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RELIABILITY EVALUATION FOR A SUBSEA TO SHORE PRODUCTION SYSTEM

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Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Oceânica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Oceânica.

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AVALIAÇÃO DE CONFIABILIDADE DE UM SISTEMA SUBMARINO DE PRODUÇÃO DO POÇO À COSTA

Junkai Feng

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Na indústria offshore, a confiabilidade dos equipamentos instalados é de suma importância, devido à segurança operacional, impacto ambiental e conseqüências econômicas. Os custos de interrupção da produção e manutenção não planejadas também têm altas implicações econômicas. A tese tem como objetivo a avaliação da confiabilidade de um novo conceito de produção offshore, do poço à costa, e a relação entre confiabilidade do sistema e garantia de fluxo.

O sistema de produção offshore é assumido como um sistema multi-estado e tratado sob o enfoque da função de geração universal. Com base na análise de probabilidade, a confiabilidade do sistema para todos os cenários de produção prováveis foi abordada. A confiabilidade da produção está altamente relacionada ao retorno financeiro ao investimento, enquanto a confiabilidade do sistema está relacionada com as despesas operacionais durante o ciclo de vida do campo.

A tese considera um sistema de produção submarino do poço à costa para realizar análises de confiabilidade e garantia de escoamento. A confiabilidade da produção depende do desempenho da garantia de fluxo. O ponto vulnerável do sistema é determinado usando a priorização dos níveis de importância dos componentes, conforme proposto por Birnbaum. A relação entre a confiabilidade do sistema e a garantia de escoamento é discutida no contexto dos volumes de petróleo e gás produzidos.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

RELIABILITY EVALUATION FOR A SUBSEA TO SHORE
PRODUCTION SYSTEM

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In the offshore industry, the reliability of installed equipment is of paramount concern due to operational safety, environmental impact, and economic consequences. The costs of unplanned shutdowns and maintenance have also high economic implications. This thesis focuses on system reliability evaluation of a new offshore production concept, the Subsea to Shore system, and the relationship between reliability and flow assurance.

The offshore production system is assumed as a multi-state system and treated with the universal generating function approach. Based on probability analysis the system reliability for all probable production scenarios has been addressed. Production reliability is highly related to the financial return on the investment while the system reliability relates to operational expenditure during the field life cycle.

The thesis considers a Subsea to Shore production system to perform both reliability and flow assurance analyses. Production reliability depends on flow assurance performance. The system weakness point is determined using components importance ranks as proposed by Birnbaum. The relationship between system reliability and flow assurance is discussed in the context of the amount of produced oil and gas.

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Chapter 1.

Introduction

1.1 Background

The demand for oil and natural gas drives the offshore exploration and production to move into deeper and marginal fields. Nowadays, fixed platforms and floating storage platforms have been employed for the production, but for many fields, these concepts are not justified due to economic or harsh environmental aspects. Using long tie-back pipelines to replace the platform is an alternative way to reduce the cost and increase the reliability of the production system. With all the facilities connected to shore by pipelines directly without using the platform, this concept is named Subsea to Shore. It is a new development concept, which in many cases can offer significant benefits over the conventional ones. The offshore equipment of a Subsea to Shore system may locate far away from shore. Consequently, the maintenance work for Subsea to Shore concept is much more difficult than a traditional platform-based concept. For a traditional production system, the lost production and intervention cost are a significant part of the life cycle cost of a subsea well (Brandt & Eriksen, 2001). Unplanned shutdown and maintenance have high economic and even environmental pollution consequences (Rydén, 2003). For a Subsea to Shore system, the consequences will be more serious. Therefore, the reliability of the subsea production system is of paramount concern.

A key component failure that leads to total or partial production loss can also be a flow assurance challenge to the system. Water and hydrocarbon fluids may form solids and disrupt the flow or block the pipeline if the temperature and pressure fall below some specific values (Guo, Song, Chacko, & Ghalambor, 2005).

Overall, production reduction and, eventually, total pipeline blockage happens as the consequence of equipment failure or solid deposit. In order to avoid pipeline blockage and ensure continuous production, system quantitative reliability analysis, and flow assurance analysis are required, the relationship between them also needs to be studied.

1.2 Objectives

Considering that equipment reliability, flow assurance, and the interaction between them directly influence the system production, the thesis aims to contribute to a better understanding the associated failures.

The objectives of the thesis are:

(1) Develop a method for reliability calculation for a Subsea to Shore production system;

(2) Design a Subsea to Shore system;

(3) Perform reliability and flow assurance analyses of the proposed system;

(4) Investigate the interaction of equipment reliability and flow assurance.

In order to achieve these objectives, the traditional reliability analysis method and the universal generating function techniques are introduced for reliability calculation. An eight-wells Subsea to Shore production system is designed considering reliability and flow assurance analyses. Production probabilities are calculated considering equipment failure rate data. Flow assurance analysis is carried out considering equipment in working and failure conditions. Finally, the interaction between equipment reliability and flow assurance is discussed.

1.3 Thesis Organization

The thesis is organized into seven chapters with the main content of each chapter as follows.

Chapter 1 provides a brief introduction to the research background. The Subsea to Shore production system concept is introduced. Motivation and thesis organization are presented in this chapter.

Chapter 2 contains an overview of the open literature and methods related to this topic, including reliability research in offshore engineering, reliability theory of the binary system and multistate system, and flow assurance analysis. The need for reliability is discussed as well as how it is assessed and achieved. Thermal management methods are also reviewed.

Chapter 3 explains the theoretical method for reliability calculation. Universal generating function (UGF) techniques are introduced and then two case studies are carried out, one for a pipeline end manifold and the other one for a n slots manifold.

In Chapter 4, a Subsea to Shore production system is designed. The working principle of the equipment is discussed. In addition, the failure modes and failure rate data for all equipment are presented. Manifold layout methodology is also discussed.

Chapter 5 provides the system reliability calculation process. The production reliability for several production ratios is calculated.

Chapter 6 provides a flow assurance analysis for the Subsea to Shore production system. System cool-down time and power needed for several scenarios are assessed. The relationship between reliability and flow assurance is discussed.

Chapter 7 presents the most important conclusions and some suggestions for further investigations.

Chapter 2.

Literature Review

2.1 Subsea to Shore Production System Overview

The demand for oil and natural gas drives the offshore exploration and production to move into deeper and marginal fields. Nowadays, fixed platforms and floating storage platforms have been employed for the production, but for many fields, these concepts are not justified due to economic or harsh environmental aspects. Using long tie-back pipelines to replace the platform is an alternative way to reduce the cost and increase the reliability of the production system. With all the facilities connected to shore directly without using the platform, this concept is named Subsea to Shore. It is a new development concept, which in many cases can offer significant benefits over the conventional ones. Two recent projects are good examples of the Subsea to Shore production system. One is the Snohvit project (Witting, 2006),(Engebretsen, Fossan, & Nesse, 2002), as shown in Figure 2-1, which lies 140 km from the coast of northern Norway, and the other one also in Norway is the Ormen Lange field located 120 km from the west coast (Gustavsson, Eriksen, Brekke, & Kraggerud, 2003), as shown in Figure 2-2.

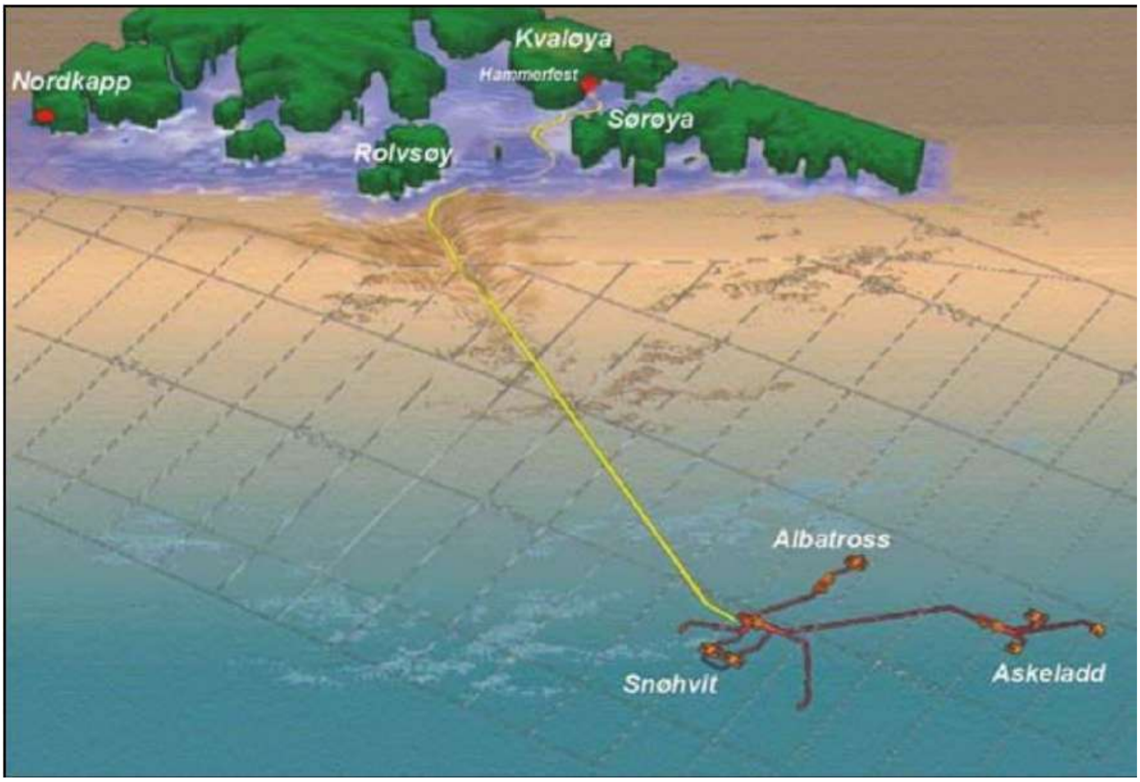


Figure 2-1 Subsea arrangements of Snohvit

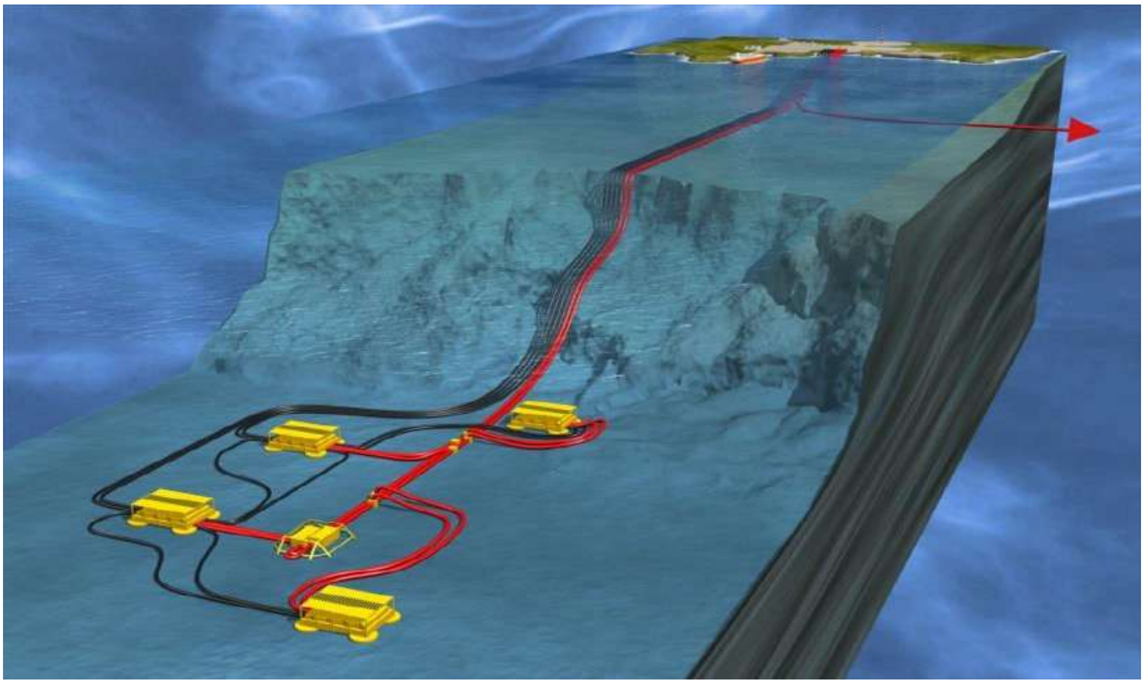


Figure 2-2 Subsea arrangements of Ormen

All the subsea facilities of Snohvit are controlled remotely from shore through one single electro-hydraulic umbilical, and the produced gas piped back to an onshore LNG plant on an island through one single, multiphase pipeline. When the gas arrives on shore, the associated CO_2 is separated from the gas, and then sent back offshore in a separate pipeline for reinjection into the reservoir. The Ormen Lange (Gustavsson et al., 2003) is a natural gas field on the Norwegian continental shelf in water depths varying between 800 to 1100m with water temperature below zero degrees Celsius. All the produced gas from 24 subsea wells is exported directly by two 30in (762 mm) pipelines to an onshore process and export terminal. Since the water temperature is below zero degrees Celsius, reliability aspects and flow assurance are main concerns. In order to prevent ice plugging, Mono Ethylene Glycol (MEG) is injected into each well via a distribution system. Some other subsea developments are listed in Table 2.1.

