some overall goals are common to most operators and easily comprehensible, for example to limit or minimize cost and maximize production. Other goals may also be present and the set of goals can change over time. These goals are relayed to more specific goals and objectives for each of the divisions and departments involved in the operations.

The location of the subsea field can influence the operations. Different countries have different laws and regulations for the petroleum activity. The influence is usually largest in the exploration and development phase but it also affects the production phase (The Norwegian Petroleum Act, 2011). It can safely be assumed that formal requirements in laws, regulation and standards are covered by the monitoring systems already in place. Therefore, only goals and objectives are considered in the development of indicators.

The goals and objectives that govern the operation form the foundation for the operational philosophy for the subsea field. However, the operations are also affected by several other factors such as the decisions of the partnership of the licenses, the supply agreements, the host platform or facility, the water depth and environmental factors. There are many examples where the supply agreements govern the whole operation. One example is the Tamar field offshore Israel that supplies power plants that supply large part of the country's electricity. Only short production stops can cause serious problems. Fields of this type may have a need for very high reliability and can allow a higher cost to ensure this (Healy et al., 2013).

The Gullfaks field is a classical oil field located in the northern North Sea on the NCS. The operations of this field is governed by the Norwegian legislation, the strategic goals of the operator Statoil, the goals and ambitions of the involved divisions and departments in Statoil, and the Gullfaks Subsea operational philosophy. The objective of this thesis is to develop indicators for a subsea management program for condition monitoring and operational management for the GFCSAT subsea production system. These indicators must be based on the same legislation, goals, ambitions and philosophy as GFCSAT. In this chapter the legislation, goals, ambitions and philosophy is reviewed in order to select these goals.

3.1. Norwegian legislation, country level

The GFCSAT is located on the NCS, making Norwegian legislation and resource management applicable. Norwegian legislation has a large number of laws, decrees and regulations that govern the petroleum activities. “ACT 29 November 1996 No.72 relation to petroleum activities” known as the petroleum law is perhaps the most important. It covers several topics such as licenses, approval of the plan for development and operations (PDO), liability and governmental oversight. Chapter 4, covering production section 4.1, starts with “Production of petroleum shall take place in such a manner that as much as possible of the petroleum in place in each individual petroleum deposit, or in several deposits in combination, will be produced” (The Norwegian Petroleum Act, 2011). This quotation outlines the primary goal for production. Perhaps the most important regulation concerning health, safety and environment is the regulation known as “The framework regulation”. This regulation’s first section contains the purpose of the regulation, which is to “*promote high standards for health, safety and the environment in activities covered by these regulations*” and to “*achieve systematic implementation of measures to comply with requirements and achieve the goals laid down in the working environment and safety legislation*” (Petroleum Safety Authority Norway, 2015). This quote is outlining primary goals such as minimizing environmental impact and keeping a high safety level.

In addition to laws and regulations, a number of standards also apply to the GFCSAT subsea production systems. For NCS the NORSOK and ISO standards are the most important ones. These standards primarily cover design requirements but also some requirements that relate to operations. By the assumption that other systems adhere to the formal requirements, the important parts for this thesis are the intentions and objectives of the standards. The NORSOK-standards objectives are described in the first sentence of the foreword of all NORSOK-standards; “The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations” (Norwegian Technology Centre, 2002).

To sum up, the goals and objectives found in the legislation and standards promote operations that maximize production with high standards within health, safety and environment.

3.2. Statoil's strategic goals

Statoil is the operator of the GFCSAT and as a result of that the operations are governed by the strategic goals, procedures and philosophy of Statoil. The company's strategic goals, values and policies are described in the publically available document named «The Statoil Book».

Statoil's strategic goals laid down in "The Statoil book" can be summed up by quoting parts of the introduction greetings by the former president and CEO Helge Lund "At Statoil, the way we deliver is as important as what we deliver. Safe, secure and efficient operations are our top priority. Together, we create value for our owners with integrity" (Statoil, 2013). The strategic goals in "The Statoil Book" are further relayed into more specific goals and objectives for the individual divisions and departments, as described for the subsea division in the next subchapter.

"The Statoil Book" also describes how the company works to achieve its goals and objectives. The company's strategic goals are relayed and developed into more specific goals that are measured by key performance indicators (KPIs). This is done at several levels in the organization and down to each department.

3.3. Subsea division and department goals and ambitions

The subsea division in Norway has specified the division's goals and objectives in a document named "Ambitions towards 2016". The goals relevant for subsea operations are listed in figure 6.

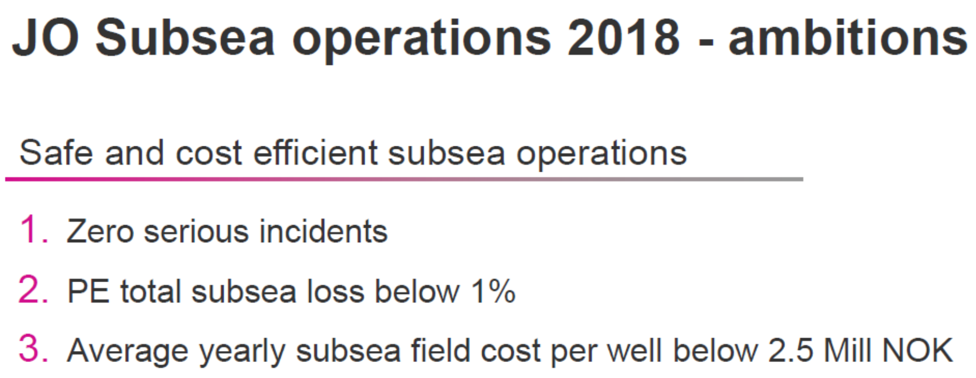

Figure 6: The subsea division's ambitions towards 2016 (Statoil, 2015G)

The subsea operations at the GFCSAT is managed by the subsea operations department in Bergen. This department's strategic objectives and KPIs are therefore most relevant for GFCSAT. The strategic objectives and KPIs appear on an internal web page with corresponding indicators showing the latest development, as illustrated in table 1. Only the strategic objectives and KPIs that are relevant for the operations are listed in table 1 retrieved from (Statoil, 2015H).

Strategic objectives	KPI
No harm to people the environment and assets.	Serious HSE incidents:
Ensure technical integrity and barriers for Subsea fields.	Number of serious spills:
Reliable subsea facilities.	PE loss contribution:

Table 1: The table is an illustration of how the strategic objectives and key performance indicators of the subsea operations department appear on the internal web page. The arrows to the right side should indicate the latest development of the KPIs, the arrows

3.4. Goals and objectives for developing indicators

The objective of this thesis is to develop indicators for a subsea management program that should help the subsea operations department in condition monitoring and operational management. To develop these indicators, they must be based on the same goals that govern the operations and subsea operations department. For the subsea operations department managing the GFCSAT production system there are several set of goals as shown in the previous parts of this chapter. Using multiple levels of goals would complicate the development. To simplify only one goal within each of the areas safety, production and cost are used to develop indicators. These three areas reflect the areas the subsea division uses for their ambitions, shown in figure 6.

For health, safety and environment, there are goals on each level; from legislation that has the purpose to "promote high standards for health, safety and environment…" to the subsea operations department's strategic goals "No harm to people, the environment and asset". All the goals can be shortened to the ambition of minimizing the number of accidents, and thereby high safety levels and minimized environmental impact. For a subsea production system, there are few scenarios where a serious accident does not involve leaks. To achieve no leaks integrity is the key, as the subsea divisions goal "Ensure technical integrity on subsea facilities" emphasize. To cover the ambitions in the goals in all levels and to emphasize the most likely scenarios the goal "no serious incidents, including leaks" have been chose to cover the HSE area. This goal is well suited to cover the subsea departments two HSE related KPI's, "serious HSE-incidents" and "number of serious spills".

For an oilfield in operation the important cost is the operational expense or OPEX. OPEX is all costs related to production and maintenance operations. Simple economic theory indicates that when the OPEX-costs exceed the income the field is decommissioned. This illustrates the importance of limiting or minimizing OPEX-costs, especially for mature oilfields. In the legislation and Statoil's strategic goals listed previously in this chapter, only formulations like "value added", "creating value" and "cost effectiveness" are mentioned. The subsea division has the very specific ambition "Yearly OPEX cost pr. subsea well below 2,5 million NOK". To keep the goals simple the goal "minimize OPEX-cost" is selected in the cost area.

For the production area the "petroleum law" states that the goal is simply to produce as much as possible of the resources that are in place. This is an overall goal that depends on several different disciplines and factors. In the daily operations ensuring high production efficiency (shortened to "PE") is the most important goal for ensuring this. For the subsea department PE is primarily about minimizing subsea related PE-losses. This is emphasized in both the subsea divisions ambition “PE total subsea losses below 1%” and the subsea operation department KPI “PE loss contribution”. To summarize the goals in the production area the goal “minimize subsea related PE-losses” is chosen as one of the goals.

To summarize, the indicators will be governed by the following three goals:

- No serious incidents, including leaks
- Minimize OPEX-cost
- Minimize subsea related PE-losses

These three goals are to govern the development of the indicators. These goals should reflect the subsea operations’ goals, and therefore indicators developed according to these goals should be well suited to help the subsea operations department achieve their goals.

4. Analysis

In the previous chapter the goals that make the foundation for the indicators to be developed, were reviewed. The following three goals were selected as pillars for these indicators:

- No serious incidents, including leaks
- Minimize OPEX-cost
- Minimize subsea related PE-losses

To achieve these three goals a thorough analysis of data for each goal has to be conducted. The purpose of the analysis is to find the most common and critical failures that cause HSE-incidents, avoidable OPEX-costs and PE-losses in order to find the failure modes that need to be indicated to detect these failures. In order to find critical failure modes and failure mechanisms, historical records for the GFCSAT subsea production system have been analyzed. For more details about the initial systematization and analyzation process see Appendix A.

Production at the GFCSAT-wells started in 2001 and 2007, making the records date back 14 and 8 years respectively (Knudsen, Tor W.; Sølvik, Nils A., 2011). Since the subsea production systems have not been changed much the historical data should be a good prediction for future events (Rotter, 2014). Identifiable trends are analyzed to add predictive value. For example, some system weaknesses can have caused many problems in the early years and may be less relevant now, while other failure mechanisms may come as a result of wear and tear over the years and can be more relevant for predicting future events.

To complement the analysis of historical data external sources of similar information will be reviewed. This is a useful way to tell if the findings are similar to earlier studies and to find possible new or overlooked critical or common failures. If the findings in the other sources differ significantly from the GFCSAT-data the reason must be found. If a failure is significantly more common in the other similar production systems and no good reason for the difference can be found it can have implications for the choice of indicators. There is also a possibility that critical failures with low probability has not showed up in the GFCSAT-data. This may also have implications for the choice of indicators.

This chapter is divided into five sections. The three first sections are presentations of each of the three analyses and contain information about how and what information that is acquired.

The fourth section is a presentation of the combined results of the three analyses divided into categories. For each category, the key findings including the needed indicators are presented.

In the last section, the analyzed data is summarized and it is drawn conclusions about which categories that is applicable for development of indicators.

4.1. Health, safety and environment

To achieve the goal "*No serious incidents, including leaks*", data about historical accidents and HSE related incidents must be analyzed. Since the indicators to be developed are for monitoring the GFCSAT- wells in operation, only accidents and incidents related to the operations of subsea production systems are of interest. These rules out some of the more serious subsea related accidents like the Macondo accident, which was related to subsea well completion (BP, 2010). One internal and one external source of information have been used. The internal source of GFCSAT-data that has been analyzed is historical records of incidents. The external source used is the DNV-GL report "Subsea Facilities – Technology Developments, Incidents and Future Trends" that was made in 2014 on behalf of the Norwegian Petroleum Safety Authority (DNV GL, 2014).

4.1.1. GFCSAT HSE-data

The GFCSAT incident reports were retrieved from Synergi, Statoil's system for recording HSE related data. The purpose of the system is to monitor, improve and learn from passed incidents (Statoil, 2015I). For this analysis the search in Synergi has been narrowed down to HSE-related incidents and non-conformities reported in 2001-2014.

Statoil defines HSE incidents as "*HSE incidents are hazards or accidents that have resulted in, or could result in, harm to persons and the environment*" (Statoil, 2015J). Non-conformities are defined in Synergi as "*Incidents or situations that: 1. Do not constitute hazard or accident situations and have resulted in harm, loss or defect. 2. Constitute hazard or accident situations that have not resulted in, or could not have resulted in, harm to persons or the environment*" (Statoil, 2015I). Both HSE-incidents and non-conformities are part of the analysis and are referred to as Synergi-reports.

The search in the Synergi database has been limited by means of the location. All reports that have the location GFC Subsea have been reviewed in detail. All report headlines for the locations GFC, GFC unspecified, GFC C-05, GFC C-08, GFC M-11, GFC M-19 and GFC M-

19 have been review to find GFCSAT related reports. These cover the general locations, and the location of the key components on the subsea production system topside (Rotter, 2014). In addition to the above search, a spread sheet record from the subsea operations department of past incidents from 2001-2009, which contains references to the Synergi-system, has been reviewed. This search is not bulletproof and relevant reports that did not appear in this search are left out.

The Synergi search and spread sheet record resulted in a total of 76 Synergi-reports for the analysis. Of these 76 reports, 24 were deemed as irrelevant. These reports were discarded either due to duplicated reports or that the incidents were caused by human error, operational conditions, or other causes that are not relevant for developing indicators.

Most of the Synergi-reports are from the years 2001-2009 with only a few reports in the years 2010 – 2014. The primary reason for this was a change in the way all malfunctions including non-conformities are reported. In 2009 the subsea operations department started using the maintenance management system SAP to a larger extent. This led to strongly reduced reporting of non-conformities in Synergi (Rotter, 2014).

All Synergi reports are classified into 5 degrees of seriousness by Statoil, based on the actual consequence or the possible consequence under slightly different circumstances. The most serious degree relates to serious accidents like large spills, and the least serious degree is typically used for non-conformities that has led to or could have led to production losses (Statoil, 2015I). This is illustrated in table 2.

	Category	
Consequence	1	Sever
	2	Major
	3	Moderate
	4	Minor
	5	Insignificant

Table 2: Simplified figure of the consequence categories used for classifying the Synergi-reports. Statoil uses the color codes, but the wording is added in this thesis. The Statoil table also contains detailed information about the criteria for the classification (Statoil, 2015I).

By using this consequence classification, the Synergi reports are differentiated, giving a weighted result. A weighted result can to some extent emphasize the Synergi-reports that are most important for reaching the goal “No serious incidents, including leaks”. The method used is to give all incident-reports a score inversely proportional to the consequence category, i.e. a consequence category 1 (red) get a score of 5 and a category 5 (green) get a score of 1.

4.1.2. HSE-data from external sources

The external sources were recently reviewed by DNV-GL in the report “Subsea Facilities – Technology Developments, Incidents and Future Trends” that was made on behalf of the Norwegian Petroleum Safety Authority. This report has a chapter that covers incidents related to subsea facilities, with the main focus on leaks. In this chapter several sources of information regarding incidents in Norway, USA and UK are reviewed.

The first problem DNV-GL encountered was finding data that for a certainty is related to subsea production systems, the second problem was finding data that show the root cause for the incidents.

Of the relevant reports there were few reports that for a certainty could be related to subsea operations making the results less important for finding needed indicators. There were however some useful information about subsea related leaks and the most serious incidents in both Norway and UK. (DNV GL, 2014)

4.2. OPEX-cost

The second goal for developing indicators is «*minimize OPEX cost*». To reach this goal OPEX-costs must be examined to find possibilities for cost reductions. The allocation of OPEX-costs for the Gullfaks Satellites in 2011 is shown in figure 7. Although this figure includes more wells than just GFCSAT wells, the numbers should be representative (Rotter, 2014).

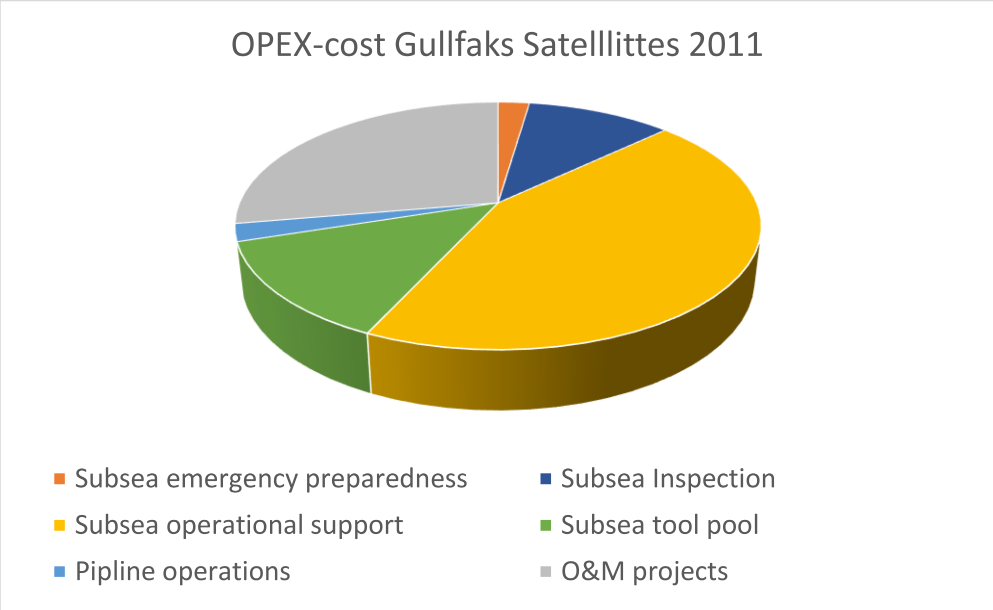

Figure 7: Distribution of OPEX-cost for Gullfaks subsea facilities in 2011. The cost is broken down according to the budget structure (Rotter, 2014).

The cost related to Subsea Inspection, Subsea emergency preparedness, Subsea tool pool and Pipeline operations are fixed costs. O&M projects is the cost of ongoing projects related to the operations of the Gullfaks Satellites, this is a non-fixed cost but it is not considered part of the scope of this thesis. Subsea operational support is the cost associated with daily operation and maintenance of the Gullfaks Satellites. About 70 % of this cost is related to maintenance, with the cost of intervention vessels and repair of modules as the two largest parts (Rotter, 2014). The remaining 30% cover all other support functions such as the subsea operations department. This distribution show that maintenance is the largest part of non fixed OPEX-costs for the Gullfaks Satellites. Based on this, the maintenance cost will be studied in detail in this thesis.

To minimize maintenance costs, past costs have to be analyzed in order to find areas where reductions can be made. Since the goal is to develop indicators for the subsea production system, this thesis aims to detect failures early and help keep track of existing failures in order to cut maintenance cost and thereby OPEX-cost. Doing this may contribute to efficient and economical maintenance management.

The primary sources of maintenance records to be analyzed are the records for the GFCSAT-production system. In addition to this, the OREDA database is used. This database has registered maintenance data from the GFCSAT production system and other similar systems (SINTEF, 2009).

4.2.1. GFCSAT maintenance data

Failures and malfunctions are reported in the maintenance management program SAP. These malfunction reports or M2 notifications are processed in daily meetings. If action is to be taken a work order is created from the notification. All activities related to fixing the malfunction should be recorded in the notification or work order. Work orders should amongst other things contain information about cost.

The search for relevant notifications in SAP was limited to notification on the tag numbers of the GFCSAT wells, the system tag and all tag numbers starting with the system number. Reports for the period 2001-2014 were used in the analysis. In addition the subsea operations department spread sheet record of past malfunctions from 2001-2009 was included.

The SAP and spread sheet record contains a total of 507 malfunction reports. All of these reports were analyzed. 258 malfunction reports were found to be irrelevant. The three primary reasons for the irrelevant reports were that the report did not contain a malfunction, duplicated reporting and minor topside malfunction. Only topside malfunctions that pose a risk to the subsea production system were used in the analysis of common and critical failures. This is in accordance with which malfunctions the subsea operations department is involved in today (Rotter, 2014).

The SAP records show that the offshore part of the operations has used SAP for recording malfunctions in M2 notifications since 2001. However, the subsea operations department onshore did not use SAP to full extent before 2010. Most of the malfunctions for the subsea production system for the years 2001-2009 are therefore retrieved from the spreadsheet record. The spreadsheet data is similar to the notification data, but less detailed. Differences in the SAP-records and the spreadsheet record makes it more difficult to find trends. The main function of the malfunction reports in SAP is to report malfunctions in order to create work orders for fixing the problem. The spreadsheet records were primarily made to keep track of ongoing tasks and for historical records (Rotter, 2014).

Classification of the malfunction reports in terms of severity or importance for reaching the goal “minimizing OPEX-cost” is not possible without multiple, and possible large sources of error. It is impossible to find the actual cost of repairing the reported failures. Costs can be found on SAP work orders created from the SAP malfunction reports. However, they do not necessarily contain all costs. A typical example is that the cost of an intervention for correcting multiple failures is not distributed on all the appropriate work orders. Another possibility for classification would be to use a priority classification assigned to all SAP malfunction reports. This classification is not assigned to say anything about costs, only about how critical it is to fix the malfunction. In addition to these sources of error the spread sheet records contain neither priority nor costs. Therefore the malfunction reports are not weighted and only the numbers count.

4.2.2. Maintenance data from external sources

An external source of maintenance data for both comparing data and for finding possible overlooked failure modes is the OREDA database. The data is collected from 8 worldwide companies including Statoil, and it is compiled and presented in a useful way. OREDA's main purpose is the collect and analyze data for improving reliability, availability, maintenance and safety. The data used in this thesis is collected in the period 1997 to 2003, and presented in the OREDA offshore reliability data handbook 5 edition, 2009. (SINTEF, 2009)

The OREDA data is divided into, and presented in equipment classes, subunits and components. Subsea equipment is divided into the 8 equipment classes *Control Systems, Flowlines, Manifolds, Pipelines, Risers, Running tools, Templates* and *Wellhead and X-mas tree*. The equipment classes *Running tools, Risers* and *Pipelines* are outside the scope of this thesis because they are not relevant for the daily operation of the GFCSAT.

Each equipment class is divided into equipment units. Control Systems are for example divided into *Control Systems X-mas tree* and *Control Systems Manifold*. This thesis does not separate between the equipment units, but use totals from each equipment class.

The equipment classes are further divided into subunits such as *Subsea control module*. For each subunit several different failure modes are listed and divided into 4 different severity classes. This data is later presented at a component level with the same listings of failure modes divided into severity classes. For each of these the number of units, number of failures, failure rate data and active repair time is listed, see table 3. For failure rate several numbers are listed, when referring to failure rate in this thesis the reference is to the n/τ rate (see table 3).

Taxonomy no			Item						
Population	Installations		Calendar time (10^6 hours)						
Severity class / Failure mode	No of units		No of failures	Failure rate(per (10^6 hours)					Active rep. time (hrs)
				Lower	Mean	Upper	SD	n/τ	Mean
SUBUNIT NO 1									
Severity class									
Failure modes									
Component no 1.1									
Severity class									
Failure modes									
Component no 1.p									
Severity class									
Failure modes									

Table 3: The format of the reliability data tables in the OREDA offshore reliability handbook volume 2 Subsea, (SINTEF, 2009, s. 35).

The data is also complied in tables showing failure mechanisms versus failure modes at component level, se table 4.

Component	**Failure mechanism**	**Failure mode 1**	**Failure mode 2**	**…**	**Σ C+D**	**Total**
Component 1.1	Failure mechanism 1					
	Failure mechanism 2					
	….					
Component 1.p	Failure mechanism 1					
	Failure mechanism 2					
	….					

Table 4: Format of the failure mechanism versus failure mode tables (SINTEF, 2009, s. 37).

OREDA-data is categorized and presented for each system and component with related failure mechanisms and failure modes. The OREDA-data and the analyzed GFCSAT data are collected with different purposes; OREDA analyzes the reliability of components and systems while the GFCSAT data in this thesis is analyzed in order to find relevant indicators. Direct comparison of the failure rates with the GFCSAT-data and the OREDA-date is therefore challenging and of little use.

The OREDA data is reviewed in order to evaluate the data from GFCSAT, both in terms of the ratio of failures in each category, and to determine if all failure modes are included. Where the GFCSAT categories and the OREDA equipment classes or subunits are comparable the failure rates are listed. However no calculations for comparison are performed. It is just for comparing the failure rate to other failure rates in OREDA, in turn the ratio can be compared to the ratio in the GFCSAT data. The most important comparison between GFCSAT and OREDA data is comparing failure modes and failure mechanisms. This is especially to find common or critical failures that have not showed up or have been overlooked in the GFCSAT analysis. If new failure modes are found it is a possibility that the needed indicators must be changed. If the OREDA data show that failures in one category is significantly more common than the GFCSAT data indicate there may be need to emphasize the category beyond what the GFCSAT-data originally indicated.

4.3. PE-losses

The third and last goal for the indicators is "*minimize subsea related PE-losses*". Since the indicators are for monitoring the subsea production system only subsea related PE-losses are of interest. No external sources of relevant information were found, but Statoil internal data has been briefly reviewed.

4.3.1. GFCSAT PE-data

All production losses on Statoil operated fields or facilities are to be registered on a daily basis. Each loss is registered with start, stop, category, volume, involved tag or system number and a comment (Ravneberg, 2015). For the GFCSAT-wells, closing production wing valves will automatically generate a production loss report in the computer program EC. Additional information is registered by the CCR-operator and quality is assured in both daily and monthly meetings. If the production loss is not related to reservoir management it is counted as a production efficiency loss or PE-loss.

The program EC has only been used to record this data for GFCSAT-wells since 2010. Recordings before 2010 are more uncertain and are categorized differently (Ravneberg, 2015), and are therefore not used in this analysis. All losses related to or caused by problems in the subsea system are categorized in a category of its own.

The search for subsea related PE-losses for the GFCSAT wells was conducted in a PE-analysis program that retrieves its data from EC. To ensure the correctness of the search it was conducted by analyst Hanne Ravneberg (Ravneberg, 2015). The search resulted in 12 PE-losses. 6 of these losses were caused by human error, well testing or other causes irrelevant for developing indicators.

The total PE-loss in standard cubic meters (Sm^3) of oil are given for all the PE-losses. By using this unified measure the PE-losses' severity and relevance for achiving the goal "Minimize subsea related PE-losses" can be classified. Neither the reporting program EC nor the analysis program has a classification system. Therefore, the classification system for production losses or economical losses in Synergi has been used for the classification:

Consequence	Category	Description
	1	Very large cost/losses
	2	Large cost/losses
	3	Medium cost/losses
	4	Minor cost /losses
	5	Negligible cost/losses

Table 5: Synergi classification for production losses and costs (Statoil, 2015I).

According to the requirements for Synergi consequence classification, all the PE-losses found are classified as either minor or insignificant. As for the Synergi-reports the method used is to give all PE-loss reports a score inversely proportional to the consequence category, i.e. a consequence category minor gets a score of 2 and insignificant gets a score of 1. The severity classification is done to emphasize the larger and more important losses.

4.3.2. PE-data from other sources

A search in external sources uncover many publications that emphasize the need for high production efficiency. The department of Energy & Climate Change in the UK even identified it as a key challenge in 2013 after a significant drop in production efficiency the last years (Cowie, 2014). However, few documents contain more than general terms and none of the publications found are relevant for minimizing PE-losses on a subsea production system.

Since no relevant PE-data from external sources are found, some Statoil internal data has been quickly reviewed. The neighboring Gullfaks South wells tied back to Gullfaks A show similar findings with few losses. A quick look at other subsea fields reveal that one have to go no further than to the oil field Tordis that is tied back to Gullfaks C to find different numbers (Ravneberg, 2015). However, this facility is much more complex with water injection and subsea separation and therefore less relevant for GFCSAT (Statoil, 2015K). As no relevant PE-data from other sources are found, only Statoil internal data is used for this analysis.