Table 2.1 Subsea developments

Field	Reserve Type	Water Depth	Distance	Date
Repsol “Poseidon”	Gas & condensate	75-150m	56km	1996
East Spar	Gas	100m	63km	1996
Total Nuggets	Gas	850m	67km	2000
Gorgon	Gas	200m	100km	2008
Burullus Simian Sienna	Gas	650-1100m	112km	2005
Ormen Lange	Gas	120m	120km	2007
Statoil Snøhvit, Norwegian CS	Gas	140m	192km	2006
Shtokman field (Russian Arctic)	Gas & condensate	320m	500km	2016

2.2 Reliability Research in Offshore Engineering

Although the subsea production loss is relatively low in proportion to non-subsea, the cost of failure is significantly higher. Because of the production system is far away from shore, consequently, the maintenance work is much more difficult. In order to ensure continuous production and avoid exporting line blockage, system quantitative reliability analysis is required. Although the reliability of subsea system has been considered important, the offshore industry has few standards for reliability methods and programs. In order to mitigate problems on deepwater developments and ensure that it is perceived as the most cost-effective technology for the exploitation, BP initiated a Deepwater Subsea reliability strategy project in late 1999 with Cranfield University and key subsea equipment manufacturers (Duell & Fleming, 2001). Thirteen inter-linked key processes, such as reliability requirements, reliability analysis, reliability improvement etc.., have been identified as important to well-defined reliability engineering and risk management capability. The researchers found that no specific guidance existed for the setting and allocation of reliability requirements in the subsea process industry (Berg, 2010). Overall the setting of reliability goals was found weak when BP intends to introduce reliability into its subsea system requirements and demand greater assurance from suppliers that reliability can be achieved (Duell & Fleming, 2001).

Witting (Witting, 2006) discussed the limiting factors and technology barriers related to Subsea to Shore. It was concluded that with the use of technology solutions from the Snohvit development and conventional technology already in use elsewhere, it would be technically feasible tie-back distances up to three times that now in place. However, when developing an ultra-long distance field with Subsea to Shore concept, it is important to investigate areas related to flow assurance, power supply, communications, and umbilicals. The key component failure that leads to total or partial production loss of the system can generate flow assurance problems. Water and hydrocarbon fluids can form hydrate and block the pipeline. The deposit of wax and asphaltenes on the pipe wall can also block the pipeline (Guo et al., 2005). Estefen (Estefen et al., 2009) performed an evaluation of technical feasibility, operational reliability and financial return of a particular field offshore Brazil for different scenarios using subsea arrangements associated with the semi-submersible platform, fixed platform, and Subsea to Shore concept. Comparing with dehydrated gas obtained by other scenarios, without water separation in Subsea to Shore scenario means that there will be a higher probability of hydrate formation and consequent pipeline block. Even with this handicap, the cost analysis indicated that the Subsea to Shore scenario had the best net present value. As a general conclusion of this analysis, Subsea to Shore is the best option. However, additional technological developments associated with subsea gas and water separation and gas compression are strongly recommended in order to have a better commercial option available for the innovative concept. Qualitative reliability analyses for each of the three scenarios were considered in Estefen's work. Figure 2-3 illustrates the Subsea to Shore scenario considered in the comparative analysis.

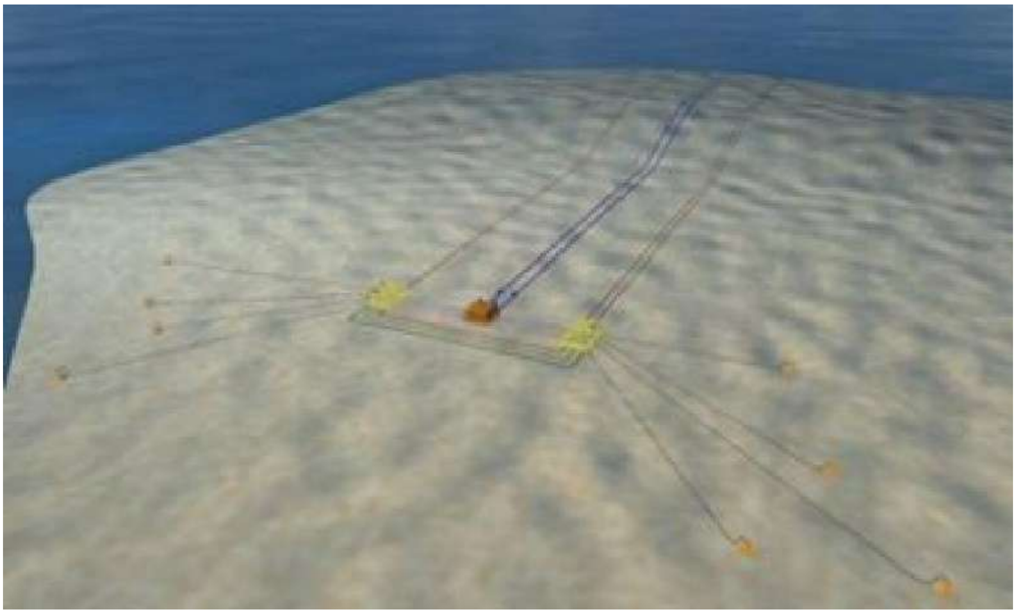


Figure 2-3 Subsea to Shore arrangement

2.3 Reliability Evaluation Techniques

2.3.1 Introduction

Reliability has been praised as a human attribute for a very long time. However, the reliability concept was first applied to a technical system just after World War I in comparing the operational safety of one-, two-, and four-engine airplanes. During the World War II, when Robbert Lusser, a mathematician, tries to analyze the missile system, he derived the product probability law of series components. It says that the reliability of such a system is equal to the product of the reliabilities of the individual components which make up the system. If the system comprises a large number of components, the reliability of the system may be rather low, even though the individual components have high reliabilities. For a long time, systematic analysis of reliability was not carried out, however, by improving the quality of the individual components to compensate the low-reliability system. Professor Norman C. Rasmussen of the Massachusetts Institute of Technology headed the landmark Reactor Safety Study (NUREG, 1975) in the early 1970s. In his study, the risks of the system and the components had to be estimated, rather than measured, because there have been no nuclear accidents to data resulting in significant releases of radioactivity in U.S. commercial nuclear power plants. This study established the formal discipline of Probabilistic Risk Assessment (Sagrilo, de Lima, Henriques, & Rodriguez), and for this, he is known as the father of PRA and Probabilistic Safety Assessment (PSA). After that, similar work had been carried out in other areas, i.e. aerospace and oil engineering. In order to evaluate a system, the most important aspect is to have a complete understanding of the engineering implications of this system. Because of evaluation technique is only a tool for transforming engineer's knowledge into a likely mathematical model that represents the system. An evaluation technique can be chosen only after the complete understanding of the way that the system operates which and how a component can fail, the consequences of the failures and the failure rate data of components. A component or an item in a system is an entity that is no further subdivided. This does not mean that the item cannot be made of parts but as a self-contained unit and is not analyzed in terms of the functioning of its constituents. There are two main categories of reliability evaluation techniques: stochastic simulation and direct analytical techniques (Billinton & Allan, 1992).

2.3.2 Stochastic Simulation

Simulation is a very valuable method which is widely used in the solution of real engineering problems. The process of simulation is the process of replicating the real world based on a set of assumptions and conceived models of reality. The simulation may be performed numerically or experimentally. In practice, theoretical simulation is usually performed numerically; this has become a much more practical tool since the advent of computers (Billinton & Allan, 1992). In effect, theoretical simulation is a method of numerical or computer experimentation. Monte Carlo Simulation is the mainstream method for simulation techniques. By generating a representative configuration of the system to simulate the actual process millions of times, this method can obtain exact results without the need to solve the problem analytically. Monte Carlo methods are especially useful for simulating phenomena with significant uncertainty in inputs and systems with a large number of coupled degrees of freedom. The solution time for Monte Carlo is usually extensive. This is becoming less important with the modern computers and dedicated machines.

2.3.3 Analytical Techniques

Analytical techniques evaluate the system by mathematical solutions for a mathematical model that represents the real system. The mathematical model, or reliability network, may not necessarily have the same topological structure like the real system. Failure modes and effects analysis (FMEA) (Rausand & Arnljot, 2004) and fault tree analysis (FTA) (Stamatelatos et al., 2002; Volkanovski, Čepin, & Mavko, 2009) are the most common analytical solutions.

FMEA is a methodology used to identify and analyze all the potential failure modes, the effects of these failures and how to avoid and/or mitigate the effect of the failures in the whole system. This method is the most widely used reliability analysis technique in the initial stages of product/system development. FMEA is described as mainly a qualitative analysis method in (El-Hawary, 2001; Rausand & Arnljot, 2004). One disadvantage of this method is that differences will appear when split the failure modes from one specialist to another for calculating reliability data. Therefore, the reliability of one system may be reduced or increased based on how the failure modes are split.

FTA is a top-down, deductive failure analysis in which an undesired state of a system is analyzed. This method centered about determining the causes of an undesired event, which referred as the top event since fault trees are drawn to it at the top of the tree. Top events are usually failures of major consequence, engendering serious safety hazards or the potential for significant economic loss. The construction of a fault tree in itself provides the analyst with a better understanding of the potential sources of failure and thereby a means to rethink the design and operation of a system in order to eliminate many potential hazards. Although both qualitative and quantitative evaluations could be performed on an FTA, it is important to point out that a fault tree in principle is a qualitative model, but often could be evaluated quantitatively. The quantitative FTA could be described as a procedure of combining component failure rates to determine the probability of a system fails to perform its required functions. A commonly adopted assumption underlying the quantitative analysis of the FTA is that the system is constituted of binary components, with just two states: functioning or faulty. If the system has more than two output states, the fault tree method will be inapplicable due to its inherent weakness.

2.3.4 Comparison of Simulation and Analytical Solutions

The difference between the analytical and simulation approaches is the way in which the reliability indices are evaluated (Billinton & Allan, 1992). Analytical techniques represent the system by a mathematical model, while simulation techniques estimate the reliability indices by simulating the actual process of the system. There are advantages and disadvantages to both approaches. The analytical technique is relatively time-saving to simulation technique and providing an accurate result if the model is accurate, while the result of the simulation depends on the random number generator and the number of simulations. Simulation techniques can provide complete probability density functions while the analytical method usually can provide only the expected values.

2.3.5 Binary System

A traditional binary model allows only two possible states for a system: perfect functionality and complete failure. Many theories and algorithms exist for evaluating the reliability of the binary system (Billinton & Allan, 1992; Kuo & Zuo, 2003). FTA is a widely used method of evaluation reliability of the binary system (Čepin & Mavko, 2002).

2.3.6 Multistate System

Many real-world systems are composed of multi-state components. For example, system factors that relate to production management, system maintenance that cannot be clearly defined as functioning or faulty. For a subsea production system, the production can be settled on different levels (e.g. 100%, 80%, and 50%) of the nominal capacity, depending on the operating conditions of the constitutive multi-state elements or some sub-system maintenance. This kind of production system is referred to as Multi-State

System (MSS). The difficulty of the modeling task is caused by MSS operational dependency between the system overall state and the state of its components (Zio, 2009). The first attempts to replace the function-or-failed component by multistate component were done in (Barlow & Wu, 1978; El-Neweihi, Proschan, & Sethuraman, 1978; Ross, 1977). By the mid-1980s the basic multistate reliability theory was established. An accident in a French pressurized water reactor provided ample motivation for the multistate reliability theory. In this accident, the emergency battery, which was operating the control system, began to run down from 48V to 30V over a period of three hours instead of precipitous to zero as assumed in the "all or nothing” risk analysis. In response, a number of circuit breakers tripped out until finally the reactor still at full power-300 MW without a cooling system. Even more, unfortunately, the first generator failed to switch on because of the loss of control circuit. Luckily the only backup generator in the system switched on and averting a serious accident. The magazine *Nature* writes: 'The Le Bugey incident shows that a whole new class of possible events had been ignored those where electrical systems fail gradually. It shows that risk analysis must not only take into account a yes or no, working or not working, for each item in the reactor, but the possibility of working with a slightly degraded system.' (Natvig, 2010). A review of the development of the multistate system was given by Natvig in 2007 (Natvig, 2007). In 1986, Natvig (Natvig, Sørmo, Holen, & Høgåsen, 1986) presented a case study on an electrical power generation system for two oil rigs, as shown in Figure 2-4.

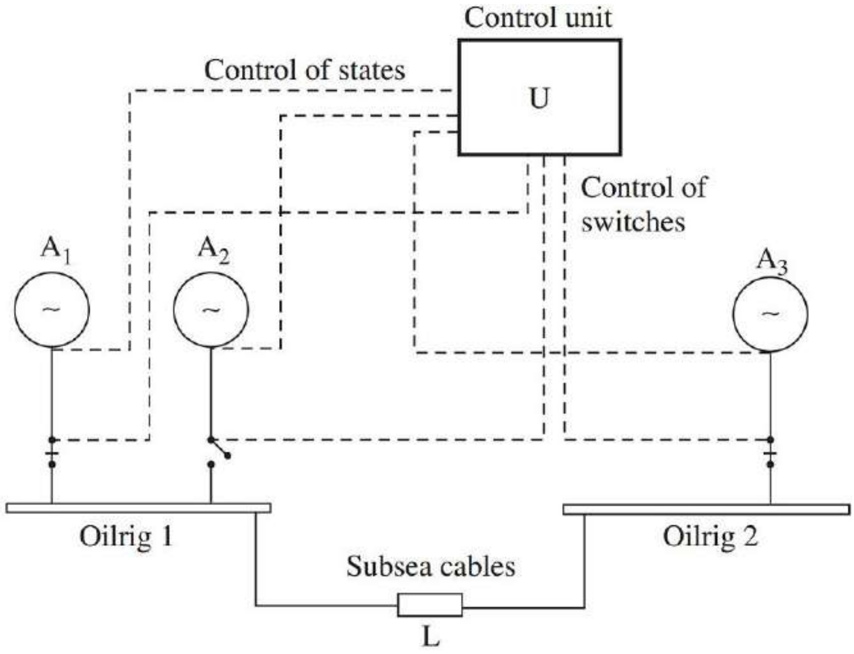


Figure 2-4 Outline of an offshore electrical power generation (Natvig et al., 1986)

Generators A_1, A_2 and A_3 each has a capacity of 50 MW. A_2 is a standby generator that switched into the network in case of an outage of A_1 or A_3. Control unit U continuously supervises the system and automatic control of the switches. All the components have three states *(Engebretsen et al., 2002)*. These states are interpreted in Table 2.2.

Table 2.2 States interpret for the power system

Component	State0	State2	State4
A1,A2,A3	No power supply	Maximum of 25 MW	Maximum of 50 MW
U	Switch A1, A2, A3 off	Can not switch A2 on	Functioning perfectly
L	No power transferred	50% power transferred	100% power transferred

Assume that no power is transferred from A_2 to oilrig 2 if A_2 is needed at oilrig 1 or transferring all power from A_2 needed at oilrig 2. When letting $\varphi 1$ and $\varphi 2$ represent the amount of power that can be supplied to oilrig 1 and 2, and the components A_1, A_2, A_3, U, L successively 1, 2, 3, 4, 5. Then $\varphi 1$ and $\varphi 2$ are given respectively by:

$$\emptyset_1 = I(x_4 > 0)\min(x_1 + x_2 I(x_4 = 4), 4)$$

$$\emptyset_2 = I(x_4 > 0)\min(x_3 + x_2 I(x_4 = 4) I(x_1 = 4) x_5/4, 4) \quad (2.1)$$

Further calculations are presented in (Natvig et al., 1986). Even this method can calculate the reliability of the multistate system, the calculation process is quite complex. Rashid (Rashid et al., 2015) presented a model to assess the reliability of helicopter main gearbox lubricating system. The model used a combination of FTA and influence diagram to analyze key failure mechanisms and the contributory. An MSS analysis was performed using fault tree with binary algorithms (Wood, 1985). It confirms that an MSS is quite difficult to represent by analytical modeling. According to Zio`s work (Zio, 2009), Monte Carlo Simulation appears to be the only feasible approach quantitatively to capture the realistic aspects of the MSS stochastic behavior. Another work was performed earlier to assess the availability of an offshore installation by Monte Carlo Simulation (Zio, Baraldi, & Patelli, 2006). The work showed that the MC is feasible to simulate the production process, although quite complex to produce the code and very time-consuming to run the program. Aven et al. (Aven & Pedersen, 2014; Zio, 2009) conducted a production analysis using flow network modeling and Monte Carlo Simulations. Khakzad (Khakzad, Khan, & Amyotte, 2011) compared fault tree and Bayesian networks by analyses safety aspects of process facilities. The work showed that Bayesian network is feasible to modeling issues which FT is incapable of handlings, such as multi-state variables, dependent failures, and uncertainty. The recently emerged universal generating function (UGF) techniques can provide the entire MSS performance distribution based on the performance distributions of its elements by algebraic procedures. The UGF approach is straightforward, effective and universal. Based on intuitively simple recursive procedures and provides a systematic method, this approach can replace extremely complicated combinatorial algorithms used for enumerating the possible states in MSS and obtained the system's performance in a short time (Levitin, 2005). In addition, The UGF approach is universal. It means the same recursive procedures can be applied to a system with different physical structure and element interaction (Levitin, 2005).

2.3.7 Reliability Data

Available, reliable and consistent data are required to support quantitative reliability evaluation. Generally, the data come from experimental tests or from operational field data. The former is only applicable for small-scale components, which can be tested in sufficient quantities without creating excessive costs. The latter has to be used in all other situations . There are several well-known sources of data, such as NERC-GADS (North American Electricity Reliability Council) and OREDA (Offshore Reliability Data). In this thesis, OREDA database is the main data sources. The OREDA project was initiated by the Norwegian Petroleum Directorate (now: Petroleum Safety Authority) in 1981. Now, the project is sponsored by eight oil and gas companies with worldwide operations. These companies are Total, Statoil, Shell, Petrobras, GDF SUEZ, Gassco, ENI, and BP. The main purpose of OREDA project is to collect and exchange reliability data among the participating companies within the oil and gas industry. Offshore subsea and topside equipment are primarily covered, but onshore equipment is also included (OREDA, 2002). Generally, the result of a Reliability, Availability & Maintainability (RAM) analysis are often lower than experienced in real life, this could relate to the data collection method (Wanvik, 2015).

2.3.8 Reliability Acceptance Criteria

The goal of reliability analysis is to eliminate the unreliability, but it would be naive to believe that this may be completely achieved. As escalating the demand to improve the performance of a product, reducing their cost is also very important to the owner. Fischhoff et al. (Fischhoff, Lichtenstein, Slovic, Derby, & Keeney, 1984) claim that a risk should never be acceptable unconditionally. How high to keep the reliability should be the result of a trade-off analysis. Generally, the reliability should be increased to the As High As Reasonably Practicable region (Vatn, 1998).

2.4 Flow Assurance

The term Flow Assurance was first used by Petrobras in the early 1990s in Portuguese as “Garantia do Escoamento”, meaning literally “Guarantee of Flow” or Flow Assurance. This concept developed because traditional approaches are inappropriate for deepwater production due to extreme offshore distances, water depths, high production pressures and low temperatures involved (Bauck, 2012). Gas hydrate and wax deposits may form and cause blockage, which will reduce or totally shut down the production. Flow assurance is concerned with the ability of a production system to transport the fluids from the tubing bottom to the host facility in a predictable manner over the life of a project. For a general definition, flow assurance describes the phenomena of precipitation and deposition of solids and offers technical solutions. In the development of an oil field, flow assurance is applied during all stages of the development, from the system selection, detailed design, surveillance, to the troubleshooting operation problems and increased recovery in late life. And it is a key factor for the development of a field (Esaklul, Fung, Harrison, & Perego, 2003). In each stage, many specialized subjects such as handling solid deposits of gas hydrates, paraffin (wax), asphaltenes, scale are involved in the flow assurance analysis, usually one or two of these problems dominate in a given oil/gas field. WASDEN (Wasden, 2003) discussed the flow assurance problem that met in deepwater development. Wax and hydrate plug formation are considered as the main problems. In some case, asphaltenes precipitate is formed in heavy crude oil and deposited on the pipe wall (Aja & Ramasamy, 2016). The challenge of flow assurance increases with increasing water depth because the temperature decreases as water depth increase. Typical wax appearance temperatures are 30-50^{o}C while the hydrate formation temperature is typically 20 ^{o}C at 100 Bar. Thus, gas hydrates and wax deposit can occur above some deep-water seabed temperature. Chemical inhibitors, thermal management, and thermo-chemical management are the main available techniques solutions for flow assurance. For long tieback or export pipelines, the volumes of chemical inhibitor required to prevent hydrate or wax deposit without thermal insulation may sometimes be impracticable. Although these chemicals can be recovered to some degree, in Subsea to Shore development, an additional umbilical is necessary for chemical injection, while in traditional subsea development the recycling equipment occupies valuable space on the platform.

2.4.1 Natural Gas Hydrates

Natural gas hydrates are a common threat to production system due to the fact that it can slow or completely block gas flow (Fadnes, Jakobsen, Bylov, Holst, & Downs, 1998), as shown in Figure 2-5. In many cases, within multiphase transportation systems, natural gas hydrate can form a solid or semi-solid mass when gas under conditions of low temperature, high pressure, and present of free water. The formed hydrate particles can attach to the pipe walls, instruments, and other structures within the pipeline, which can then lead to gas measurement errors or instrument failure due to solid particle attachment or high-velocity impacts (Wasden, 2003). Hydrates can also agglomerate and form plugs that can lead to a total flow blockage, which can be a serious safety and operational concern for pipeline operators.

Figure 2-5 Hydrate plug removed from a flowline (Photograph courtesy of Petrobras)

The hydrate forming conditions are predictable with computer programs, such as PVTsim and Multi-Flash etc. There are several methods used for preventing hydrate formation. The obvious methods to avoid hydrate formation are to keep the temperature high, or to keep the pressure low or to dilute water. Chemical injection is one of the most effective ways to avoid hydrate. Mono ethylene glycol (MEG), which shifts the hydrate equilibrium curve from the pipeline operational zone, as shown in Figure 2-6, is the most used chemical for pipeline injection. To reduce costs and the quantity of wasted MEG, MEG is often regenerated.

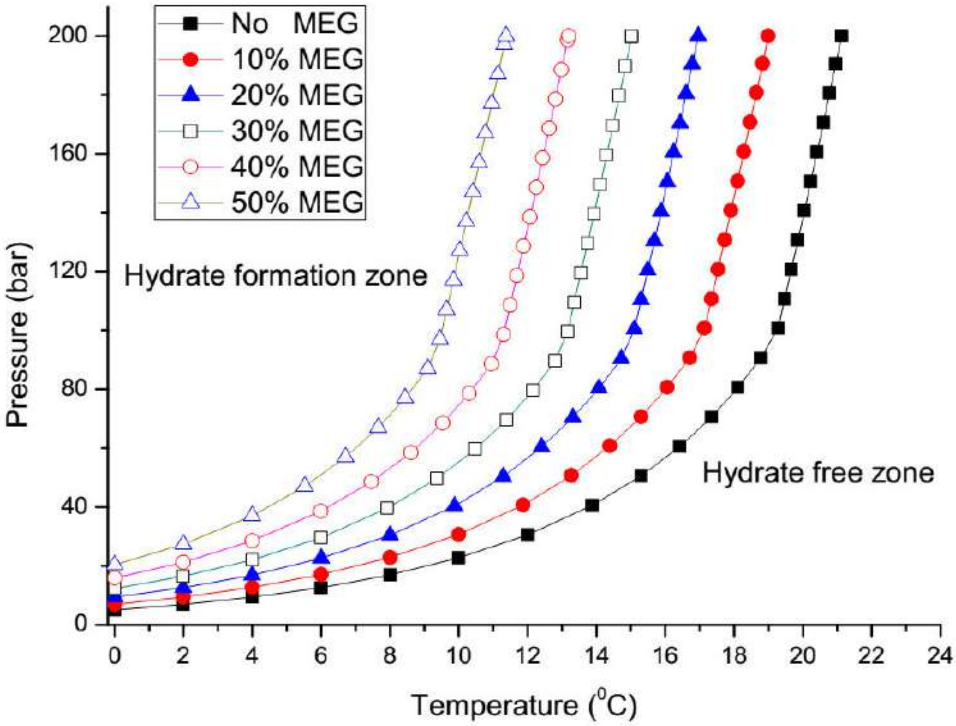


Figure 2-6 Hydrate formation curve with MEG

Although natural gas hydrates, whether occurring in gas/condensate or oil systems, represents the most dramatic flow assurance problem for the deepwater project, luckily identification of pressure and temperature conditions that leads to hydrate formation is a mature technology (Golczynski & Kempton, 2006).

2.4.2 Wax Precipitation and Deposition

Crude oil is a complex mixture of hydrocarbons which consists of aromatics, paraffin, naphthenics, resins, asphaltenes, diamondoids, mercaptans etc. When the temperature of the crude oil is reduced, the heavy components of oil, like paraffin/wax, will precipitate and deposit on the pipe wall (Guo et al., 2005). Paraffinic hydrocarbon fluids can cause a variety of problems in a production system ranging from solids-stabilized emulsions to a gelled flowline. Problems caused by wax occur when the fluid cools down from reservoir conditions and wax crystals begin to form. In some cases, the production fluids have a wax content that makes wax a more critical criterion than hydrates. The cloud point, or Wax appearance temperature (WAT), is the temperature at which paraffin wax starts to precipitate. When the flow is cooled below the cloud point, paraffin wax is precipitated. The whole pipeline can be completely blocked and would cost millions of dollars to remediate an offshore pipeline that is blocked by wax.