4.4. Analysis results

The analysis of HSE related Synergi-reports for GFCSAT in the period 2001-2014 resulted in 52 relevant reports that with severity weighting accounts for a total score of 86 points. The analysis of malfunction reports for GFCSAT from SAP and spread sheet records for the period 2001-2014 resulted in 249 relevant reports. These reports were not weighted and therefore account for a total score of 249 points. The analysis of subsea related PE-losses for the period 2010-2014 resulted in 6 relevant reports that with severity rating account for a total score of 10 points. These data are summarized in table 6.

Goal area	**Analysis material**	**Weighted score**	**Percentage of total**
HSE	Synergi reports	86	25 %
OPEX	Malfunction reports	249	72 %
PE-losses	PE-loss reports	10	3 %
Total		**345**	**100 %**

Table 6: Summary of analysis data.

The reports from these three analyses have been combined into one record. This combined record has again been divided into 11 categories based on common failure mechanisms and needed indicators. Figure 8 shows the categories and the distribution between them for the combined records.

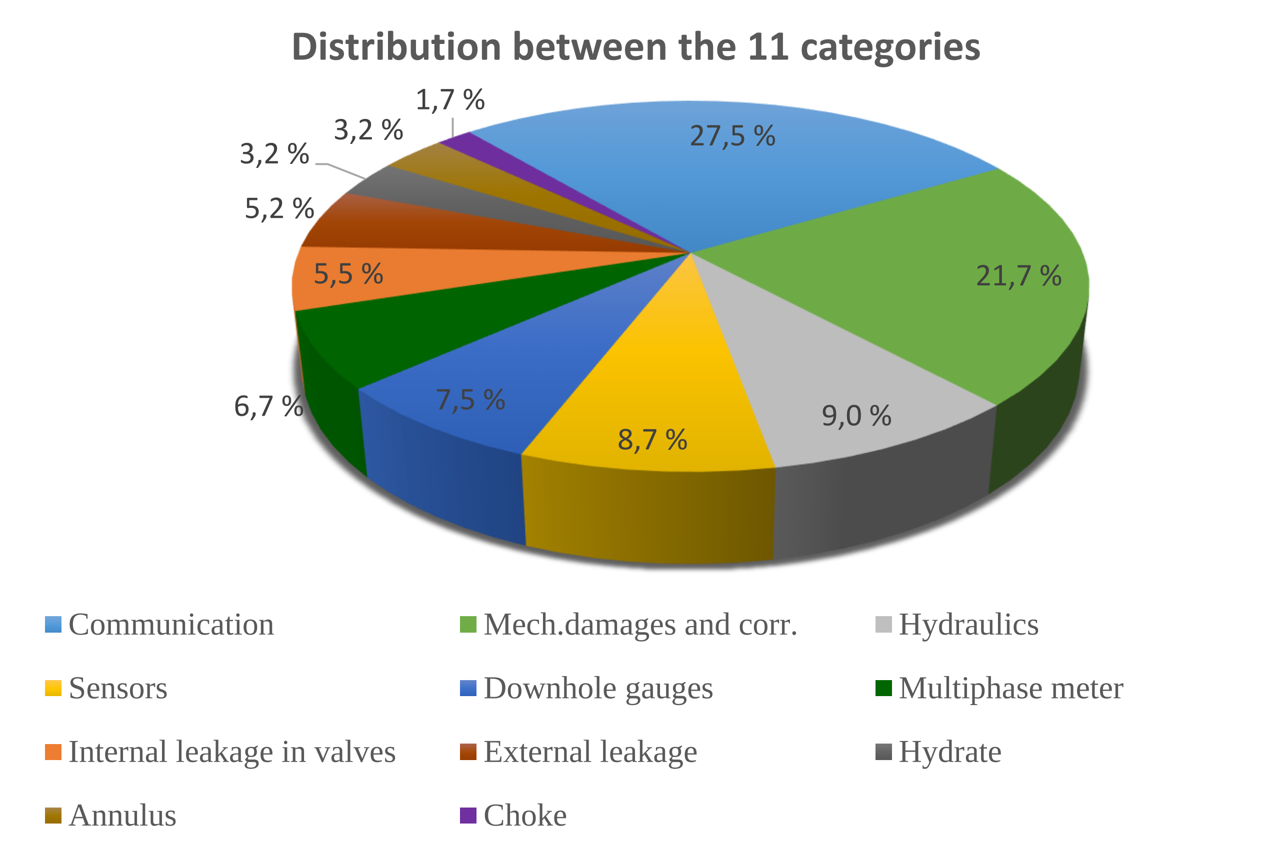

Figure 8: The distribution between the categories. The weighted scores are used, i.e. one severe Synergi and PE-loss report can count up to 5 times as much as a less serious Synergi or PE-report. All malfunction reports only account for one point.

Each of the 11 categories will in the remainder of this chapter be presented with information about the category, common failures, trends and failure modes that need to be detected by indicators. The findings in the categories will also be compared to the findings from external sources.

4.4.1. Communication

This category covers all malfunctions, incidents and PE-losses related to problems and malfunctions in the communication between the CCR and the subsea SEMs. This category also includes failures in the power supply. Since power and communication signals are distributed in the same cables, they are too closely related to differentiate in different categories.

<u>GFCSAT Analysis</u>

27,5% of the points from the combined analysis results are related to reports of communication problems. These problems are reported in Synergi reports, malfunction reports and PE-loss reports. None of the reports have received a high severity classification.

Most of the malfunctions in this category are related to no signal or erroneous communication with one or more SEMs. The causes of the problems were many, sometimes complex, and the available information was not always sufficient to determine the cause rof the error. The problems were either fixed by problem solving from GFC or by replacement of units. The PE-losses are primarily related to these replacements. The most common unit to fail is the SEM or the components inside the SEM units.

There are also some cases where several SEMs are not communicating properly. In these cases, the problems are somewhere in the infrastructure between the SEM and PCDA, often related to the communication cables and jumpers or in the overpower protection system topside.

There has been changes in the reporting practice during the time period analyzed. This makes it challenging to analyze trends. There is however a tendency towards more reports in later years.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- No signal from one SEM
- No signal from multiple SEMs
- Failures in the electrical power supply

<u>Analysis of other sources</u>

The data from the DNV-GL report does not contain information about failures in the communication system (DNV GL, 2014). Failures in the communication system should generally not cause serious incidents alone but it could contribute, e.g. failure in the control system was an important part of the Macondo incident (BP, 2010).

OREDA contains information about an equipment class named *control systems*, which covers much of the same systems and components as the communication category in this thesis. The primary difference between the two is that OREDA's equipment class is somewhat wider. It does for example include subsea sensors and the hydraulic systems. The failure rate for the equipment class *control systems* of 162,35 failures per million hours of operation is by far the highest for any of the subsea equipment classes. The most common unit to fail is the subsea control module with the most common subunit to fail being the subsea electronic module.
The most common failure modes for control systems when hydraulic and sensor related failures are not included are; *other, failure to function on demand, control or signal failure, transmission failure* and *short circuit*. The most common failure mechanisms are *control failure*, *earth/isolatio*n *fault* and *electrical failure*. (SINTEF, 2009)

The findings in OREDA are mostly similar to the findings in the GFCSAT data. One failure mode that came up in OREDA that is not listed before is failure to function on demand. This is however a failure mode that is less relevant for an indicator since it would be detected at once by the operator sending the signal. There are not found any reasons to change the failure modes nor to put additional emphasize on the category communication.

4.4.2. Mechanical damages and corrosion

This section covers all reports of mechanical or corrosion related damages to the subsea production system, with the exception of mechanical damages and corrosion that have led to malfunctions in other categories, i.e. a mechanical damage causing an external leak is categorized in external leaks. The category contains no failures in topside equipment.

Analysis results

21,7% of the points from the combined analysis results are related to reports of mechanical damages or corrosion. Mechanical damages and corrosion are reported in both Synergi reports and malfunction reports but not in any PE-loss reports. None of the reports have a high severity classification.

This is a category that contains a wide variety of failures or damages, most of them less extensive. The most common failure mechanism in the reports are HISC where a few are actual damages, the remaining are reported to perform work to determine the condition of equipment that could be subject to HISC. Other failures in this category are; damaged connection for control equipment, damaged hinges and locking for protective structure hatches, corrosion, damaged ROV-operated valves and some mechanical damages caused by trawl board impact.

A significant number of the reports were written before and during an extensive repair and inspection campaign. The high number of especially Synergi reports in this campaign can indicate some differences in systems used for reporting. Apart from that, there are no identifiable trends.

Mechanical or corrosion related damages are uncovered during inspections or interventions and are therefore difficult or impossible to detect for the indicators. The only damages that can be detected are leaks or damages that disrupt the function of equipment such as sensors. These possible scenarios are covered in the categories for external leaks and sensor malfunctions.

Analysis of other sources

Since this category is more or less irrelevant for finding needed indicators, no comparison of the collected data with other sources has been done.

4.4.3. Hydraulics

This category covers all reports of failures in the hydraulic system subsea, and topside problems that has the potential to disrupt supply.

<u>Analysis results</u>

9,0% of the points from the combined analysis results are related to reports of problems in the hydraulic system. Hydraulic related problems are reported in both Synergi reports and malfunction reports but not in any PE-loss reports. None of the reports have received a high severity classification.

The reports in this category are evenly divided between topside and subsea malfunctions. The topside malfunctions are internal leaks in valves or problems with supply pressure regulation. The most common subsea malfunction is leakage in the control lines for downhole equipment, i.e. hydraulic fluid leaking into the well. Other problems are external leaks in mounting base or valve actuators and internal leakage in a control valve inside the SCM.

Several of the failures are reported in two short time periods. Two possible explanations are that extensive troubleshooting initiated to uncover a malfunction uncovered multiple malfunctions, or that multiple reports related to the same underlying malfunction were generated. Apart from this, there are no significant trends.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- Internal leaks in valves topside
- Unstable or low hydraulic supply pressure
- External leakage subsea
- Internal leakage in the SCM

<u>Analysis of other sources</u>

In the incident data for NCS from 1999-2013 listed in the DNV-GL-report, hydraulics is not singled out. DNV-GL report that there are reports of 80 leaks of both hydrocarbons and control fluids. Of these leaks a significant number relates to leaks of control fluids. The report also refers to an incident in 2012 where “16.5 m3 control fluid more than planned was released over a period of 14 days. Normal release is 4.2 m3 in 14 days“ (DNV GL, 2014).

In OREDA the main parts of the hydraulic system is in the equipment class *control systems*. This equipment class covers the hydraulic system from the HPU to the SCM, including couplers, jumpers and lines in the distribution system. It is not possible to find an overall failure rate for the hydraulic system in OREDA, but for HPU the failure rate is 66,4 failures /million hours. However, this is all HPU failures. In the GFCSAT analysis only critical failures with the potential to disrupt supply is part of the analysis. Another difficulty in comparing the GFCSAT data to OREDA is that in large parts of the OREDA data it is not possible to distinguish between the hydraulic system and other utility systems, such as chemical systems. By assuming that the same failures are relevant for both hydraulics and other utility systems, the most common failure modes are *external leakage of utility medium*, *internal leakage of utility medium* and failures due to *plugging/choking*. The most common failure mechanisms are *leakage, blockage* and *burst*. In addition, there are several accounts of the failure mode *external leakage of utility medium* for valves in the equipment classes *manifolds* and for *valves* and *hydraulic couplers* in the equipment class *XMT and wellhead*. (SINTEF, 2009)

The findings in the DNV-GL report and OREDA are in accordance with the findings in the GFCSAT-data. There are not found any reasons to change the failure modes nor to put additional emphasize on the category hydraulics.

4.4.4. Sensors

This category covers all reports that relates to malfunctions in only one sensor regardless of the failure or cause.

Analysis of GFCSAT-data

8,7% of the points from the combined analysis results are related to reports of problems with sensors. Sensor related problems are reported in both Synergi reports and malfunction reports but not in any PE-loss reports. None of the reports have a high severity classification.

These reports relates to different types of sensors, from temperature gauges on the production line to voltage sensors inside the SCM. All reports are of sensors with the following problems: no signal, incorrect reading, out of range reading or unstable signal on one sensor. The most common sensor to fail is a sand sensor located on the FCM-module. Other sensors are the temperature and pressure gauges on the FCM module and sensors inside the SCM.

There is no clear trend in the data but there is a tendency towards a decreasing number of reports.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- No signal from one sensor
- Out of range reading/value
- Incorrect reading/value
- Unstable signal

Analysis of other sources

The data from the DNV-GL report does not contain information about sensor failures causing incidents. Failures in sensor systems should generally not cause serious incidents alone but it can contribute to such incidents. (DNV GL, 2014)

OREDA has a category named sensors under the equipment class *control systems*. This category covers the same as the sensor category in this thesis making the results comparable. The failure rate in the OREDA data is 8,49 failures/million hours in operations. The sensors with highest failure rates are flow sensors, sand detection sensors and combined pressure and temperature sensors. The most common failure modes are *erratic output, abnormal instrument reading* and *signal failure*. The most common failure mechanisms are *general instrument failure, faulty signal, blockage* and *no signal*. (SINTEF, 2009)

Of the failure mechanisms and modes the only one that has not come up in the GFCSAT data is blockage. It is difficult to know for sure why this failure mechanism has not been found in the GFCSAT data. It may be because the medium that is in the system does not contain components that leads to blockage.

Based on these findings there are not found any reasons to change the failure modes nor to put additional emphasize on the category sensors.

4.4.5. Downhole gauges

This category covers all reports of malfunctions in the communication with the downhole gauges. This is a category of its own because there are a significant number of reports describing errors in the communication with the downhole gauges only.

Analysis results

7,5% of the points from the combined analysis results are related to reports of problems with the downhole gauges. Problems with downhole gauges are reported in both Synergi reports and malfunction reports, but not in any PE-loss reports. None of the reports have received a high severity classification.

The reported problems are frozen values, unstable values or no signal from one or multiple downhole gauges. Some of the problems are related to communication and are solved from Gullfaks C. Most are failures in equipment such as gauges, cables or control modules.

The data shows a small drop in number of reports the last years. This can however relate to fewer gauges in operation. Downhole equipment is generally not repaired unless recompletion of the well is done for other reasons (Rotter, 2014).

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- No signal from one downhole gauge
- No signal from all downhole gauges in one well
- Value out of range.
- Unstable signal

Analysis of other sources

There is no information or data about downhole gauges in the DNV-GL report or OREDA.