2.4.3 Thermal Management

Thermal design includes both steady-state and transient heat transfer analysis. During steady-state operation, the production fluid temperature decreases as it flows along the pipeline due to the heat transfer through the pipe wall to the surrounding environment. The temperature profile in the whole pipeline system should be higher than the requirements for prevention of hydrate and wax formation during normal operation and it is determined from steady-state flow and heat transfer calculations. If the steady flow conditions are interrupted due to a shutdown during operation, the transient heat transfer analysis for the system is required to make sure the temperature of the fluid is out of the solid formation range within the required time. It is necessary to consider both steady-state and transient analyses in order to ensure that the performance of the insulation coatings will be adequate in all operational scenarios (Bai & Bai, 2010). The thermal management strategy for pipelines can be divided into passive control and active heating. Passive control includes pipelines insulated by external insulation layers, pipe-in-pipe (PIP), bundle and burial; and active heating includes electrical heating and hot fluid heating. Applying thermal insulation on the pipeline reduces the well-stream temperature drop between the wellhead/manifold and the processing facility. For shorter distances and/or high reservoir temperatures, this may be a sufficient measure. However, during shut down and production at a lower flow, it is difficult to maintain the well-stream temperature above the critical limit. By heating the pipeline electrically, the need for chemical injection is reduced considerably. Electrical heating has shown to be very suitable for long pipelines since heat can be generated evenly along the whole length (Munkvold & Knoff, 2006; Nysveen, Kulbotten, Bomes, & Hoyer-Hansen, 2005). Nonelectrical options, such as hot water supply using pipes embedded in the thermal insulation, are not dealt with here.

2.4.3.1 Overall Heat Transfer Coefficient

There are three basic mechanisms of heat transfer: conduction, convection, and radiation. The term conduction refers to the heat transfer that occurs across a stationary medium, which may be a solid or fluid. In contrast, the term convection refers to heat transfer that occurs between a surface and a moving fluid when they are at different temperature. The radiation happens between surfaces at different temperatures even if there is no medium between them as long as they face each other (Bergman, Lavine, Incropera, & Dewitt, 2011).

The temperature profiles may be determined in cylinder coordinates for each pipe layer

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = 0 \tag{2.2}$$

The heat transfer rate in the radial direction is expressed by:

$$Q = -KA\frac{\partial T}{\partial r} \tag{2.3}$$

Where k is material thermal conductivity and A is the area normal to thermal flow, and the constant Q is the heat transfer rate.

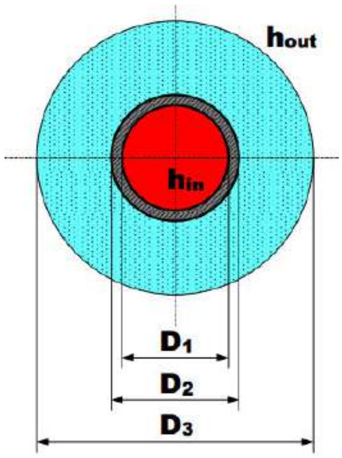


Figure 2-7 Pipeline cross section

For a pipeline shown in Figure 2-7, the overall heat transfer coefficient U, which is a measure of the overall ability of a series of conductive and convective barriers to transfer heat, can be obtained by

$$U = \frac{1}{\frac{D_3}{D_1 \cdot h_{in}} + \frac{D_3 \cdot \ln\left(\frac{D_2}{D_1}\right)}{2 \cdot k_{pipe}} + \frac{D_3 \cdot \ln\left(\frac{D_3}{D_2}\right)}{2 \cdot k_{insulation}} + \frac{1}{h_{out}}} \tag{2.4}$$

where h is the heat transfer coefficient, k is the material thermal conductive.

2.4.3.2 Active Heating

Active heating systems are a practical and cost-effective development option for control of solid formation. This concept provides increased operational flexibility through control of the pipeline temperature above the hydrate formation and wax deposition temperatures, allowing for prolonged shutdowns, conditioning of the line for resuming operation or melting of hydrate/wax plugs formed during extended shutdowns (Esaklul et al., 2003). This is also a cost efficient and environmentally sustainable flow assurance method that replaces the use of chemicals.

Direct Electric Heating (DEH) is based on using the thermally insulated flowline as part of the electric circuit, and allowing the electrical losses to heat and keep the pipeline and its content above the critical temperatures. A DEH system arrangement is shown in Figure 2-8. Today, DEH is a mature technology that has been in use since the year 2000. The main data of DEH system are presented in Table 2.3.

Table 2.3 Main data of DEH system

Main Data		State of the art
Typical current range	700A up to 1600A	Yes
Typical voltage range	2 kV up to 26 kV	Yes
Typical power range	1000-12000 kW	Yes
Typical pipe length	4-50 km	No

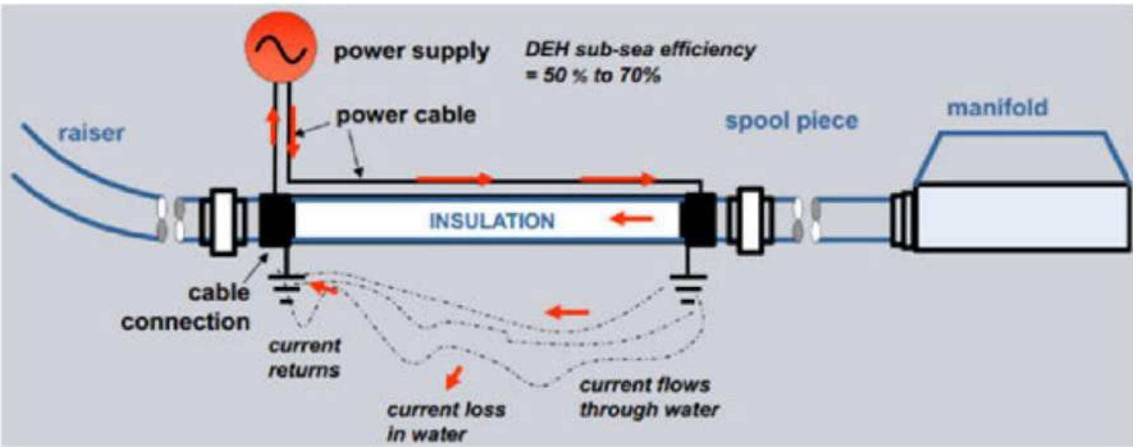


Figure 2-8 A DEH system arrangement

Chapter 3.

Theoretical Background

3.1 Reliability Calculation

It is necessary for engineering analysis to define reliability quantitatively as a probability. Thus reliability is defined as the probability that a system will perform its intended function for a specified period of time under a given set of conditions (Lewis, 1994). Here the system can be subsystem, equipment, components or part. In the broadest sense, the system also can be a software, even a human. A system is said to fail when it ceases to perform its intended function. Then a failure is defined as the termination of the ability of an item to perform a required function (Terminology, 2001). After the failure, the item has a fault. For some system, a fault can be a total cessation of functional valve can`t open, while for some other system, the fault may be a deterioration of functional pipeline with solid deposited and reducing delivery capacity. A probability density function (PDF) is a function, denoted by $f(t)$, that describes the relative likelihood for a random variable to take on the given value. When describing the probability of a discrete random variable exactly equal to some value, the function is called probability mass function (PMF). Based on this characteristic, the PDF and PMF are nonnegative everywhere, and its integral over the entire space is equal to one. Cumulative distribution function (CDF), denoted by $F(t)$, describes the probability that a real-valued variable T with a given probability distribution will be found to have a value less than or equal to t. The CDF can be expressed as the integral of its PDF.

$$F(t) = Pr(T < t) = \int_0^t f(t)dt \qquad for \;\; t > 0 \tag{3.1}$$

where $P_r(A)$ denotes the probability of event A. $F(t)$ is the probability that a system will fail during a specific period of $(0;t]$. Reliability is the probability that a system will not fail during $(0;t]$. The reliability of an item is defined by:

$$R(t) = 1 - F(t) = \int_t^{+\infty} f(t)dt \tag{3.2}$$

An example of the curve of cumulative distribution and density functions are presented in Figure 3-1.

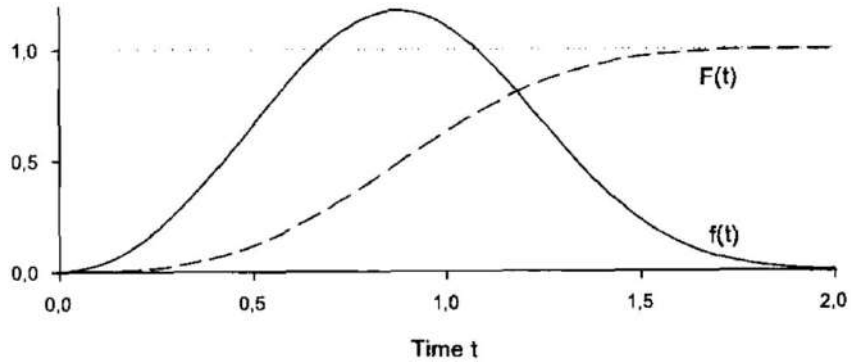


Figure 3-1 Cumulative and density function distribution

For a technical component or system, the reliability can be analyzed in two ways, the physical approach and the actuarial approach (Rausand & Arnljot, 2004). The physical approach is mainly used for reliability of structural elements, and therefore often called structural reliability analysis (Ditlevsen & Madsen, 2007; Nowak & Collins, 2012; Sagrilo et al., 1997). The actuarial approach is often used in system reliability analysis.

In the physical approach, the strength of a technical item and the load it is exposed are modeled as two random variables. A failure will occur as soon as the load is higher than the strength. The distributions of the strength and the load are illustrated in Figure 3-2.

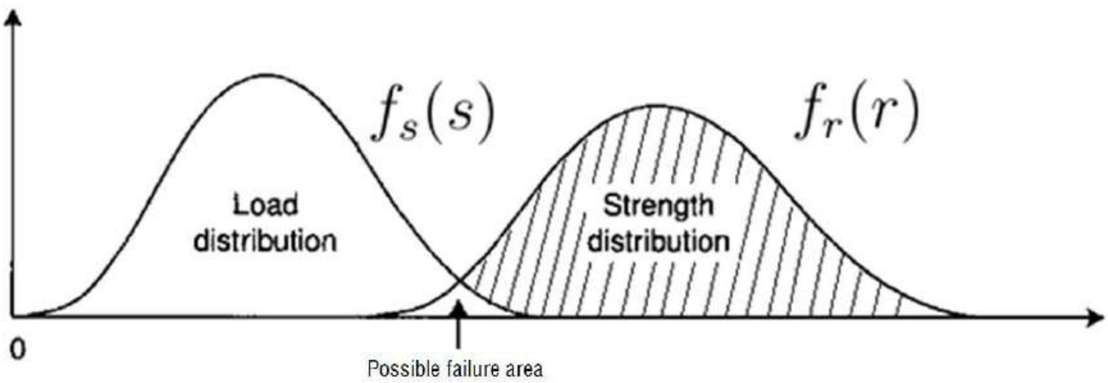


Figure 3-2 Load and strength distributions

The reliability *R* is defined as the probability that the strength is greater than the load,

$$R = P_r(S > L) \tag{3.3}$$

$$R(t) = \int_{-\infty}^{+\infty} f_r(r)\left[\int_{-\infty}^{r} f_s(s)ds\right]dr \tag{3.4}$$

In the actuarial approach, no modeling of the loads and the strength is carried out. Reliability characteristics are deduced directly from the probability distribution function obtained from the results of tests or experiments. Consider there are N_0 identical components being tested, $N_f(t)$ components fail and, $N_s(t)$ components survive during the time, the reliability function is given by:

$$R(t) = \frac{N_s(t)}{N_0} = 1 - \frac{N_f(t)}{N_0} \tag{3.5}$$

When we have failure rate data from identical items that have been operating under the same or similar operational and environmental conditions, we have a so-called homogeneous sample. The only data we need to estimate is the failure rate $\lambda(t)$ for a homogeneous sample are the observed number of failures and the aggregated time in service. Let $\lambda(t)$ be the number of units failing per unit time. In practice, the aggregated time in service is usually expressed in 10^6 hours and consequently, the failure rate is expressed in the number of failures per 10^6 hours. The estimator of failure rate is given by (OREDA, 2002):

$$\lambda(t) = \frac{Number\ of\ \ failures}{Aggregated\ time\ in\ service} = \frac{N_f(t)}{N_0 \times t} \tag{3.6}$$

The uncertainty of the estimate λ may be presented by a confidence interval. For a 90% confidence interval, the true value is covered by the interval with a probability of 90%. With failures during an aggregated time τ , this 90% interval is given by:

$$\left(\frac{1}{2\tau} z_{0.95,2n}, \frac{1}{2\tau} z_{0.05,2(n+1)} \right) \tag{3.7}$$

where $z_{0.95,\nu}$ and $z_{0.05,\nu}$ denote the 95% and 5% percentiles, respectively, of the χ^2 distribution with ν degrees of freedom.

The equation (3.6) is valid under the assumption of a so-called homogeneous sample or for identical items under the same operation station. In many cases, the aggregated data for an item may come from different installations with different operational and environmental conditions. In these cases, we may decide to merge several homogeneous samples into what's called a multi-sample. This procedure will not be discussed here, but it is presented in the reference OREDA (OREDA, 2002).

The general expression for failure rate at a time t is

$$\begin{aligned}\lambda(t) &= \frac{dN_f(t)}{dt}\cdot\frac{1}{N_s(t)} \\ &= \frac{dN_f(t)}{dt}\cdot\frac{1}{N_0}\cdot\frac{N_0}{N_s(t)} \\ &= \frac{dF(t)}{dt}\cdot\frac{1}{R(t)} \\ &= -\frac{dR(t)}{dt}\cdot\frac{1}{R(t)}\end{aligned} \tag{3.8}$$

According to the integral algorithm, the $R(t)$ may be obtained by:

$$R(t) = exp\left[-\int_0^t \lambda(t)dt\right] \tag{3.9}$$

The failure rate $\lambda(t)$ changes throughout the life of an item. In reliability literature, it is suggested that the failure rate varies with time for a technical item according to a bathtub shape. The failure rate function curve has three evident partial shapes and the lifetime may generally be split into three phases: the burn-in phase, the useful life phase, and the wear-out phase. The whole curve is called “bathtub” curve because of its characteristic shape and is often claimed to be a realistic model for mechanical equipment (OREDA, 2002), as shown in Figure 3-3.

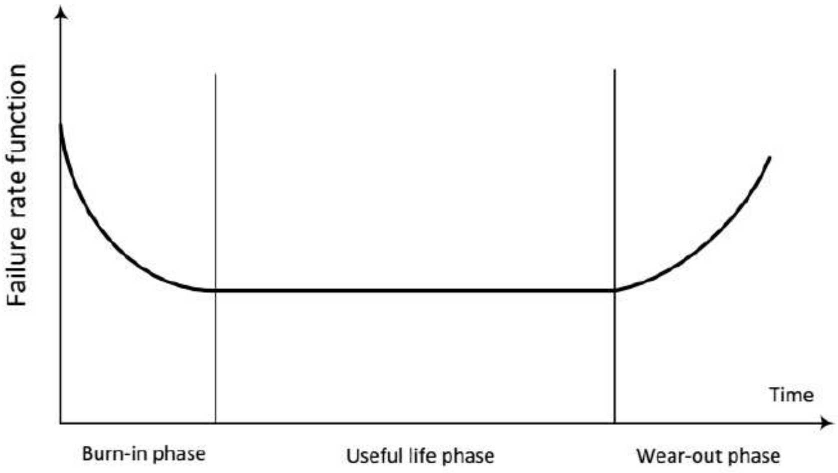


Figure 3-3 Bathtub shape of the failure rate

The So-called burn-in problems may be caused by inherent quality problems with the item, or by installation problems. For a subsea production system, because the inherent quality and installation problems may be removed by careful testing, meanwhile the items often be replaced or refurbished before they reach the wear-out phase, most of the failure events, therefore, come from the useful life phase, where the failure rate is close to constant. This specific relationship is used when estimating the average failure rate for a number of items (OREDA, 2002). For this special case,

$$\lambda(t) = \lambda \tag{3.10}$$

Therefore, the reliability of an item follows an exponential distribution, Equation (3.9) simplifies to

$$R(t) = e^{-\lambda t} \tag{3.11}$$

There are two basic reliability networks for a system: series and parallel. For items whose functions are organized in series, or must all items work for a system success, are called series system, as shown in Figure 3-4. The reliability of the network can be obtained by the product of the reliability of each item, as indicated in Equation (3.12).

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{3.12}$$

For items whose functions are in parallel or only one item necessary working for a system success, is called parallel system, as shown in Figure 3-5. The parallel system reliability can be calculated by:

$$R_s(t) = 1 - \prod_{i=1}^{n} \left[1 - R_i(t)\right] \tag{3.13}$$

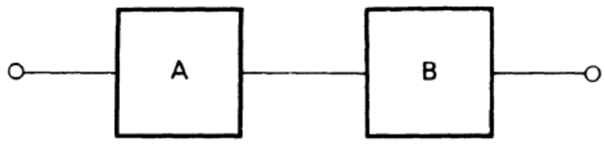


Figure 3-4 Two component series system

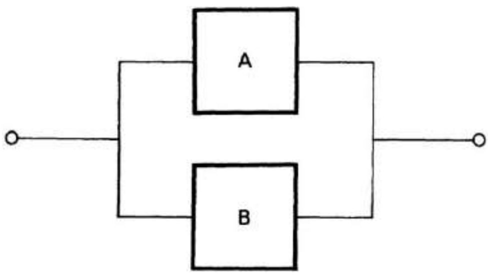


Figure 3-5 Two component parallel system.

A combination of two types of the system described previously is called a series-parallel system, as shown in Figure 3-6. This system can be analyzed by combining appropriate series and parallel branches until a single equivalent element remains. A partially-redundant system, also called k-out-of-n system, is a system of components that functions (fails) if at least k components function (fail). Consider a trial in which the only outcome is either success or failure. The variable is said to be a Bernoulli Random Variable if the probability mass function is given by (Verma, Srividya, & Karanki, 2010):

$$\begin{aligned} P(X=1) &= p \\ P(X=0) &= 1-p \end{aligned} \tag{3.14}$$

where p is the probability that the trial will success. The probability of k components will function of a k-out-of-n system is given by:

$$P(k \mid n) = C_n^k p^k (1-p)^{n-k} \qquad k = 0,1,2,...n \;\; k \le n \tag{3.15}$$

A k-out-of-n system function if k or more components function. The probability of a k-out-of-n system success is given by:

$$P(X \ge k) = \sum_{i=k}^{n} C_n^i p^i (1-p)^{n-i} \qquad k = 0,1,2,...n \;\; k \le n \tag{3.16}$$

The parallel system consists of two or more branches connected in parallel and both branches were operating simultaneously. In some case, the redundant components may not be continuously operating but in a standby mode until when a normally operating component fails. This system is called standby redundant system, as shown in Figure 3-7.

If the system does not fail during switching operation, the reliability of the system is given by:

$$R_s = 1 - R_A \times R_B \tag{3.17}$$

A more complicated system that cannot be analyzed by simple techniques provided previously is called Bridge type system, as shown in Figure 3-8. The system success requires that at least one of the parts AC, BD, AED or BEC is good. There are several techniques available for solving this type of network, including the conditional probability approach, cut set analysis and tree diagrams (Billinton & Allan, 1992). The conditional approach is to reduce sequentially the system into subsystem structures that are connected in series/parallel and then to recombine these subsystems using the conditional probability method.

$$\begin{aligned} R_s &= [1-(1-R_A)(1-R_B)]*[1-(1-R_C)(1-R_D)]*R_E \\ &\quad +[1-(1-R_A*R_C)*(1-R_B*R_D)]*(1-R_E) \\ &= R_AR_C + R_BR_D + R_AR_DR_E + R_BR_CR_E - R_AR_BR_CR_D \\ &\quad - R_AR_CR_DR_E - R_AR_BR_CR_E - R_BR_CR_DR_E \\ &\quad - R_AR_BR_DR_E + 2R_AR_BR_CR_DR_E \end{aligned} \tag{3.18}$$

which, if $R_A = R_B = R_C = R_D = R_E = R$, gives

$$R_S = 2R^2 + 2R^3 - 5R^4 + 2R^5 \tag{3.19}$$

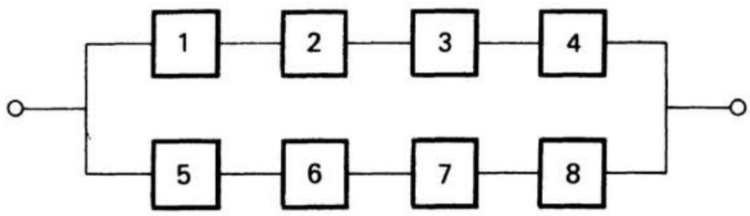


Figure 3-6 Series-parallel system

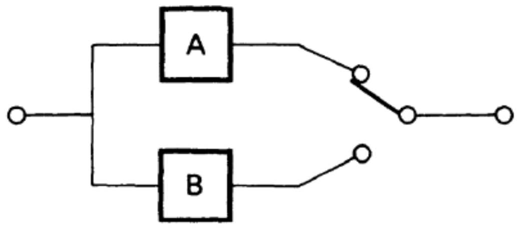


Figure 3-7 Standby Redundancy System

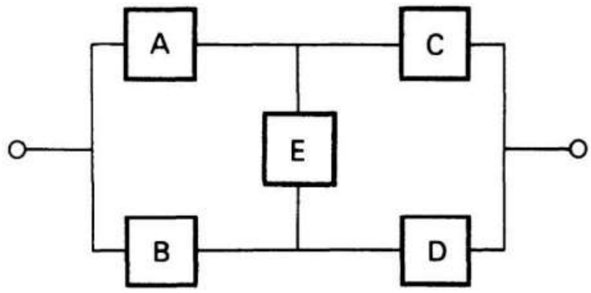


Figure 3-8 Bridge-Type System

3.2 Multistate Reliability Calculation

Before proceeding to the system reliability evaluation, a short introduction to some of the main concepts in multistate reliability theory is given. Some definitions are also given in Natvig's paper (Natvig et al., 1986).

Consider a random variable S that can take on a finite number of possible values represented by the finite vector $s = \{s_0, s_1, .., s_k\}$, the $k+1$ states representing successive levels of performance ranging from the perfect functioning level k down to the complete failure level 0. The corresponding probabilities of the vector s are represented by a finite vector $p = \{p_0, p_1, .., p_k\}$ consisting of the $p_i = \Pr\{X = x_i\}$. Depending on the system complexity, k can be set as at least 1 for a binary component or a larger number for a multistate component. The mapping from s to p is called the

PMF. S must take one of the values s_i. The PMF is nonnegative everywhere and its integral over the entire space is equal to one, therefore

$$\sum_{i=0}^{k} p_i = 1 \tag{3.20}$$

The mean or expected value of S is defined as a weighted average of the possible values that S can take on, where each value is weighted by the probability that S takes on that value:

$$E(S) = \sum_{i=0}^{k} s_i p_i \tag{3.21}$$

The expected value measures the center of the probability distribution - the center of mass. For a particular equipment, for example, a subsea X-mas tree, the expected value of the probable production states represents the average production output. The moment-generating function $m(t)$ of the discrete random variable S with PMF is defined for all values of t by:

$$m(t) = E(e^{tS}) = \sum_{i=0}^{k} e^{ts_i} p_i \tag{3.22}$$

There is a one-to-one correspondence between the PMF and the moment generating function. By replacing the function e^t by a variable z in equation (3.22), the transform function of a discrete random variable S can be obtained by (Grimmett & Stirzaker, 2001; Ross, 2014).

$$\omega(z) = E(z^S) = \sum_{i=0}^{k} z^{s_i} p_i \tag{3.23}$$

The moments of the random variable can be obtained by successively differentiating. It is easy to observe that the expected value of S is equal to the first derivative of $\omega(z)$ at $z = 1$. The system reliability measure can now be obtained as $E(S) = \omega'(1)$.

$$\omega'(z) = \sum_{i=0}^{k} x_i z^{x_i - 1} p_i \tag{3.24}$$

Hence,

$$E(S) = \omega'(1) = \sum_{i=0}^{k} x_i p_i \tag{3.25}$$

The most important property for system performance evaluation is that the z-transform of the sum of independent random variables, for example, random variables X and Y, is the product of the individual z-transforms of these variables:

$$
\begin{aligned}
\omega_{X+Y}(z) &= \sum_{i=0}^{k_x}\sum_{j=0}^{k_y} z^{x_i+y_j} p_{x_i} p_{y_j} \\
&= \sum_{i=0}^{k_x}\sum_{j=0}^{k_y} z^{x_i} p_{x_i} z^{y_j} p_{y_j} \\
&= \sum_{i=0}^{k_x} z^{x_i} p_{x_i} \sum_{j=0}^{k_y} z^{y_j} p_{y_j} \\
&= \omega_X(z)\omega_Y(z)
\end{aligned}
\tag{3.26}
$$

And in general, considering a system comprises n independent items with the states represented by discrete random variables $X_1, X_2, \cdots, X_n$, the z-transform of the sum of random variables can be obtained by the product of all the z-transform polynomials of each item's state:

$$
\omega_{(\sum_{i=1}^{n} X_i)}(z) = \prod_{i=1}^{n} \omega_{X_i}(z) \tag{3.27}
$$