4.4.6. Multiphase meter

This category covers all reports of problems related to the multiphase meter. This is treated as a category of its own because there are a significant number of reports describing errors in the communication with the multiphase meter. Furthermore, there are only installed multiphase meters on the five N-wells that started operating in 2007.

Analysis results

6,7% of the points from the combined analysis results are related to reports of problems with multiphase meters. Multiphase meter problems are reported in both Synergi reports and malfunction reports, but not in any PE-loss reports. None of the reports have received a high severity classification.

Most of the failures in this category are related to problems with the communication between the multiphase meters and the CCR. These failures cause frozen or no values from one or multiple multiphase meters. In most of the cases, communication was restored again after a reset or other measures conducted from Gullfaks C. In addition to communication problems, incorrect readings have also been reported.

There are only five multiphase meters, all installed in 2007. This results in a significantly shorter time span than for the other categories. Most of the reports are from the first years in operation and there is a trend towards fewer malfunction reports the last three years.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- No signal from one multiphase flow meter
- No signal from multiple multiphase flow meters
- Incorrect reading

Analysis of other sources

There is no information or data about multiphase flow meters in the DNV-GL report or OREDA.

4.4.7. Internal leak in valves

This category covers all reports related to internal leaks in subsea valves with the exception of choke valves and valves related to the annulus. Both of these valves are categories of their own. The choke valves have different failure mechanisms than the barrier valves covered in this category. Valves associated with the annulus are categorized in that category when both detection and problems are related to the annulus.

<u>Analysis results</u>

5,5 % of the points from the combined analysis results are related to reports of internal leaks in valves. Internal valve leaks are reported in Synergi reports, malfunction reports and PE-loss reports. None of the reports have received a high severity classification.

Most of the leaks are discovered as a result of regular testing of barrier valves defined in the preventive maintenance program. Leaks in non-barrier valves are most often discovered as a result of testing prior to operations or projects that are going to use the valves. A few leaks are found as a result of suspicion, e.g. caused by pressure changes in closed systems. The PE-losses identified results from either testing or changes in operations as a result of a leaking valve.

The irregular testing makes it difficult to identify any trends.

Most of the leaks are detected and can only be detected by testing the valves. There are however a few failures where an indicator could have been used for detecting unusual pressure or pressure changes in closed systems. In addition, degradation of the valves can be found by analyzing the valve profile, but this can hardly be done by simply applying an indicator.

Based the finding this category is not applicable for development of indicators.

<u>Analysis of other sources</u>

The DNV-GL-report does not contain information about internal leaks in valves.

The valves included in the OREDA report for this category are divided into two types of valves; *manifold process isolation valves* and *XT process isolation valves*. Downhole valves are not a part of the OREDA-data. For manifold process isolation valves the failure rate is 1,42 failure /million hours. The most common failure mechanisms are *mechanical failure* and *leakage*. The most common failure modes are *external leakage of process medium*, *failure to close on demand* and *leakage in closed position*. For XT process isolation valves the most common failure mechanism are *leakage*, and the most common failure mode is *leakage in closed position*. (SINTEF, 2009)

Apart from the external leaks in manifold process isolation valves that are not covered by this category, the failure modes and mechanisms are to some extent comparable to the findings in the GFCSAT data. The OREDA data does not contain any information that changes the conclusion that this category is not applicable for development of indicators.

4.4.8. External leaks

This category covers all reports of external leaks of both hydrocarbon and all utility mediums, with the exception of hydraulic fluids and annulus related leaks that are covered in other categories.

Analysis results

5,2 % of the points from the combined analysis results are related to reports of external leaks from the subsea production. External leaks are reported in Synergi reports and malfunction reports, but not in any PE-loss reports. This category consists of the only two incidents that have high severity classifications.

There have been reported only four external leaks. These four leaks get 5,2% of the points because of a high severity classification, and because the same incidents come up as both Synergi and malfunction reports. The most serious leak and the only incident in consequence category red 1 out of all the 52 Synergi reports was a gas leak detected during inspection in 2003. Gas was leaking from a HISC caused crack in one of the seabed flowlines connecting the templates to Gullfaks C. Similar HISC-problems also caused leaks on other fields in that time period (Tveit, 2006).This incident is the only one related to hydrocarbon leakage, the other three are leaks related to utility systems. One of these leaks is severity classified as red 2 due to the quantity of the release.

All the reports are more than 10 years old, indicating that leaks were a larger problem in the first years in operation.

It can be challenging to detect external leaks from all parts of the system. However an indicator that can detect some of the leaks is a possibility. An indicator for this category should detect the following failure modes:

- External leakage of hydrocarbons
- External leakage of utility medium

Analysis of other sources

The DNV-GL report focuses on external leakage of hydrocarbons in the incident chapter. The key findings for NCS in the period 1999-2013 is that there was about 80 releases of both hydrocarbons and control fluid. Most of these have unknown causes and only 10 can be directly linked to causes related to operations. The key findings for UK are somewhat limited due to difficulties in distinguishing between topside and subsea leaks. 22 reports can be linked to subsea leaks of hydrocarbons. Most of these have unknown causes and only 4 are directly related to operations. The most serious incidents are listed for both NCS and UK. Out of these 6 incidents all but one are more than 10 years old. The only new incident was a release of 2,5 tons of oil due to an error operation of a bleed valve. The other five were caused by rupture in a connection, wrong operation of a valve, mechanical failure, dropped object and HISC. The conclusion drawn in the report is that “releases from subsea production systems are relatively few and small compared to releases from other activities e.g. installation, work, and drilling”. (DNV GL, 2014)

OREDA has two failure modes that are relevant for this category; these are external leaks of process medium and external leaks of utility medium. Since these are failure modes, and not equipment classes or subunits, the approach for analyzing the data is different.
For the equipment class *control systems* only the failure mode *external leaks of utility medium* is listed. The leaks are mostly related to hydraulics, and only 10 accounts of leakage in chemical injection couplers are relevant.
For the equipment class *flowlines* there are two accounts of external leaks of process medium but both are in flexible pipes and are therefore not relevant.
For the equipment class *manifold* there are 33 accounts of external leaks of process medium and 5 accounts of external leaks of utility medium. The most common component to leak is process isolation valves and the most common failure mechanism is mechanical failure.
For the equipment class *XMT and Wellhead* there are 11 accounts of external leaks of process medium and 22 accounts of external leaks of utility medium. The most common component to leak process medium is connectors and the most common failure mechanism is leakage. For leaks of utility medium most are related to hydraulics. (SINTEF, 2009)

Based on these findings there are not found reasons to change the failure modes nor to put additional emphasize on the category external leaks.

4.4.9. Hydrates

This category covers all problems caused by hydrates.

Analysis results

3,2% of the points from the combined analysis results are related to hydrates. Hydrate problems are reported in both Synergi reports and malfunction reports, but not in any PE-loss reports. None of the reports have a high severity classification.

Most hydrates are located in the annulus bleed line also referred to as the service line. There are also a few reports of hydrates in the production line downstream of the choke valve. One report also describes hydrates affecting valve operations. The most common cause seems to be operations in connection with start-up of a well.

There is no significant trend in the data.

Based on the reports, hydrates is not a problem during normal operations and is therefore not applicable of the development of indicators.

Analysis of other sources

There is no information or data about hydrates in the DNV-GL report or OREDA.

4.4.10. Annulus

All reports related to fluids leaking in or out of the production annulus is covered by this category.

Analysis results

3,2% of the points from the combined analysis results are related to leaks in or out of the production annulus. Annulus leaks are reported in Synergi reports, malfunction reports and PE-loss reports. None of the reports have a high severity classification.

Nearly all the reports relate to pressure buildup due to fluids leaking into the annulus and only a few are of unstable or dropping pressure. The most common cause is internal leak in valves, especially the XOV-valve.

Most of the reports are from the last six years. This may be the result of annulus-related leaks is a growing problem or that the increase is a result of changes in the reporting procedures in 2009.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- Pressure build up in the annulus
- Small pressure drops in the annulus

Analysis of other sources

The DNV-GL report contains no information about leaks related to the production annulus.

In OREDA the XOV-valve can not be distinguished from other process isolation valves. However, the most common failure mechanism for these valves are *leakage*, and the most common failure mode is *leakage in closed position*. There are no data for leakages in the well but both internal and external leakage in the tubing hanger and annulus seal assembly is reported in the OREDA data. The failure rate is very low. (SINTEF, 2009)

Based on these findings there is not found any reason to change the results from the GFCSAT data, the failure modes, or emphasize the category beyond the points it has received in the GFCSAT data analysis.

4.4.11. Choke

This category covers all problems that are related to the subsea choke valves.

<u>Choke related problems</u>

1,7% of the points from the combined analysis results are related to choke valves. Failures related to choke valves are reported in both Synergi reports and malfunction reports, but not in any PE-loss reports. None of the reports have a high severity classification.

The reports in this category are related to failures in the position sensor, damaged valve or abrasion of the valve interior.

There is no trend in the data.

Based on the reports in this category there is need for indicators that can detect the following failure modes:

- Mismatch between flow and reported position
- Abrasion of the choke valve

<u>Analysis of other sources</u>

The DNV-GL report contains no data related to choke valves.

In OREDA choke valves can be found under the equipment classes *Wellhead and X-mas trees* and *choke module*. The total failure rate is 19,07 failures /million hours in operation. The most common failure mechanisms for choke valves are control failure, leakage and mechanical failure. The most common failure modes for choke valves are failure to function on demand common /combined cause and failure to close on demand. (SINTEF, 2009)

Based on these findings there is not found any reason to change the results from the GFCSAT data, the needed indicators or emphasize the category beyond the points it has received in the GFCSAT data analysis.

4.5. Conclusion

Based on the results from the analysis, there are few or none failure modes that are detectable by sensor signals for the categories: *Mechanical damages and corrosion, internal leakage in valves* and *hydrates.* The remaining eight categories will be further studied for development of indicators in chapter seven.

The GFCSAT-analyses for the eight remaining categories are in accordance with findings from external sources. This supports the findings in the analysis, and the relevance of these findings. It was not deemed necessary to change the results from the GFCSAT data, the failure modes nor emphasize the category beyond the points it has received in the GFCSAT data analysis for any of the categories.

5. Development of indicators

The continuous condition monitoring of the GFCSAT subsea production system is conducted by the CCR-operators on Gullfaks C. They report abnormalities and failures to the appropriate onshore departments. The majority of reports will be reported to the subsea operations department that troubleshoot and conduct measures. In addition the subsea engineers on a daily basis collect and review data to ensure that they have an overview of parameters of importance to the technical integrity and availability of the system. (Rotter, 2014). The indicators developed in this chapter are intended to be a tool in this process. By finding a few key condition indicators for each well the subsea engineers can obtain a quick overview of the technical condition of each well.

These key condition indicators can be shown as simple traffic light indicators that indicate as many of the failure modes found in the analysis in chapter 6 as possible. To develop the indicators each of the remaining 8 categories relevant for finding indicators will be studied in detail. In each of the 8 categories possible indicators are found for each relevant failure mode and reviewed using a checklist approach. Based on the checklists for the possible indicators, one or a combination of several possible indicators are selected. The selected indicator is checked against the reports in the corresponding category to get a measure of what percentage of failures that could be detected by the selected indicator. The selected indicators for each of the 8 categories are compared before the final selection of key condition indicators.

This chapter is divided into 9 subchapter, one for each of the 8 categories relevant for indicators and a final subchapter for selection of the 4 key condition indicators. The system descriptions are based on theory presented in chapter 2.

5.1. Communication

This category covers all failures in the power and communication system between the CCR and the SEM-units subsea.

System description

The CCR-operators control and monitor the subsea production system from the operator stations (OS) in the CCR. All sensor readings displayed and all commands that are initiated come from or are relayed to the subsea control unit (SCU). The SCU is a computer for operating the subsea production system. All communication between the SCU and the subsea systems pass through the SPCU. In the SPCU modems enable transmission of the communication signals over the power lines, i.e. both power and communication are distributed over the same lines to the subsea systems. The SPCU and the distribution system is built with redundancy.

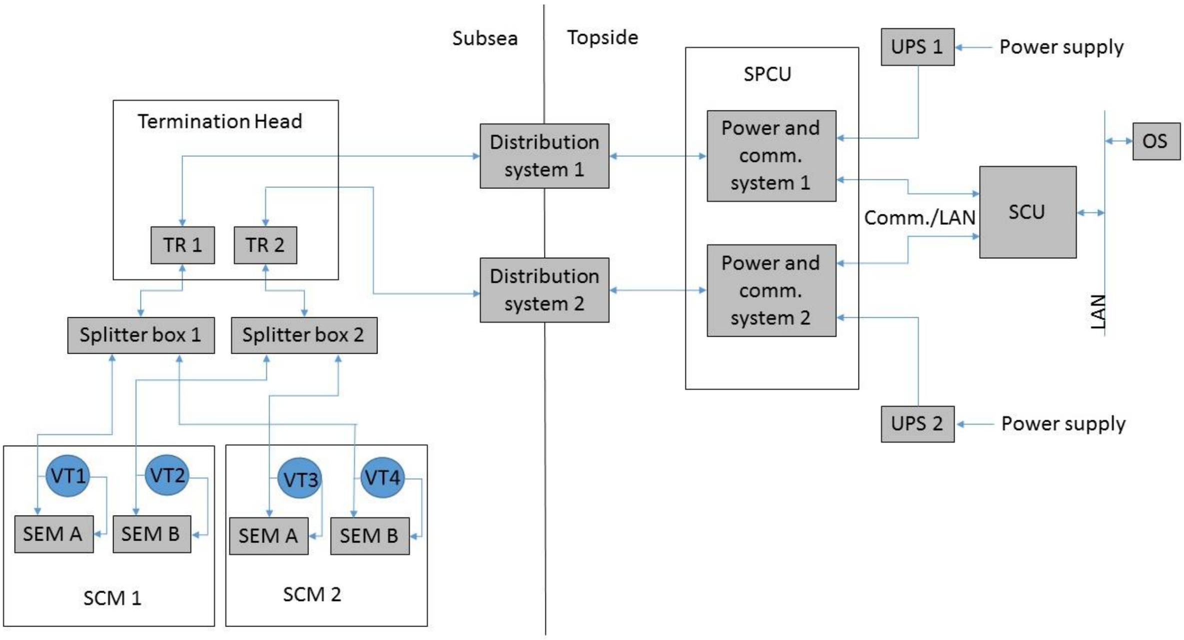

Figure 9: A simplified overview of the relevant equipment for the category *Communication.*

At the individual templates subsea, the power lines from the SPCU connect to an umbilical termination head. The termination head contain two transformers for stepping down the voltage, before the cables connect to two splitter boxes that divide the power and communication. Each splitter box has one line to each of the wells, i.e. two lines for each well. These lines connect to the SCM that connects one line to each of the two SEMs. Each SEM has modems for sending and receiving communication and transformers for supply voltage. Each SEM can in turn control and monitor the whole system connected to the SCM. This ensures a redundant system from the SPCU to the individual sensors or control valves.