The composition operation method for the z-transform of n independent variables may differ from the polynomial product. Considering a component comprises two independent items with the states represented by discrete random variables X_1, X_2. If the two items in a series structure, the performance of the component can be obtained by finding the minimum value of the composition in each combination of X_1 and X_2, as $Y = \min(X_1, X_2)$. In converse, if the two items in a parallel structure, the performance of the component will be obtained by finding and sum the maximum value of the composition in each combination, as $Y = \max(X_1, X_2)$, more details will be calculated in the following case study parts. Therefore, a more general composition operator $\frac{\bigcirc,x}{f}$ with the arbitrary function f is introduced. The function can be to find the min, max or sum of the combinations. The technique based on using the z-transform composition operator $\frac{\bigcirc,x}{f}$ is named the universal generating function (UGF) technique. The UGF technique is based on enumerative approach, which is extremely resource consuming. For example, each possible value of function f corresponds to a combination of the values of its arguments $X_1, X_2, \cdots, X_n$, therefore the total number of possible combination is

$$K = \prod_{i=1}^{n} (k_i + 1)$$

Fortunately, many different combinations produce the same value, therefore the probability of this value equals to the sum of the probabilities of these combinations producing this value. This simplification technique will reduce considerably computational burden. The function of the items state X_n and the system state Y can be expressed by the deterministic function, which also called the system structure function, as:

$$Y = \phi(X_1, \ldots, X_n) \tag{3.28}$$

The total flow of n parallel pipes equals to the sum of the flows through each of these pipes, therefore, the total flow can be obtained as:

$$
\begin{aligned}
Y &= \emptyset(X_1, X_2, \dots, X_n) \\
&= \omega(X_1 + X_2 + \cdots + X_n) \\
&= \omega(X_1) \frac{\bigcirc,x}{+} \omega(X_2) \dots \frac{\bigcirc,x}{+} \omega(X_n) \\
&= \prod_{i=1}^{n} \omega_{X_i}(z)
\end{aligned}
$$

For the reliability of a component with n items in a series structure, the state of the component can be obtained by:

$$
\begin{aligned}
Y &= \emptyset(X_1, X_2, \dots, X_n) \\
&= \omega\left(X_1 \frac{\bigcirc,x}{min} X_2 \frac{\bigcirc,x}{min} \dots \frac{\bigcirc,x}{min} X_n \right) \\
&= \omega(X_1) \frac{\bigcirc,x}{min} \omega(X_2) \dots \frac{\bigcirc,x}{min} \omega(X_n)
\end{aligned}
$$

For the reliability of a component with n items in a parallel structure, the state of the component can be obtained by:

$$
\begin{aligned}
Y &= \emptyset(X_1, X_2, \dots, X_n) \\
&= \omega\left(X_1 \frac{\bigcirc,x}{max} X_2 \frac{\bigcirc,x}{max} \dots \frac{\bigcirc,x}{max} X_n \right) \\
&= \omega(X_1) \frac{\bigcirc,x}{max} \omega(X_2) \frac{\bigcirc,x}{max} \dots \frac{\bigcirc,x}{max} \omega(X_n)
\end{aligned}
$$

The MSS behavior is unambiguously characterized by its states. Generally, the entire set of possible system states can be divided into two main disjoint subsets corresponding to acceptable and unacceptable system state. The MSS reliability can be defined as its ability to remain in the acceptable states during the operation period Levitin (2005). An MSS state acceptability depends on the relation of MSS real performance and the demand performance. A state is acceptable if its performance is in the internal of demand performance, if not, this state is unacceptable. Assuming an MSS can take on a finite number of possible values represented by a finite vector $S = \{s_0, s_1, \dots, s_i, s_j, \dots, s_m, s_n, \dots s_T\}$, the $T+1$ states representing successive levels of performance ranging from the maximum output level T down to the complete failure level 0. The corresponding probabilities of the vector S are represented by a finite vector $P = \{p_0, p_1, \dots p_i, p_j, \dots, p_m, p_n, \dots p_M\}$. When the demand performance is ranging from A to B, the system availability can be obtained by:

$$F(S, A) = \sum_{n=j}^{m} p_n \quad s_i < A \leq s_j \;\; s_m < B \leq s_n \tag{3.29}$$

3.2.1 A Case Study of PLET Production

Consider a pipeline end manifold (PLET) which receives the production flow from two pipelines, as shown in Figure 3-9. The two valves are assumed to be intact. Let two independent discrete random variables X_1 and X_2 represent the states of flow for each flowline. The two variables with PMF $s_1 = (0,1)$, $p_1 = (0.1, 0.9)$ and $s_2 = (0, 0.5, 1)$, $p_2 = (0.1, 0.4, 0.5)$.

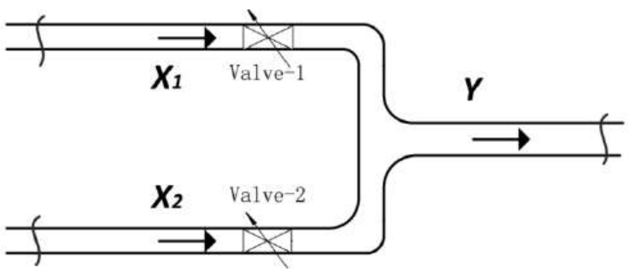


Figure 3-9 Flow of a PLET

The production for the PLET is the sum of the two variables X_1 and X_2. Thus the system structure function is expressed as

$$Y = X_1 + X_2$$
$$\omega(Y) = \omega(X_1)\omega(X_2) \tag{3.30}$$

According to Equation (3.23), the z-transform of each variable takes the form:

$$\omega(X_1) = \sum_{i=0}^{1} z^{s_{1i}} p_{1i} = 0.1z^0 + 0.9z^1 \tag{3.31}$$

$$\omega(X_2) = \sum_{j=0}^{2} z^{s_{2j}} p_{2j} = 0.1z^0 + 0.4z^{0.5} + 0.5z^1 \tag{3.32}$$

The z-transform for the total production the PLET can be obtained by

$$\begin{aligned}\omega_Y(z) &= \omega(X_1)\omega(X_2) \\ &= (0.1z^0 + 0.9z^1)(0.1z^0 + 0.4z^{0.5} + 0.5z^1) \\ &= 0.01z^0 + 0.04z^{0.5} + 0.05z^1 + 0.09z^1 + 0.36z^{1.5} + 0.45z^2 \\ &= 0.01z^0 + 0.04z^{0.5} + 0.14z^1 + 0.36z^{1.5} + 0.45z^2\end{aligned} \tag{3.33}$$

The expected value of Y can be obtained by

$$E(Y) = \omega'(1) = 0.04\times0.5 + 0.14\times1 + 0.36\times1.5 + 0.45\times2 = 1.6 \tag{3.34}$$

3.2.2 A Case Study of Manifold Production

This case is for calculating the total output production for two export pipelines of a Manifold. Consider a simplified n slots manifold receiving flow from n flowlines and then exporting the flow to two export pipelines, as shown in Figure 3-10.

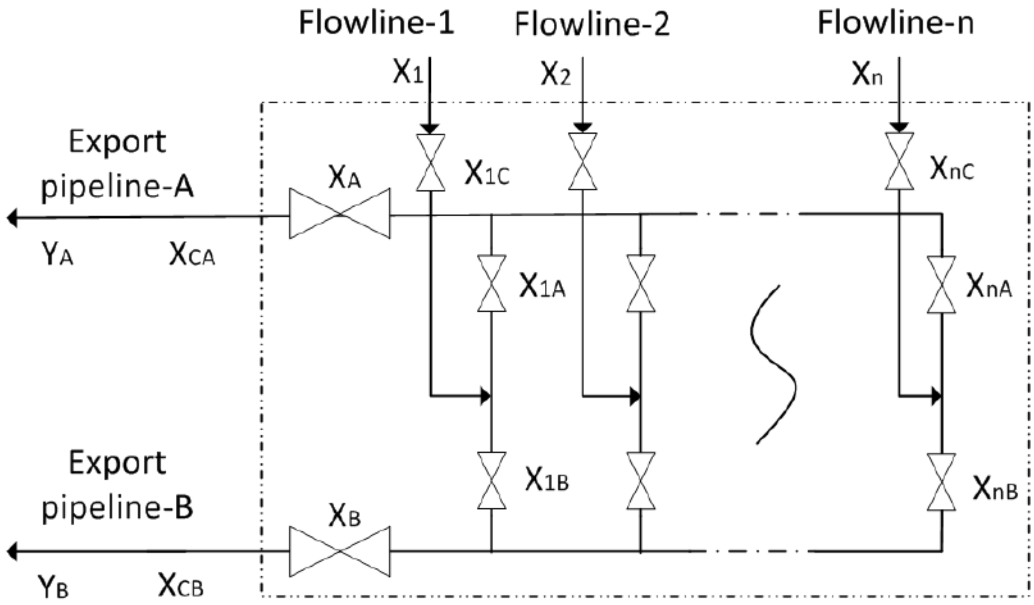


Figure 3-10 Flow of a Manifold

Let n independent discrete random variables $X_1, X_2, ..., X_n$ represent the flow states for the n flowlines. In order to simplify the calculation, the n flowlines are assumed to have the same production states, which equivalent to $X_1 = X_2 = ... = X_n$. Let $X_{1A}, X_{1B}, X_{1C}, X_A, X_B$ represent the states of the valves in the Manifold. The valves are assumed to have just two states, full functioning or total fail. Let X_{CA}, X_{CB} represent the capacity of the two export pipelines. The capacity indicates the transportability for an item. Generally, the nominal capacity of an item is equal or a little larger than the required normal production state transportation capacity; but in some case, a pipeline will transport more to increase production when the other one in a shut-in situation or in a reduced production situation. Needless to say, the maximum capacity of a pipeline is covered by designed safety range. In this case, the capacity for each of the two export pipelines is 60% of the Manifold capacity. Let Y_A, Y_B represent the flow state inside the two export pipelines and let Y_M represents the state of the total flow transported out. The PMF of these variables is presented in Table 3.1. For the items with same PMF, only one set of variables is presented.

Table 3.1 PMF of random variables

X_1	s	1	0.80	0
	p	0.95	0.04	0.01
X_A	s	1	0	-
	p	0.99	0.01	-
X_{CA}	s	0.6n	0	-
	p	0.99	0.01	-

- represents no this state

The three variables X_{1C}, X_{1A} and X_{1B} constitute a subsystem. This subsystem fails either if the valve represented by X_{1C} fails or the two the valves represented by X_{1A} and X_{1B} failing simultaneously. Because of every valve only have two states in this case, the subsystem is also called a series-parallel binary system. Although the evaluating method for binary system reliability is well developed, the multistate method is introduced considering that multistate item may be used in the other series-parallel structure case. Let Y_1 represents the state for the subsystem, and then the subsystem structure function can be expressed as

$$Y_1 = \phi\ (X_1, X_{1C}, X_{1A}, X_{1B}) = min(X_1, min(X_{1C}, max(X_{1A}, X_{1B}))) \tag{3.35}$$

Now let us introduce two auxiliary random variables, and let Y_S represents the states for the sum of production for the n subsystems. Then Y_S can be obtained by function recursively:

$$X_{T1} = max(X_{1A}, X_{1B}) \tag{3.36}$$

$$X_{T2} = min(X_{1C}, X_{T1}) \tag{3.37}$$

$$Y_1 = min(X_1, X_{T2}) \tag{3.38}$$

$$Y_S = Y_1 + Y_2 + ... + Y_n \tag{3.39}$$

The PMF of Y_1 can be obtained by using composition operators over the z-form equations as follows:

$$\begin{aligned}\omega_{X_{T1}}(z) &= max[\omega_{X_{1A}}(z), \omega_{X_{1B}}(z)] \\ &= max[(0.99z^1 + 0.01z^0), (0.99z^1 + 0.01z^0)] \\ &= 0.99 \times 0.99 z^{max(1,1)} + 0.99 \times 0.01 z^{max(1,0)} \\ &\quad +0.01 \times 0.99 z^{max(0,1)} + 0.01 \times 0.01 z^{max(0,0)} \\ &= 0.9999z^1 + 0.0001z^0\end{aligned} \tag{3.40}$$

$$\begin{aligned}\omega_{X_{T2}}(z) &= min[\omega_{X_{1C}}(z), \omega_{X_{T1}}(z)] \\ &= min[(0.99z^1 + 0.01z^0), (0.9999z^1 + 0.0001z^0)] \\ &= 0.99 \times 0.9999 z^{min(1,1)} + 0.99 \times 0.0001 z^{min(1,0)} \\ &\quad +0.01 \times 0.9999 z^{min(0,1)} + 0.01 \times 0.0001 z^{min(0,0)} \\ &= 0.989901z^1 + 0.010099z^0\end{aligned} \tag{3.41}$$

$$
\begin{aligned}
\omega_{Y_1}(z) &= min[\omega_{X_1}(z), \omega_{X_{T2}}(z)] \\
&= min[(0.95z^1 + 0.04z^{0.8} + 0.01z^0), (0.989901z^1 + 0.010099z^0)] \\
&= 0.95 \times 0.989901z^{min(1,1)} + 0.95 \times 0.010099z^{min(1,0)} \\
&+0.04 \times 0.989901z^{min(0.8,1)} + 0.04 \times 0.010099z^{min(0.8,0)} \\
&+0.01 \times 0.989901z^{min(0,1)} + 0.001 \times 0.010099z^{min(0,0)} \\
&= 0.940406z^1 + 0.039596z^{0.8} + 0.019998z^0
\end{aligned}
\tag{3.42}
$$

$$
\begin{aligned}
\omega_{Y_S}(z) &= \omega_{Y_1+Y_2+...+Y_n}(z) \\
&= \prod_{i=1}^{n} \omega_{X_{Y_i}}(z) = (\omega_{X_{Y1}}(z))^n \\
&= (0.940406z^1 + 0.039596z^{0.8} + 0.019998z^0)^n
\end{aligned}
\tag{3.43}
$$

According to the multinomial theorem,

$$
(x_1 + x_2 + \quad + x_m)^n = \sum_{k_1+k_2+...+k_m=n} \binom{n}{k_1, k_2, \cdots, k_m} x_1^{k_1} x_2^{k_2} \cdots x_m^{k_m} \tag{3.44}
$$

where

$$
\sum_{k_1+k_2+...+k_m=n} \binom{n}{k_1, k_2, \cdots, k_m} = \frac{n!}{k_1!k_2!\cdots k_m!} \tag{3.45}
$$

is a multinomial coefficient. Here n and $k_1, k_2, \cdots k_m$ are nonnegative integers subject to $k_1 + k_2 + \cdots + k_m = n$. Also, as with the binomial theorem, x^0 is taken to equal 1 (even when x equals zero). When assume the manifold is charactered by four slots, expansion the equation (3.43) and then present the PMF of these state variables in Table 3.2. The maximum production for the four slots Manifold are 4 with a probability of 78.21%, as shown in the first data rows. The production rate is the production ratio between a specific state and the maximum production (for a four slot manifold in this case, the maximum production is 4). The cumulative probability refers to the probability that the production equal or bigger than the corresponding production rate. This parameter is closely related to the flow assurance analysis, because a pipe may be blocked by solid that forming as a sequence of flow rate reduction.

Table 3.2 PMF of four slots manifold production

Probability	Production	Production rate	Cumulative probability
7.82E-01	4	100%	78.21%
1.32E-01	3.8	95%	91.38%
8.32E-03	3.6	90%	92.21%
2.34E-04	3.4	85%	92.24%
2.46E-06	3.2	80%	92.24%
6.65E-02	3	75%	98.89%
8.40E-03	2.8	70%	99.73%
3.54E-04	2.6	65%	99.77%
4.97E-06	2.4	60%	99.77%
2.12E-03	2	50%	99.98%
1.79E-04	1.8	45%	100.00%
3.76E-06	1.6	40%	100.00%
3.01E-05	1	25%	100.00%
1.27E-06	0.8	20%	100.00%
1.60E-07	0	0%	100.00%

The average production for this Manifold can be obtained by:

$$E(S) = \sum_{i=0}^{k} s_i p_i = 3.89 \tag{3.46}$$

To assess the total export capacity of the two pipelines, introducing three more auxiliary random variables X_{T3} , X_{T4} , and X_{T5} and defining the function recursively:

$$\omega_{X_{T3}}(z) = min[\omega_{X_{CA}}(z), \omega_{X_A}(z)] \tag{3.47}$$

$$\omega_{X_{T4}} = min[\omega_{X_{CB}}(z), \omega_{X_B}(z)] \tag{3.48}$$

$$\omega_{X_{T5}}(z) = \omega_{X_{T3}+X_{T4}}(z) = \omega_{X_{T3}}(z)\omega_{X_{T4}}(z) \tag{3.49}$$

Using the same composition combination methods, the z-form of the final outlet production for the considered Manifold Y_M take the form of:

$$\omega_{Y_M}(z) = min[\omega_{X_{T5}}(z), \omega_{Y_S}(z)] \tag{3.50}$$

The calculation process is not demonstrated here.

3.3 Component Importance Measures

When designing or assess a system, component importance measures are used to rank the component to identify the weak point. The system reliability may be improved by improving the reliability of a weak point. The Birnbaum`s measure for item $i$ at the time $t$ is obtained by partial differentiation of the system reliability R(p(t)) with respect to a specific component`s reliability $p_i(t)$ (Rausand & Arnljot, 2004).

$$I^B(i \mid t) = \frac{\partial h(\mathbf{p}(t))}{\partial p_i(t)} = h(1_i, P(t)) - h(0_i, p(t)) \qquad i = 1,2,...,n \tag{3.51}$$

If the importance measure is large, a small change in the reliability of component i will result in a comparatively large change in the system reliability at time t. Birnbaum`s measure for specific component gives the component importance for system production, however, it only depends on the structure of the system and the reliabilities of the other component. Improvement potential gives the information of how much the system reliability increases if a component is replaced by a perfect one. The improvement potential with respect to component i is then:

$$I^{IP}(i\,|\,t) = h(1_i, P(t)) - h(p(t))\, for i = 1, 2, ..., n. \qquad (3.52)$$

In this thesis, both Birnbaum`s measure and improvement potential are used to evaluate the importance of a specific item.

3.4 System Layout Design

Subsea cost refers to the cost of the whole project, which generally includes the capital expenditures (CAPEX) and operation expenditures (OPEX) of the subsea field development (Bai & Bai, 2010). Figure 3-11 presents examples of the breakdown of deepwater subsea CAPEX. For a specific equipment, costs are influenced by many cost driving factors, such as water depth, production pressure, and temperature. These cost driving factors should be updated based on the actual data for the time and location of field development.

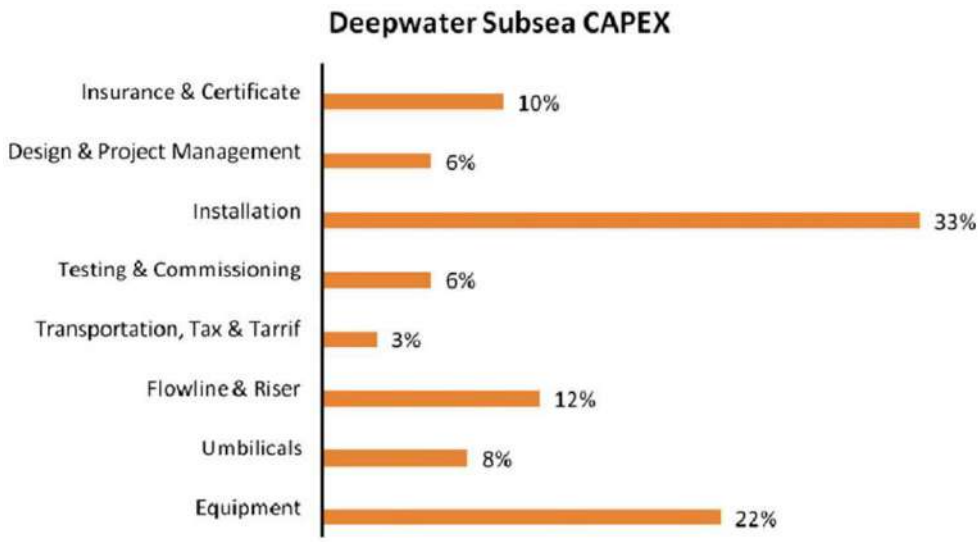


Figure 3-11 Deepwater Subsea CAPEX (Bai & Bai, 2010)

The main equipment for a Subsea to Shore system include X-mas tree, Manifold, flowlines, pipelines, separator, pumps, etc. More details of the equipment will be discussed in Chapter 4. A typical production manifold has 2, 4, 6, 8 or 10 slots for receiving flow from X-mas tree or another production manifold. For a field of dozens of wells, finding the right type of manifold (slot numbers) and location will greatly reduce the equipment cost, by reducing the length of the flowline. Meanwhile, reducing the number of equipment will improve the reliability of the system. It is an optimization problem of equipment cost, installation ability, and flow assurance. Yingying Wang present a mathematical model for subsea wells partition in the layout of the manifold (Wang et al., 2014; Wang, Duan, Xu, Wang, & Feng, 2012). In those papers, the cost of a flowline is proportional to the square of the Euclidean connection distance between the wells and the manifold. In this thesis, the cost for the subsea equipment is obtained by Questor software (IHS Energy, Inc.), which is directly linked to a large IHS database that includes geology, reservoir, production, and cost data. For a given field, Questor can generate production profiles, CAPEX and OPEX with recommending Manifold types and numbers, but the location of Manifolds and the connection between manifolds and wells cannot be provided. Lingo is used for optimizing the layout of the Manifold.

LINGO is a comprehensive tool designed to make building and solving Linear, Nonlinear, Quadratic, Quadratically Constrained, Stochastic, and Integer optimization models faster, easier and more efficient.

Chapter 4.

Subsea System Arrangement

4.1 Subsea System Design Basis

A Subsea to Shore production system for an oil and gas field offshore Brazil is proposed for layout design. The production of this field is used for the flow assurance analysis. The field located 100 km off the coast at a water depths of 500m. Test data indicate fluid of 85 bars and 70^{o}C at the wellhead, reservoir depth from Lowest Astronomical Tides is 2800m. Recoverable reserves are about 405 MMbbl, API gravity is approximately 13^o, and the GOR is approximately 70 scf/bbl.

This field will be developed with 40 production wells and 8 injection wells. The serial number and coordinates for each well are listed in Table 4.1. Wells from 1 to 40 are production wells while from 41 to 48 are injection wells. Based on the coordinate information, the location of the wells is mapped in Figure 4-1.

Table 4.1 Wells location and type

N.	X(m)	Y(m)	N.	X(m)	Y(m)	N.	X(m)	Y(m)
1	746	1133	17	6963	6646	33	15352	10033
2	1276	2100	18	8221	5272	34	15360	10481
3	1918	5247	19	8318	6101	35	15553	10074
4	2288	1024	20	8553	5907	36	15607	11055
5	2333	3288	21	8620	5245	37	16006	12045
6	2560	1926	22	9594	6382	38	16313	12040
7	2618	546	23	10397	7111	39	16379	11550
8	2632	1049	24	10538	7082	40	17057	11069
9	3215	3791	25	12911	8672	41	3855	2074
10	3525	816	26	13353	9843	42	4628	457
11	3709	2745	27	13612	9222	43	4810	893
12	4060	2493	28	14306	8776	44	9943	4686
13	4100	2487	29	14517	10745	45	10872	5036
14	4200	1614	30	14548	9862	46	17060	7657
15	4243	2550	31	15224	11001	47	18324	8590
16	4377	2418	32	15342	11083	48	19117	9175

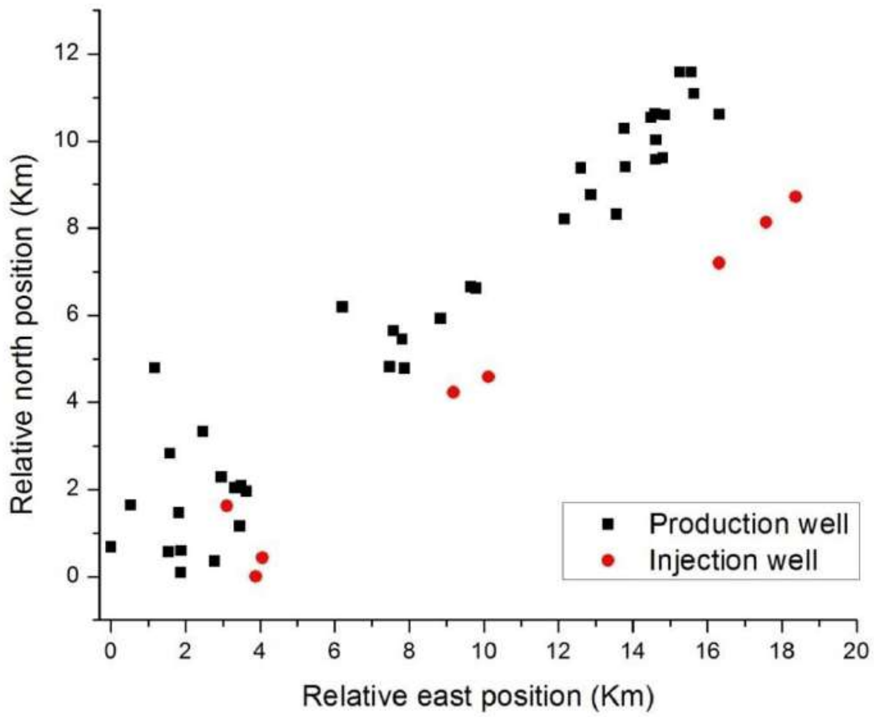


Figure 4-1 Production and injection wells layout

Three system arrangements associated with 6 slots, 8 slots, and 10 slots manifold are considered. The injection system is separated with the production manifold, and is same for the three scenarios, hence, the system arrangement design is concentrated on the layout of the production cluster manifolds. The layout for 6, 8 and 10 slots manifolds scenarios are presented in Figure 4-2, Figure 4-3 and Figure 4-4. In each figure, the wells are grouped into several sets, each set has one manifold connects to all the wells in this set.