A limiting factor in the system is the bandwidth in the communication system. To limit the amount of sent data the SEM only send the data requested by the SCU.

Development of indicators

Based on the findings in the analysis of communication related reports there is a need for indicators detecting the following failure modes:

- No signal from one SEM
- No signal from multiple SEMs
- Failures in the electrical power supply

For each of these failure modes, one or two possible indicators will be suggested in table 7. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 9.

Failure mode	Possible indicator
No signal from one SEM	1. Use the alarm signal the SCU give if requested data is not received. 2. Compare current reading to the reading one hour ago to see if it is continuously being updated for at least one sensor in each of the different parts of each SEM unit.
No signal from multiple SEMs	1. Use the alarm signal the SCU give if requested data is not received. 2. Compare current reading to the reading one hour ago to see if it is continuously being updated for at least one sensor in each of the different parts of each SEM unit.
Failures in the electrical power supply	3. Check power supply for each SEM-unit for failures by comparing reading to upper and lower operational limit. 4. Check power supply for each line in the SPCU for failures by comparing reading to upper and lower operational limit.

Table 7: Failure modes and possible indicators for the category *Communication*.

The indicators are evaluated in a checklist, see Appendix B, table 17, for details. Based on the results in this checklist, a combination of indicator 2 and 3 is selected for further development. These indicators may be combined because they use the same input signal. This indicator will hereafter be referred to as the “communication indicator”. The indicator is meant to indicate the condition of the communication for each well by checking the communication with each of the two SEMs that communicate with the SPCU on GFC. The indicator will compare the supply voltage for each of the two SEMs to the same signal some time ago and to the operational limits for supply voltage. In this way both the communication with each SEM and problems with power supply can be checked. For the N-well only the SEM temperature and not the supply voltage is available for both SEMs. The indicator for this well would be set up in the same way, but will not indicate problems with power supply unless power fails and the SEM would stop sending signals.

By comparing the supply voltage for each SEM-unit the communication with each SEM unit can be checked. If upper and lower operational limits are included the same indicator can also indicate problems with power supply. Two problems with this indicator are that failure in the voltage sensor will be indicated as communication failure and it can only indicate SEM failures that affect the voltage sensor.

A rough estimate based on the analysed records shows that such an indicator could indicate about 70% of all reported failures related to communication.

5.2. Hydraulics

This category covers all reports of failures in the subsea hydraulic system, and topside failures that has the potential to disrupt supply.

System description

The hydraulic system's function is to enable the control system to operate the subsea valves. This is done by supplying the different subsea actuators with hydraulic fluid with sufficient volume and pressure, without leaks. The system has both a HP and a LP part. These parts of the system are functionally equivalent and therefore the simplified illustration shown in figure 10 is valid for both.

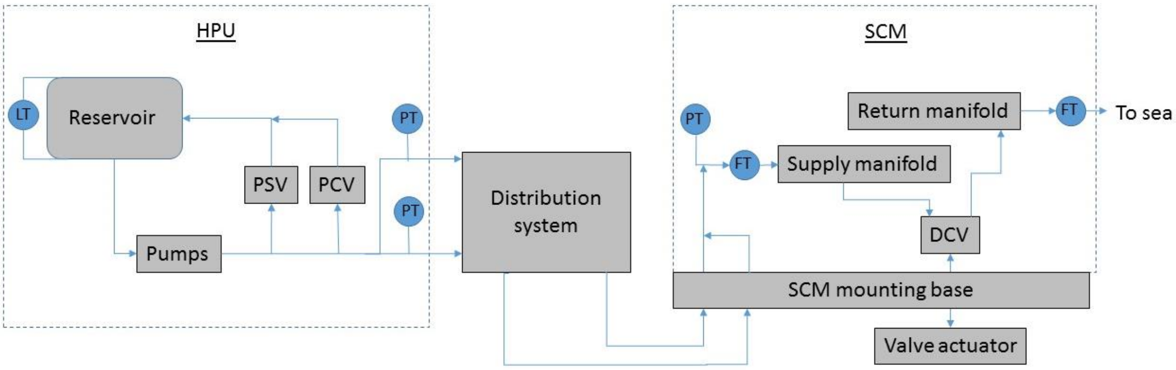

Figure 10: A simplified illustration of relevant components for the category *hydraulics*.

The hydraulic power unit (HPU) is the main part of the topside system. It consists of a reservoir supplying two pumps that are protected against overpressure by PSVs. To control the supply pressure there are pressure control valves and pressure transmitters controlling start and stop of the pumps. The hydraulic fluid is distributed to the individual SCMs through two identical distribution systems for redundancy. Inside the SCM there are transmitters measuring both the supply pressure and flow. The hydraulic supply is distributed to each of the directional control valves through a supply manifold. The directional control valves distribute pressure to the valve actuators if a valve changes position. The hydraulics returning from the valve actuators are commingled in the return manifold and are discharged to the sea. This type of hydraulic system is known as an open system, i.e. no return system. This requires an environmentally friendly fluid and a flowmeter that measures the discharged amount.

Development of indicators

Based on the findings in the analysis for the hydraulic related reports there is a need for indicators detecting the following failure modes:

- Internal leaks in valves topside
- Unstable or low hydraulic supply pressure
- External leakage subsea
- Internal leakage in the SCM

For each of these failure modes, one or two possible indicators are suggested in table 8. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 10.

Failure mode	Possible indicator
Internal leaks in valves topside	1. Number of pump starts versus valve operations subsea. 2. Number of pump starts versus accumulated return flow subsea.
Unstable or low hydraulic supply pressure	3. Detecting low distribution pressure from the HPU by comparing pressure reading to operational limits. 4. Detecting low supply pressure in SCM by comparing pressure reading to operational limits.
External leakage subsea	5. Changes in reservoir level versus valve operations subsea. 1. Number of pump starts versus valve operations subsea.
Internal leakage in the SCM	5. Changes in reservoir level versus valve operations subsea. 1. Number of pump starts versus valve operations subsea.

Table 8: Failure modes and possible indicators for the category *Hydraulics*.

The indicators are evaluated in a checklist, see Appendix B, table 18, for details. Based on the results in this checklist, indicator 1 is selected for further development, hereafter referred to as the hydraulics indicator. This indicator would calculate the number of pump starts and valve operations and compare the numbers. If the pumps start multiple times without valve operations, it is an indication of a leakage somewhere in the system. An indicator showing number of pump starts versus valve operations can monitor all failure modes in table 8 except *unstable of low hydraulic supply pressure*. The main weakness is that it is difficult to detect leaks when valves subsea are operated. The indicator would therefore work better when the valves are not operated.

A rough estimate based on the analyzed records shows that such an indicator could indicate about 90% of all reported failures related to hydraulics.

5.3. Sensors

This category covers all reports related to failures in only one sensor regardless of cause.

System description

The system description in figure 11 is a simplified description of the principles of two typical sensors that are covered by this category. The first sensor is a pressure sensor (PT) mounted on the XT between the PMV and PWV. The reading from this sensor is referred to as the wellhead pressure. The sensor measures the pressure and converts it to a signal that is transmitted to the SCM through connections in the SCM mounting base. Within the SCM the signal is sent to both SEM units for processing.

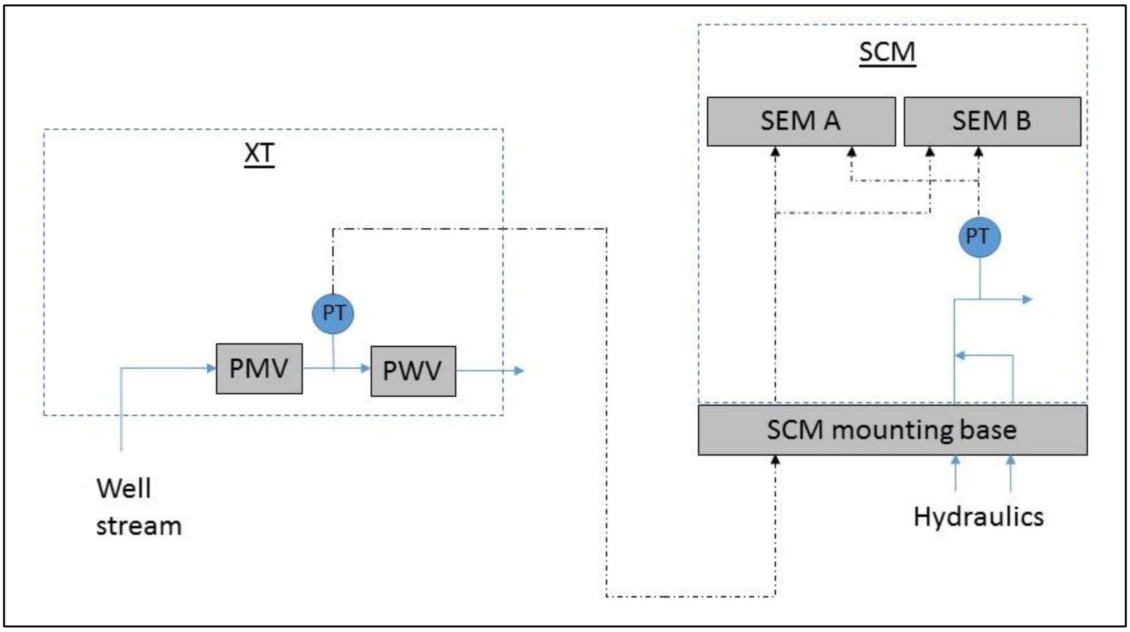

Figure 11: A simplified overview of the relevant equipment for the category *Sensors*.

The second sensor is a pressure sensor mounted inside the SCM. This sensor measures the hydraulic supply pressure and converts it to a signal that is transmitted to both SEMs for processing. Both SEMs receive signal from all the sensors, but signals are only transmitted upon request from the SCU topside.

Development of indicators

Based on the findings in the analysis for the sensor related reports there is a need for indicators detecting the following failure modes:

- No signal from one sensor
- Incorrect reading/value
- Out of range reading/value
- Unstable signal

For each of these failure modes, one or two possible indicators will be suggested in table 9. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 11.

Failure mode	Possible indicator
No signal from one sensor	1. Compare current reading with the reading some time ago.
Incorrect value	2. Compare sensor value to the upper and lower operational limits. 3. Compare reading to readings from other sensors in same system.
Out of range value	2. Comparing sensor value to the upper and lower operational limits. 3. Compare reading to readings from other sensors in same system. 4. Compare sensor values to upper and lower range limits.
Unstable signal	1. Compare current reading with the reading some time ago.

Table 9: Failure modes and possible indicators for the category *Sensors*.

The indicators are evaluated in a checklist, see Appendix B, table 19, for details. Based on the results in this checklist, a combination of indicators 1 and 4 is selected for further development, hereafter referred to as the “sensor indicator”. This indicator would compare the current sensor reading to the range limits and the sensor signal some time ago. If the readings are outside the range or completely stable this is an indication of a failure in the sensor. There are several sensors on each well. By performing the process for each sensor, the total number of failed sensors for that well can be found.

A rough estimate based on the analysed records show that such an indicator could indicate about 60% of all reported failures related to sensors.

5.4. Downhole gauges

This category covers all reports of failures in the communications with the downhole gauges.

System description

Downhole pressure and temperature gauges are installed as part of the completion of a well. These gauges measure pressure and temperature inside the tubing and send the electrical signals to the wellhead. The signal cables are mounted on the outside of the tubing and connected to a penetrator that is part of the XT. As shown in figure 12, the only difference between the systems for the L- and M-wells and N-wells are the electrical control module (ISEM). For L- and M-wells the signals from the penetrator are transmitted directly to the SCM. The signals are distributed to the two SEMs for processing and transmission to GFC.

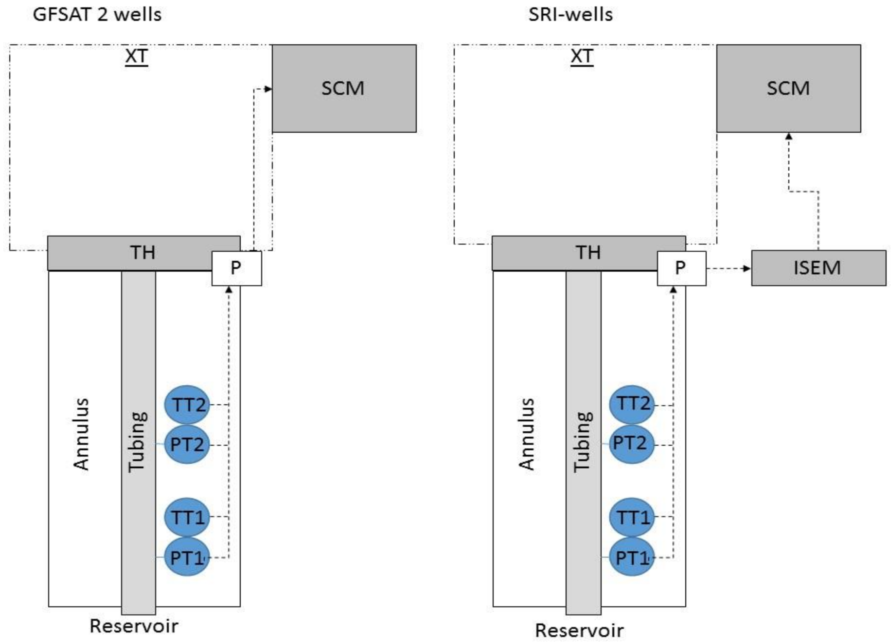

Figure 12: A simplified overview of the relevant equipment for the category *Downhole gauges*.

For the N-wells the signal from the penetrator connects to ISEM for control of downhole equipment. The unit process the signals from the downhole gauges before transmitting the signals to the SCM. From the SCM the signals are transmitted to GFC.

Development of indicators

Based on the reports related to downhole gauges there is a need for indicators that can detect the following failure modes:

- No signal from one downhole gauge
- No signal from all downhole gauges in one well
- Value out of range.
- Unstable signal.

For each of these failure modes, one or two possible indicators will be suggested in table 10. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 12.

Failure mode	Possible indicator
No signal from one downhole gauge	1. Compare current reading with the reading some time ago.
No signal from all downhole gauges in one well	1. Compare current reading with the reading some time ago.
Value out of range.	2. Comparing sensor value to the upper and lower range limits.
Unstable signal.	1. Compare current reading with the reading some time ago. 2. Comparing sensor value to the upper and lower range limits.

Table 10: Failure modes and possible indicators for the category *Downhole gauges*.

The indicators are evaluated in a checklist, see Appendix B, table 20, for details. Based on the results in this checklist, a combination of indicators 1 and 2 is selected for further development, hereafter referred to as the downhole gauge indicator. This indicator would compare the current gauge reading to the range limits and the gauge signal some time ago. If the readings are outside the range or completely stable this is an indication of a failure in the gauges. Some wells have several gauges. By performing the process for each gauge, the total number of failed gauges can be found.

This indicator if working according to plan could indicate about 95% of the failures reported in the analyzed GFCSAT-reports classified within the downhole gauges category.

5.5. Multiphase flow meter

This category covers all reports of problems related to the multiphase flow meter.

System description

Multiphase flow meters (MFM) are an integrated part of the flow control modules (FCM) for SRI wells. The MFM is located upstream of the choke valve in the well stream flowloop of the FCM. The raw signals from the MFM is sent to the SCM through cables connected to the top of the SCM. The SCM module transmits the signals to the SPCU topside.

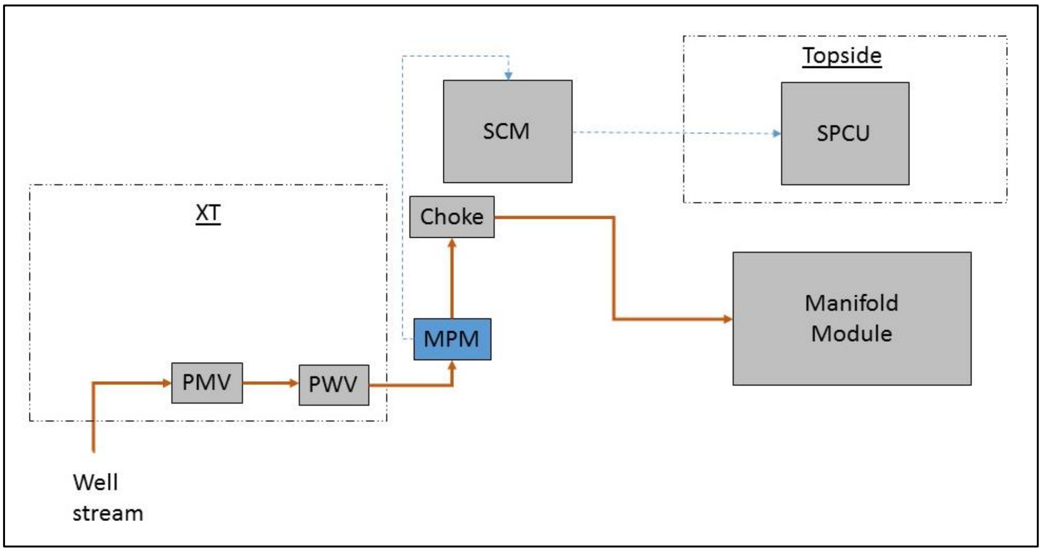

Figure 13: A simplified overview of the relevant equipment for the category *Multiphase flow meter.*

The calculations needed for finding the flow of all three phases are conducted in the SPCU unit topside.

Development of indicators

Based on the findings in the analysis of multiphase flow meter related reports there is a need for indicators detecting the following failure modes:

- No signal from one multiphase flow meter
- No signal from multiple multiphase flow meters
- Incorrect reading

For each of these failure modes, one or two possible indicators will be suggested in table 11. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 13.

Failure mode	Possible indicator
No signal from one multiphase flow meter	1. Compare current reading with the reading some time ago.
No signal from multiple multiphase flow meters	1. Compare current reading with the reading some time ago.
Incorrect values	2. Compare reading to average production last 24 hours. 3. Compare reading to predefined limits

Table 11: Failure modes and possible indicators for the category *Multiphase flow meter*.

The indicators are evaluated in a checklist, see Appendix B, table 21, for details. Based on the results in this checklist, a combination of indicators 1 and 3 is selected for further development, hereafter referred to as the multiphase flow meter indicator. This indicator would compare the current MFM reading to the predefined limits and the MFM-signal some time ago. If the readings are outside the predefined limits or completely stable this is an indication of a failure in the MFM.

If working according to plan, this indicator could indicate about 90% of the failures reported in the analyzed GFCSAT-reports in the multiphase flowmeter category.

5.6. External leaks

This category covers all reports of external leaks of both hydrocarbon and all utility mediums, with the exception of hydraulic fluids and annulus related leaks that are covered in other categories.

System description

A simplified system of a well stream is illustrated in figure 14 and described below. Detection of leaks can in prinsiple be done in a similar way for other systems.

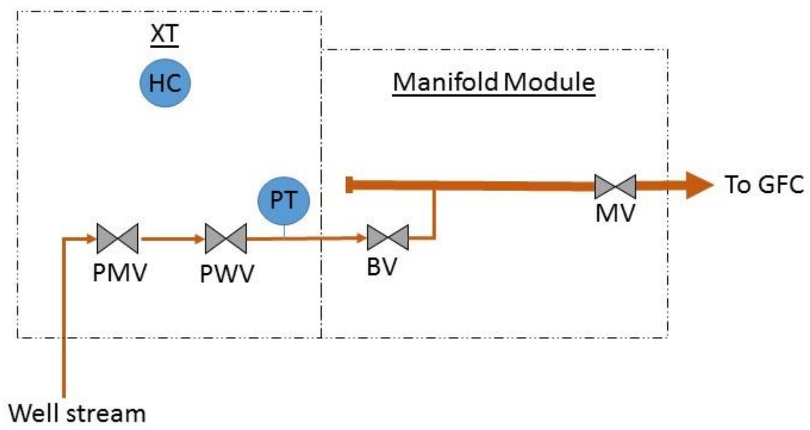

Figure 14: A simplified overview of the relevant equipment for the category *External leaks.*

Hydrocarbon leak detectors are installed on each XT as a part of the FCM. These detectors should indicate hydrocarbon leaks from XT and associated equipment. Large leaks can also be detected by pressure sensors in the system, illustrated by a pressure transmitter measuring the pressure downstream of the PWV in figure 14.

Development of indicators

Based on the reports related to external leaks there is a need for indicators that can detect the following failure modes:

- External leakage of hydrocarbons
- External leakage of utility medium

For each of these failure modes, one or two possible indicators will be suggested in table 12. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 14.

Failure mode	Possible indicator
External leakage of hydrocarbons	1. Significant pressure drop in the system 2. HC-leak detector
External leakage of utility medium	1. Significant pressure drop in the system

Table 12: Failure modes and possible indicators for the category *External leaks*.

The indicators are evaluated in a checklist, see Appendix B, table 22, for details. The evaluation shows that the readings from the HC-leak detector is unavailable for excel. The only possible indicator for external leaks is therefore an indicator that indicate leakage when there is a significant pressure drop in the system of interest. However, a significant pressure drop can only be caused by a large leakage. Large leaks require immediate action and are therefore of little interest for the development of indicators for a subsea management program, which main function is periodically, not continually, monitoring. Consequently, there are no applicable indicators for this category.

5.7. Annulus

All reports related to fluids leaking in or out of the production annulus is covered by this category.

System description

The production annulus is the space between the production tubing and the production casing. The space is filled with completion fluid during completion of the well. For pressure control, the production annulus is connected to the annulus bleed system. This system allows for bleeding access pressure to flare or drain system on board GFC.

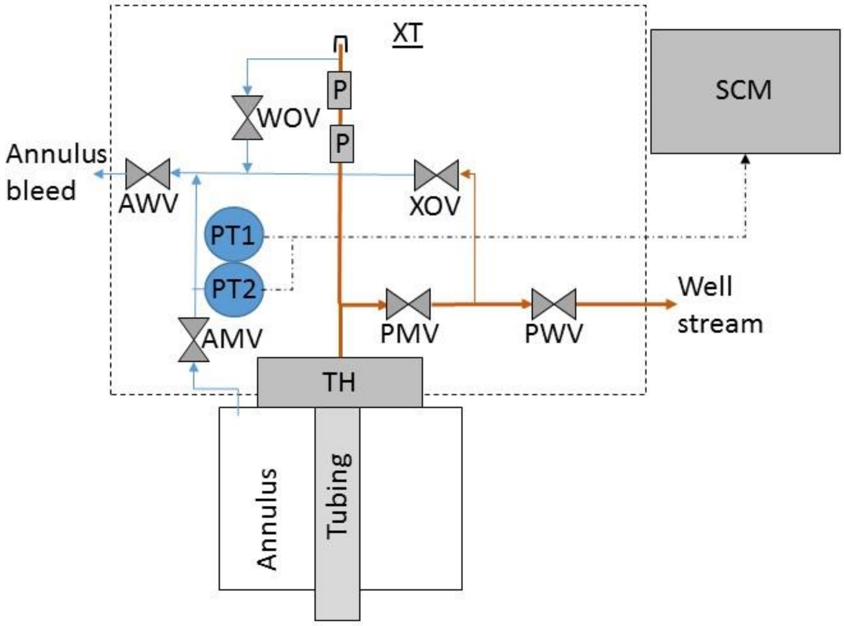

Figure 15: A simplified overview of the relevant equipment for the category *Annulus.*

Pressure changes in the production annulus can result from temperature changes or leaks. The annulus bleed system is also connected to the production line and to the sealed compartment on top of the XT. The main valves and pressure transmitter in the system are shown in figure 15. Under normal operations, the AWV, WOV and XOV valves would be closed, sealing the production annulus. The AMV would be open to allow for monitoring of the pressure.

Development of indicators

Based on the result for the analysis of annulus related reports there is a need for an indicator that can detect the following failure modes:

- Pressure build up in the annulus
- Small pressure drops in the annulus

Both of these failure modes can only be detected during normal operations when the annulus is sealed off and monitored by pressure transmitters. All indicators must therefore include some algorithm that only triggers failure indication when the valves are in normal position.

For each of these failure modes, one or two possible indicators will be suggested in table 13. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 15.

Failure mode	Possible indicator
Pressure buildup in the annulus	1. Comparing annulus pressure (PT1 and PT2 in figure 15) to predefined high pressure alarm limits. 2. Comparing annulus pressure to the same pressure some time ago to indicate if the pressure has changed.
Small pressure drops in the annulus	2. Comparing annulus pressure to the same pressure some time ago to indicate if the pressure has changed.

Table 13: Failure modes and possible indicators for the category *Annulus*.

The indicators are evaluated in a checklist, see Appendix B, table 23, for details. Based on the results in this checklist, a combination of indicators 1 and 2 is selected for further development, hereafter referred to as the annulus indicator. This indicator would compare the current annulus reading to the predefined limits and the annulus-signal some time ago. If the readings are outside the predefined limits or completely stable this is an indication of a failure in the MFM.

This indicator, if working according to plan, could indicate about 90% of the failures reported in the analyzed GFCSAT-reports in the multiphase flowmeter category.

5.8. Choke

This category covers all problems that are related to the choke valves subsea.

<u>System description</u>

The choke valve is the main component in the FCM. The FCM is essentially a flow loop for the well steam between the XT and the manifold module. The choke valve is a control valve with position indication (CP) that regulates and controls the well steam. The flow control module also contains a number of sensors. The most important ones for development of indicators are included in the system illustration in figure 16.

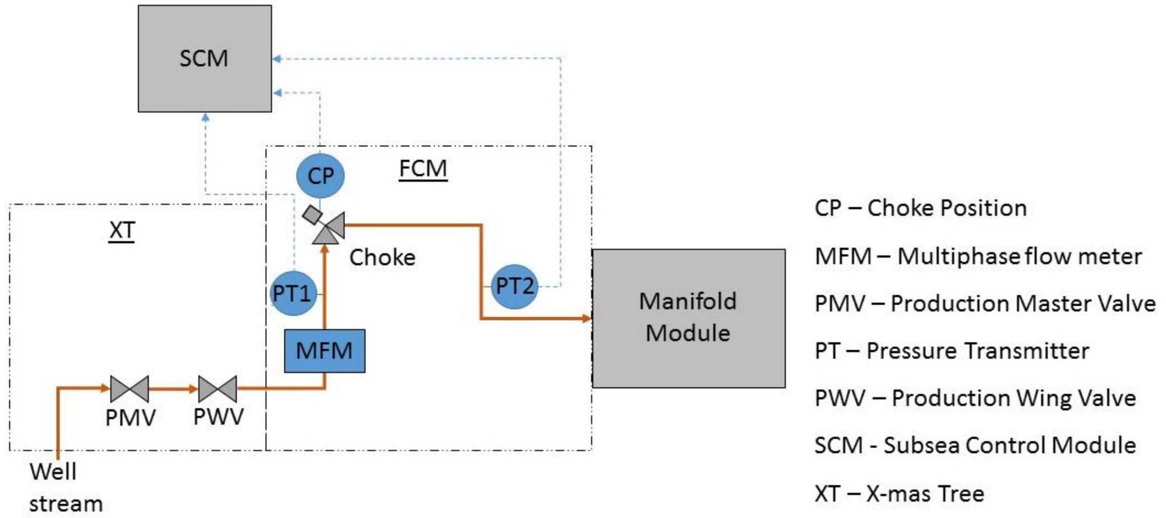

Figure 16: A simplified overview of the relevant equipment for the category *Choke.*

Pressure and temperature transmitters are installed both up stream and down stream of the choke valve. MFMs are only included on the five N-wells. All sensors in the FCM are connected to the SCM by jumpers connected to the top of the SCM.

The well stream from the FCM flows into the manifold module where it commingle with other wells streams before the flowlines lead it to Gullfaks C. Topside on GFC the commingled well streams is controlled by an additional choke valve before entering the processing facility.

<u>Development of indicators</u>

Based on the findings in the analysis of choke related reports there is need for indicators detecting the following failure modes:

- Mismatch between flow and reported position
- Abrasion of the choke valve interior.

The difference between this failure modes is the rate of the change. Sudden changes must be related to the position indicator or sudden damages to the valve. A mismatch can develop over time and be caused by abrasion in the valve.
For each of these failure modes, one or two possible indicators will be suggested in table 14. Possible indicators are based on prior knowledge and knowledge gained through working with this thesis, for example by developing the system description in figure 16.

Failure mode	Possible indicator
Mismatch between flow and reported position	1. Comparing ratio between choke position (CP) and flow measurement(MFM) to ratio some time ago.* 2. Comparing ratio between choke position and pressure differential (differential between PT1 and PT2) to ratio some time ago.*
Abrasion of the choke valve interior.	3. Measuring flow coefficient of the choke

Table 14: Failure modes and possible indicators for the category *Choke*.

*If there is significant change to the ratio it can indicate choke failure.

The indicators are evaluated in a checklist, see Appendix B, table 24, for details. Based on the results in this checklist, indicator 1 is selected for further development, hereafter referred to as the choke indicator. This indicator compares the ratio between pressure differential and choke position to the ration some time ago. If the mismatch is larger than a predefined limit, it indicates failure.

This indicator if working according to plan could indicate about 60% of the failures reported in the analyzed GFCSAT-reports in the choke category.

5.9. Key condition indicators

In the previous 8 subchapters one indicator for each of the 8 categories relevant for selecting indicators have been found. To select key condition indicators from this list of 8 selected indicators all relevant information must be considered. The relevant information is retrieved from both chapter 4 and the previous 8 subchapters, and is presented in table 15.

Category	GFCSAT-analysis		Development of indicators
	Total %	Trend	Quality
Communication	27,5	↗	70%
Hydraulics	9,0	-	90%
Sensors	8,7	↘	60%
Downhole gauges	7,5	↘	95%
Multiphase meter	6,7	↓	90%
External leaks	5,2	↓	0%
Annulus	3,2	↑	90%
Choke	1,7	-	60%

Table 15: Summary of relevant information for developing indicators.

Total % represents points each category received from the combined analysis, divided by total points. For categories with a trend towards fewer or more failures, a straight arrow is used. For categories with a tendency, inclined arrows are used. Quality gives information of the percentage of reported failures the selected indicator for that category would detect if working according to plan.

Based on the data presented in table 15, *communication, hydraulics, sensors, downhole gauges* and *multiphase meter* are the obvious key categories.

The indicators for these key categories are to work as follows:

<u>Communication indicator</u>

This indicator indicates the condition of the communication for each well by checking the communication with each of the two SEMs that communicate with the SPCU on GFC. The indicator is to comparing the supply voltage for each of the two SEMs to the same signal some time ago and to the operational limits for supply voltage. In this way both the communication with each SEM and problems with power supply can be checked. For the N-well only the SEM temperature and not the supply voltage is available for both SEMs. The indicator for these well would be set up in the same way will not indicate problems with power supply. (Unless power fails and the SEM would stop sending)

<u>Hydraulics indicator</u>

This indicator would calculate the number of pump starts and valve operations and compare the numbers. If the pump starts multiple times without valve operations, it is an indication of a leakage somewhere in the system.

<u>Sensor indicator</u>

This indicator would compare the current sensor reading to the range limits and the sensor signal some time ago. If the readings are outside the range or completely stable this is an indication of a failure in the sensor. There are several sensors on each well. By performing the process for each sensor, the total number of failed sensors for that well can be found.

<u>Downhole gauge indicator</u>

This indicator would compare the current gauge reading to the range limits and the gauge signal some time ago. If the readings are outside range or completely stable this is an indication of a failure in the gauges. Some wells have several gauges. By performing the process for each gauge, the total number of failed gauges can be found.

<u>Multiphase flow meter indicator</u>

This indicator would compare the current MFM reading to the predefined limits and the MFM-signal some time ago. If the readings are outside the predefined limits or completely stable this is an indication of a failure in the MFM.

5.10. Test of key condition indicators

The indicators were initially developed to be a part of a subsea management prototype. This prototype has not been developed as part of the thesis. The indicators have, however, been tested with promising results.

All the well specific indicators indicate failure if a signal is stable or out of range. When a sensor does not send new signals, the last known value will be shown. This means that a stable signal is an indication of lack of new updates, i.e. a failure on a sensor or the communication.

In a test of the well specific indicators, the number of failures were known in advance. All known failures the indicators should detect on the L, M and N templates were detected, with two exceptions. One downhole gauge that was reported to have failed did not indicate failure. By checking the CCR control system, the gauge readings were moving within range, i.e. it is uncertain why this gauge was reported as failed. The second exception was an erroneous indication of failure in a SEM in one of the N-wells. The most likely cause is that the stable temperature in the SEM caused an erroneous indication of failure. The indicator interprets the stable signal as no signal. Another and less likely cause is that a new and previously unknown failure was detected. If this is the case, the most likely cause is a failure in the temperature sensor in the SEM since the communication status showed no signs of failure.

These two possibilities for erroneous indication of SEM failure illustrate two weaknesses for the SEM communication indicator. Primarily, the indicator is dependent on signals that do not have a stable value. For the N-wells, the only signal available in excel for both SEMs is the SEM temperature. The relatively stable SEM temperature is not ideal for the purpose, since a stable signal is interpreted as a failure. To compensate, the signals could be checked for stability with comparing current value to values retrieved for four or five different times, instead of three different times as used in the indicators. See figure 18 for details about the formulas used in the indicators. This source of erroneous indication is also valid for the sensor, downhole gauge and multiphase flow meter indicators, but less likely for the other, less stable parameters. The second weakness is that any failure affecting the signal from the temperature sensor will be indicated as a SEM failure. These weaknesses are also valid for the communication indicators for the L and M wells, where the only signal available for both SEMs is supply voltage. Further troubleshooting should be performed in order to find the reason for the detected failures.

Based on the result of the test, the well specific indicators work fairly well to detect failure. By structuring the indicators into an interface as suggested in figure 17, they can be helpful in both detecting new failures and keeping track of existing failures.

6. Discussion

As part of this thesis, all relevant goals and objectives for GFCSAT have been reviewed to ensure that the chosen indicators are according to, and can help to achieve, these goals. The chosen goals are essential for the analysis and consequently also for the indicators chosen. This suggests that the indicators are specific for GFCSAT only. The final goals in this thesis are, however, general goals for the subsea industry. Since the goals are general, they should be applicable for other subsea fields as well.

The goals have led to the analysis of three different types of reports. These different reports are in turn combined into one common record for analysis. By this approach, the goals are not weighted equally in the selection process. The uneven weighting results in OPEX-costs dominating the analysis and in turn the indicators. PE is poorly represented due to few reports. Even though the PE-loss reports represent a shorter time period, the low number of reports indicates that this goal does not have as much room for improvement as the other goals. It can therefore be argued that by this approach the goals with the most room for improvement will be the one dominating the indicators. I.e. if the number of PE-losses increases, this goal could increase its importance. Another option would be to treat the three goals equally. This would have put a disproportionate weighting on the few PE-losses compared to the many malfunction reports, and could in turn have reduced the predictive value of the developed indicators.

The analysis process with non fixed categories and different type of reports containing somewhat different data, it was not always obvious which category a report should be categorized as. The evaluation was based on the writers limited experience and is therefore to some extent subjective. Some of these issues are summarized in the next two paragraphs.

The same failure may appear in different reports and several times for the same type of reports. When it appeared several times in the same type of reports, the duplicated report was discarded. It is however likely that not all duplicated reports are found. When the same failure is found in different type of reports, they are included in the analysis. This may add emphasis on some failures, for example is this the case for all failures in the category external leaks. These are included in both malfunction and synergi reports. This is not considered to be duplicated reporting, only to add emphasis on important failures. These types of failures are deemed to be important because they cover different types of failure reports. For example, a failure reported in a malfunction report that also results in a PE loss report (OPEX as well as PE loss), will most likely be more important than one that only appears as a failure in the malfunction report (only OPEX).

When reports of similar failures are found during a short time interval, they are treated as duplicates. When several days separate the reports of similar failures, they are not considered to be duplicates. The same underlying failure may however cause several reports over a longer period of time. It can be argued that these types of reports add too much emphasis on some categories, which in turn could affect the chosen indicators. However, for these types of failures, it may be more important to oversee their function, and an indicator might thus be justified. Therefore it is not assumed to affect the analysis results negatively that these types of failures are not discarded.

The final results are very clear (see table 15 page 75), and therefore only large differences in the method used for analyzing data would result in different key condition indicators.

The analysis of categories was subjective. No experts have been used for categorizing, and incidents have not been studied in detail. Only descriptions found in the incident reports were used. However, the findings are well in accordance with OREDA.

The possible indicator for each of the failure modes was primarily based on system reviews and the knowledge acquired through working with this thesis. It is therefore a possibility that some information could have been missed. This could in turn have affected the evaluation. However, the promising results for the indicator test show that the selected key indicators are useful and have value-adding qualities.

6.1. Further work

6.1.1. Excel prototype

The indicators are developed to be implemented as a part of an excel prototype of a subsea management program. Although the development of the program has not been a part of the thesis, some considerations regarding the development of such a program have been prepared. First and foremost, the program must have an interface providing the indicators a well-structured and intuitive way to get a quick overview of the condition of the wells.

Important information can be included in the prototype, such as whether the well is in production or not, and the production volume. This information adds context to the results from the indicators. For example, if there are detected problems with communication on a high production well, this could be more critical than if the same is indicated for a well that is not in production.

If an indicator indicates a failure, the prototype must be built in such a way that it may easily be understood why a failure is indicated, but the actual troubleshooting should be conducted in the more detailed systems.

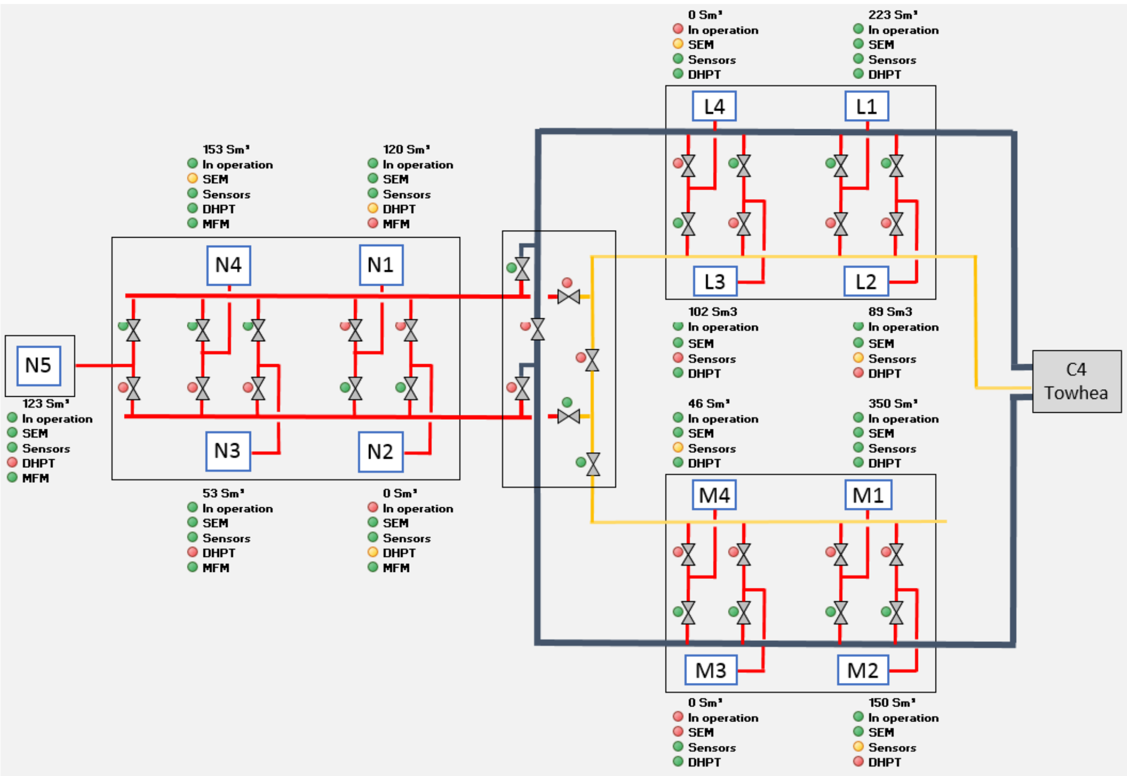

Figure 17: Illustration of a possible set up for the GFCSAT prototype in excel

	A	B	C	D	E	F	G	H	I	J
1	Description	Tag	Current value	+1 hour value	+2 hour value	COM OK?	LOWER RANG	UPPER RANGE	RANGE OK?	Indicator
2	Temp. SEM A	19-TT-0001A	25,05	25,01	25,03	TRUE	0	100	TRUE	
3	Temp. SEM B	19-TT-0001B	21,74	21,74	21,74	FALSE	0	100	TRUE	
4	SEM total									
5										
6				=IF((ABS(2*C3-D3-E3))>0,0001;TRUE;FALSE)				=IF(AND(C3>G3;C3<H3);TRUE;FALSE)		
7										
8										

Figure 18: Illustration of how the SEM-communication indicator could be set up in excel.

6.1.2. Further development of the subsea management system

The full purpose of the program is not evident when it is only applied to some 13 subsea wells. The time saved when using the indicators developed and the suggested prototype compared to viewing more detailed systems for only 13 wells is limited. Similar indicators must therefore be developed for more wells. An obvious first step would be to add the Gullfaks Satellite wells tied back to Gullfaks A. Since the equipment is more or less the same for the Gullfaks Satellite wells, the key indicators will most likely be similar or could even to some extent be based on the findings in this thesis. This could also be the case for other fields with similar equipment. By applying these indicators for subsea fields with several wells, the time saved can be substantial. This is useful in a streamline industry.

When applied to fields with many wells, and to multiple fields, it may be useful to apply the program as an analysis tool. For example, it can be used to get an overview of number of wells with reduced redundancy for SEMs on multiple fields, or to analyze the development of failures over time.

On the other hand, the program can be extended by adding more detailed indicators. Extensive development in this direction may not be as useful, due to more detailed tools that are already in place.

7. Conclusion

Based on the analysis and indicator development process the key condition indicators are found to be the indicators within the categories *communication, hydraulics, sensors, downhole gauges* and *multiphase meter*. The hydraulics-indicator is a system indicator aimed at detecting leaks. The other four indicators are well specific and are all aimed at detecting the failure modes *no signal* and *out of range signal* for the equipment within the respective categories.

These key condition indicators are all for monitoring the control system. This is in accordance with OREDA data for subsea where the equipment class *Control systems* had the highest failure rates by far.

The testing of the indicators shows promising results with only two possibly erroneous indications. Based on this test the indicators should be applicable for use in a prototype program for GFCSAT, and can provide valuable input for future development of a mid-level conditional monitoring and operational management program.

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9. Appendices

9.1. Appendix A

The format of the spreadsheets used for analyzing and systemizing reports is shown in table 16, Short description of each column is provided in the list below the table.

ID number	Date	Severity	Description	Equipment	Category	Comments

Table 16: Spread sheet for systemizing reports.

- ID number for identification. The original report numbers were used when possible.
- Date for looking at trends and identifying possible duplicated reporting.
- Severity, when the reports have a severity classification this is used to highlight the reports that are of most importance to achieving the goal. Not all reports have such a severity classification.
- Description or title, usually the original title of the report unless it is misleading or ill fitted for the purpose.
- Equipment describes which equipment failed or was involved. Usually simple descriptions of items/units. E.g. SCM.
- Category is used for categorizing the reports.
- Comments include a short description of available information that is not in any of the other columns.

9.2. Appendix B

<table>
<tr><td colspan="2">Category: Communication</td></tr>
<tr><td colspan="2">Possible indicator 1
Use the alarm signal the SCU give if requested data is not received.</td></tr>
<tr><td>Question</td><td>Answer</td></tr>
<tr><td>Which failure mode can this indicator detect?</td><td>No signal from one SEM and
No signal from multiple SEMs</td></tr>
<tr><td>Is all required data available in excel:</td><td>No, signal is only available for some wells</td></tr>
<tr><td>Is similar monitoring in place already:</td><td>Yes, CCR has the same alarm</td></tr>
<tr><td>Sources of erroneous indication:</td><td>-</td></tr>
<tr><td>Comment:</td><td>Not applicable for all wells</td></tr>
<tr><td colspan="2">Possible indicator 2
Compare current reading to the reading one hour ago to see if it is continuously being updated for at least one sensor in each of the different parts of each SEM unit.</td></tr>
<tr><td>Which failure mode can this indicator detect?</td><td>No signal from one SEM and
No signal from multiple SEMs</td></tr>
<tr><td>Is all required data available in excel:</td><td>No, only signal for SEM supply voltage is available for both SEMs on L and M wells. For N-wells, only signal for SEM temperature is available for both SEMs</td></tr>
<tr><td>Is similar monitoring in place already:</td><td>No, only alarm for not receiving requested data</td></tr>
<tr><td>Sources of erroneous indication:</td><td>-</td></tr>
<tr><td>Comment:</td><td>Can only detect failures that affect the sensor for supply voltage</td></tr>
<tr><td colspan="2">Possible indicator 3:
Check power supply for each SEM-unit for failures by comparing reading to upper and lower operational limit.</td></tr>
<tr><td>Which failure mode can this indicator detect?</td><td>Failures in the electrical power supply</td></tr>
<tr><td>Is all required data available in excel:</td><td>Yes, voltage for each SEM is available</td></tr>
<tr><td>Is similar monitoring in place already:</td><td>Yes, CCR high and low alarms for SEM raw voltage</td></tr>
<tr><td>Sources of erroneous indication:</td><td>-</td></tr>
<tr><td>Comment:</td><td>-</td></tr>
<tr><td colspan="2">Possible indicator 4:
Check power supply for each line in the SPCU for failures by comparing reading to upper and lower operational limit</td></tr>
<tr><td>Which failure mode can this indicator detect?</td><td>Failures in the electrical power supply</td></tr>
<tr><td>Is all required data available in excel:</td><td>Yes, voltage for each power supply line</td></tr>
<tr><td>Is similar monitoring in place:</td><td>Yes, CCR high and low alarms voltage for each power supply line</td></tr>
<tr><td>Sources of erroneous indication:</td><td>-</td></tr>
<tr><td>Comment:</td><td>-</td></tr>
</table>

Table 17: Development of the Communication indicator.

Category: Hydraulics	
Possible indicator 1 Number of pump starts versus valve operations subsea.	
Question	Answer
Which failure mode can this indicator detect?	*Internal leaks in valves topside,* *External leakage subsea* and *Internal leakage in the SCM*
Is all required data available in excel:	Yes, all position signals for valves and pump-running signal is available. No accumulated numbers for valve operations nor pump starts.
Is similar monitoring in place:	No
Sources of erroneous indication:	Can not indicate leakage if subsea valves are operated.
Comment:	To compare pump starts and valve operations algorithm for retrieving accumulated numbers must be found.
Possible indicator 2 Number of pump starts versus accumulated return flow subsea.	
Which failure mode can this indicator detect?	*Internal leaks in valves topside*
Is all required data available in excel:	Yes, all pump-running signals and accumulated return flow are available. No accumulated numbers for pump starts.
Is similar monitoring in place:	No
Sources of erroneous indication:	Can not indicate leakage if subsea valves are operated.
Comment:	Algorithm for retrieving accumulated numbers of pump starts must be developed
Possible indicator 3 Detecting low distribution pressure from the HPU by comparing pressure reading to operational limits.	
Which failure mode can this indicator detect?	Unstable or low hydraulic supply pressure
Is all required data available in excel:	Yes, distribution pressure from the HPU is available
Is similar monitoring in place:	Yes, CCR has alarms for both high and low distribution pressure from the HPU
Sources of erroneous indication:	-
Comment:	-
Possible indicator 4 Detecting low supply pressure in SCM by comparing pressure reading to operational limits.	
Which failure mode can this indicator detect?	Unstable or low hydraulic supply pressure
Is all required data available in excel:	Yes.
Is similar monitoring in place:	Yes, CCR has alarms for both high and low supply pressure to the SCMs
Sources of erroneous indication:	-
Comments:	-
Possible indicator 5	

Changes in reservoir level versus valve operations subsea.	
Which failure mode can this indicator detect?	*External leakage subsea* and *Internal leakage in the SCM*
Is all required data available in excel:	Yes, all position signals for valves and reservoir level is available. No accumulated numbers for valve operations.
Is similar monitoring in place:	No, only alarm for low reservoir level.
Sources of erroneous indication:	-
Comments:	-

Table 18: Development of the Hydraulics indicator.

Category: Sensor	
Possible indicator 1 Compare current reading with the reading some time ago.	
Question	Answer
Which failure mode can this indicator detect?	*No signal from one sensor* and *Unstable signal*
Is all required data available in excel:	Yes, all important sensor signals are available.
Is similar monitoring in place:	No, only communication failure alarms.
Sources of erroneous indication:	-
Comments:	Only applicable if no signal is received over some time.
Possible indicator 2 Compare sensor value to the upper and lower operational limits.	
Which failure mode can this indicator detect?	*Incorrect value* and *Out of range value*
Is all required data available in excel:	Yes, all important sensor signals are available.
Is similar monitoring in place:	Some sensors have alarms for upper and/or lower operational limits when it is of importance for operation of the subsea production system.
Sources of erroneous indication:	High and low process values will be indicated as sensor failures. E.g. under shut down of a well.
Comments:	
Possible indicator 3 Compare reading to readings from other sensors in same system.	
Which failure mode can this indicator detect?	*Incorrect value* and *Out of range value*
Is all required data available in excel:	Yes, all important sensor signal are available.
Is similar monitoring in place:	No alarms for deviation for sensor values are in place
Sources of erroneous indication:	-
Comments:	Limited application, only a few places have two sensors that can be compared.
Possible indicator 4 Compare sensor values to upper and lower range limits.	
Which failure mode can this indicator detect?	*Out of range value*
Is all required data available in excel:	Yes, all important sensor signal are available and range limits are available in single list
Is similar monitoring in place:	Some sensors have alarms for upper and/or lower operational limit when it is of importance for operation of the subsea production system.
Sources of erroneous indication:	-
Comments:	-

Table 19: Development of the Sensor indicator.

Category: Downhole gauges	
Possible indicator 1 Compare current reading with the reading some time ago.	
Question	Answer
Which failure mode can this indicator detect?	*No signal from one downhole gauge* and *No signal from all downhole gauges in one well* and *Unstable signal*
Is all required data available in excel:	Yes, signal form all downhole gauges are available.
Is similar monitoring in place:	No alarms for downhole gauges.
Sources of erroneous indication:	-
Comment	-
Possible indicator 2 Comparing sensor value to the upper and lower range limit.	
Which failure mode can this indicator detect?	*Value out of range* and *Unstable signal*
Is all required data available in excel:	Yes, signal from all downhole gauges are available.
Is similar monitoring in place:	No alarms for downhole gauges.
Sources of erroneous indication:	-
Comment	-

Table 20: Development of the Downhole gauges indicator.

Category: Multiphase flow meter	
Possible indicator 1 Compare current reading with the reading some time ago	
Question	Answer
Which failure mode can this indicator detect?	*No signal from one MFM* and *No signal from multiple MFMs*
Is all required data available in excel:	Yes, signal from MFM is available.
Is similar monitoring in place:	No
Sources of erroneous indication:	-
Comment	
Possible indicator 2 Compare reading to average production last 24 hours.	
Which failure mode can this indicator detect?	*Incorrect values*
Is all required data available in excel:	Yes, both signals are available.
Is similar monitoring in place:	No
Sources of erroneous indication:	Can indicate failure whenever the production is not stable.
Comment	Will give to many erroneous indications of failure.
Possible indicator 3 Compare reading to predefined limits	
Which failure mode can this indicator detect?	*Incorrect values*
Is all required data available in excel	Yes, signal from MFM is available.
Is similar monitoring in place:	No
Sources of erroneous indication:	Will indicate failure when the production is shut down or reduced if it is not linked to opening signal for relevant valves.
Comment	Must be linked to valve signals.

Table 21: Development of the Multiphase flow meter indicator.

Category: External leaks	
Possible indicator 1 Significant pressure drop in the system	
Question	Answer
Which failure mode can this indicator detect?	*External leakage of hydrocarbons* and *External leakage of utility medium*
Is all required data available in excel:	Yes, relevant pressure transmitters are available.
Is similar monitoring in place:	Yes, alarms for significant pressure drops are in place.
Sources of erroneous indication:	Shut down of a well can be indicated as a leakage
Comment	Can only indicate large leaks.
Possible indicator 2 Hydrocarbon-leak detector	
Which failure mode can this indicator detect?	*External leakage of hydrocarbons*
Is all required data available in excel:	No, the hydrocarbon leak detector is not available.
Is similar monitoring in place:	Yes.
Sources of erroneous indication:	Some hydrocarbon detectors can indicate leaks erroneously.
Comment	

Table 22: Development of the External leaks indicator.

Category: Annulus	
Possible indicator 1 Comparing annulus pressure to predefined high pressure alarm limits	
Question	Answer
Which failure mode can this indicator detect?	*Pressure buildup in the annulus*
Is all required data available in excel:	Yes, annulus pressure sensors signals are available.
Is similar monitoring in place:	Yes, CCR have alarm for high annulus pressure.
Sources of erroneous indication:	-
Comment	Can only indicate pressure buildup that exceeds the high limit.
Possible indicator 2 Comparing annulus pressure to the same pressure some time ago to indicate if the pressure has changed	
Which failure mode can this indicator detect?	*Pressure buildup in the annulus* and *Small pressure drops in the annulus*
Is all required data available in excel:	Yes, annulus pressure sensors signals are available.
Is similar monitoring in place:	No, only high pressure alarm for annulus in CCR.
Sources of erroneous indication:	Pressure changes caused by fluid expansion (temperature) can be indicated as leakage.
Comment	-

Table 23: Development of the Annulus indicator.

Category: Choke	
Possible indicator 1 Comparing ratio between choke position and flow measurement to ratio some time ago.	
Question	Answer
Which failure mode can this indicator detect?	*Mismatch between flow and reported position.*
Is all required data available in excel:	Yes, both choke position and flow measurements from the multiphase flow meter is available
Is similar monitoring in place:	No
Sources of erroneous indication:	Can give erroneous indication of choke failure when other parameters affect the flow.
Comment	Only applicable for N-wells with multiphase flowmeter, i.e 5 out of 13 wells.
Possible indicator 2 Comparing ratio between choke position and pressure differential to ratio some time ago.	
Which failure mode can this indicator detect?	*Mismatch between flow and reported position.*
Is all required data available in excel:	Yes, both choke position and pressure up and down stream of choke is available
Is similar monitoring in place:	No
Sources of erroneous indication:	Can give erroneous indication of choke failure when other parameters affect the flow.
Comment	Potentially challenging to develop a formula for ratio that does not indicate choke failure when the choke opening is changed.
Possible indicator 3 Flow coefficient of the choke.	
Which failure mode can this indicator detect?	*Abrasion of the choke valve interior.*
Is all required data available in excel	No, only flow measurements for N-wells.
Is similar monitoring in place:	No
Sources of erroneous indication:	Few sources of error if the input data is good.
Comment	For an indicator based on sensor signals it is only applicable for N-wells with multiphase flowmeter, i.e 5 out of 13 wells

Table 24: Development of the Choke indicator.