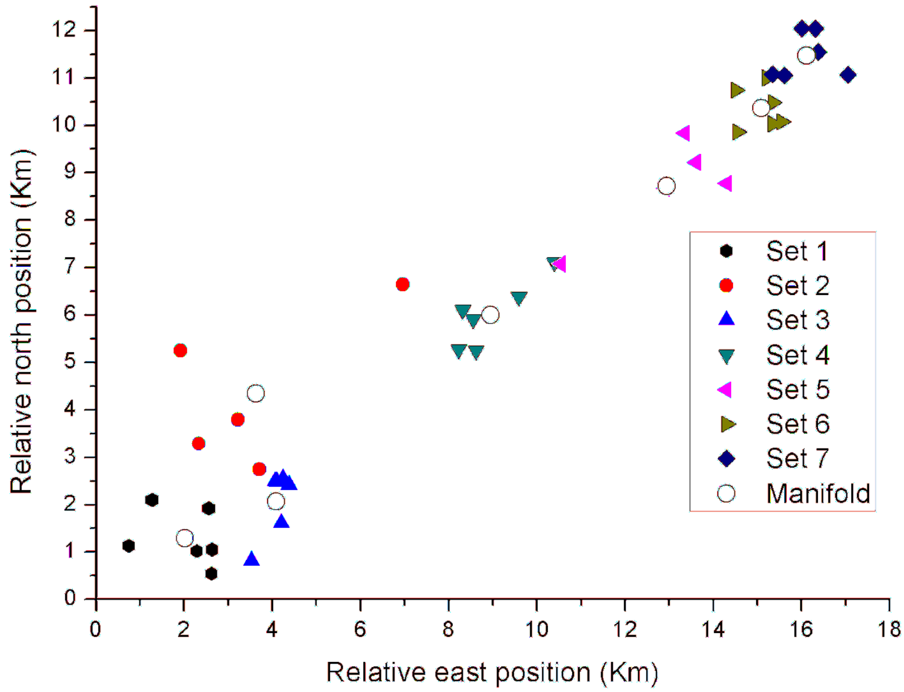


Figure 4-2 Seven 6-slots manifold layout

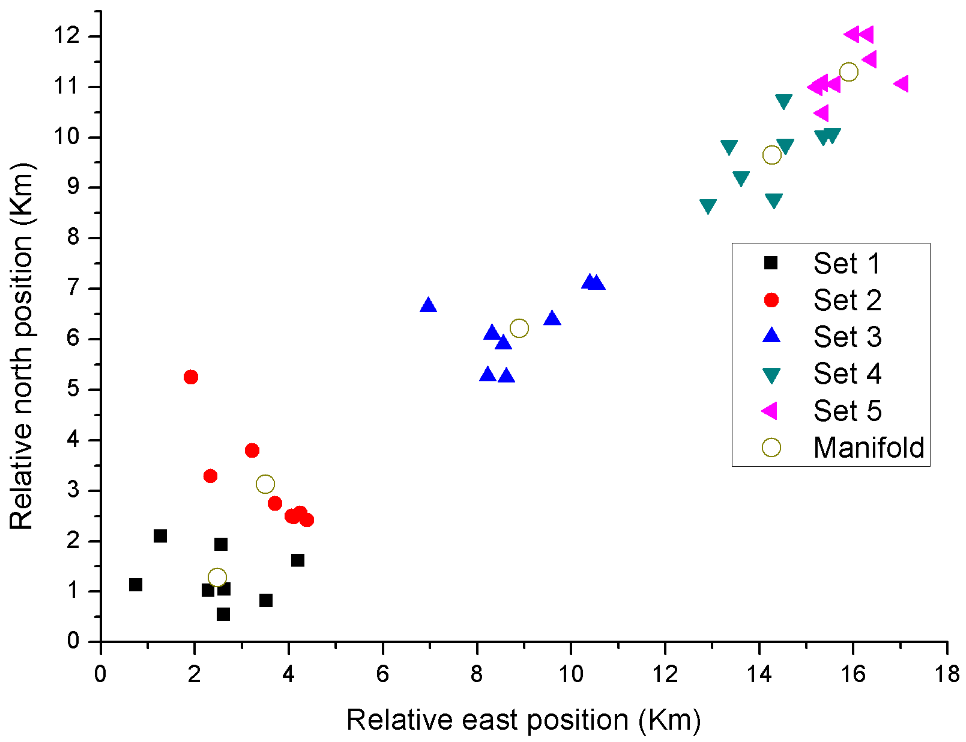


Figure 4-3 Five 8-slots manifold layout

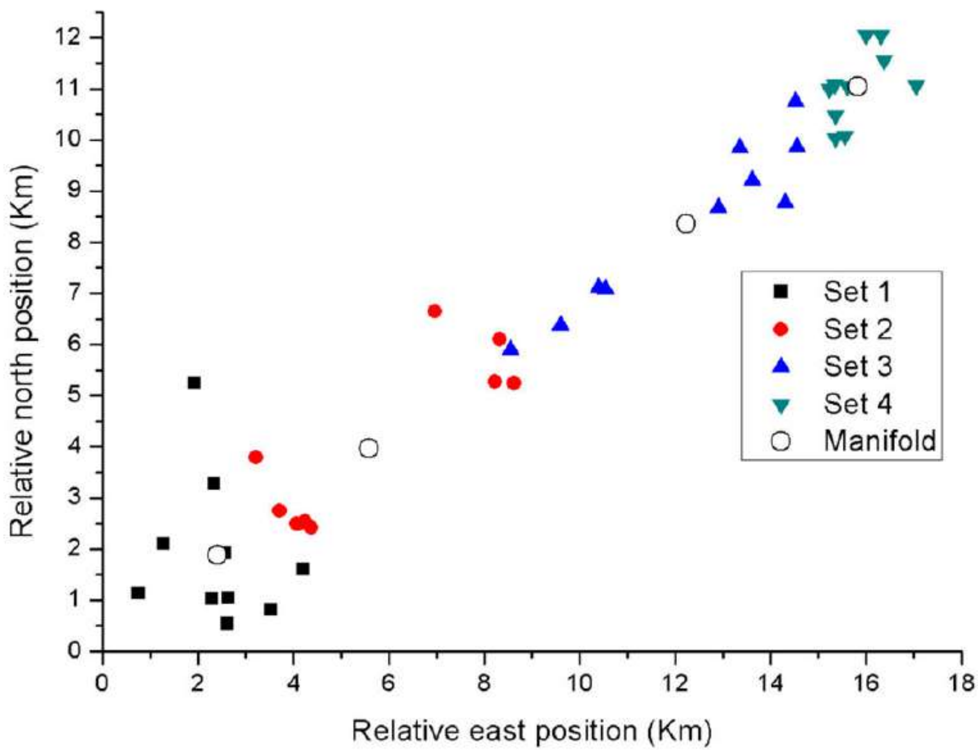


Figure 4-4 Four 10-slots manifold layout

According to the manifold layout for each scenario and well production, the diameter of a flexible pipe for each scenario, as well as costs, are obtained from the databank QUE$TOR, as shown in Table 4.2. The cost for a Manifold includes the support structure, manifold body, freight cost, control system on shore and offshore, connectors for flowlines tie-in and 40 production X-mas trees. The four-inch flexible pipe is proposed to transport production from an X-mas tree to manifold. The cost of a flexible pipe includes the cost of flexible pipe and control umbilical. Two flexible pipes link a Manifold to one of the two separators from which gathered production is guiding to export pipeline. The eight-inch flexible pipe is only applied for 6 slots Manifold scenario while the ten-inch flexible pipe is applied for 8 slots and 10 slots Manifold scenarios. The separators and export pipelines are identical for each scenario, so the cost for them are not considered here.

Table 4.2 Cost comparison (QUESTOR 2015)

Cost list	6 Slots (M$)	8 Slots (M$)	10 Slots(M$)
Manifold	372.057	352.234	350.598
4-in Flexible pipe	119.178	127.371	214.273
8-in Flexible pipe	175.392	-	-
10-in Flexible pipe	-	168,460	325.650
Installation	106.201	98.100	92.118
Total	772.828	**746.156**	982.639

Note: M$ represents million dollars; OPEX are not included

According to the cost for each scenario, 8 slots manifold scenario, which is the most economical, are selected for system design.

4.2 Subsea System Design

A Subsea production system can range in complexity from a single satellite well with a flowline tie back to a host facility, to several wells producing product via subsea processing facilities to the platform or shore directly. In this thesis, the selected field is developed with Subsea to Shore concept. A similar systematic arrangement as proposed by (Estefen et al., 2009) is adopted in this thesis for the production and system reliability analysis. The system comprises eight X-trees, two Manifolds, one Pipeline End Manifold (PLEM), two Pipeline End Terminations (PLET), two export pipelines and three umbilicals. The primary function of an X-tree is to control the wellbore flow. The manifold is employed to receive the production from X-trees. PLEM and PLET are used to link Manifolds and export pipelines. Umbilicals provide the means to inject chemicals and for services, and the export pipeline is employed to export the field production. Figure 4-5 shows the comprehensive layout for the Subsea to Shore production system.

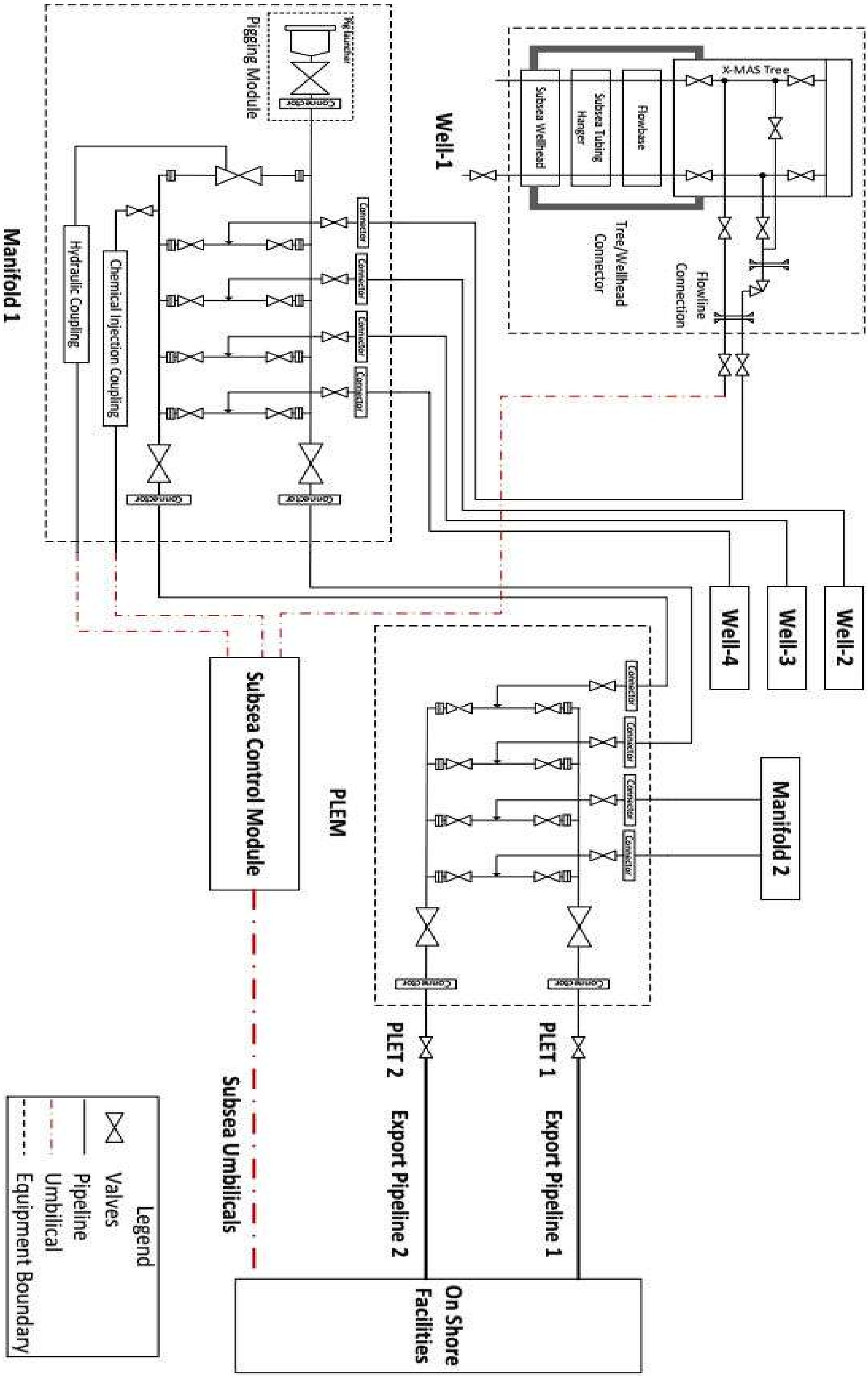


Figure 4-5 Full scheme of the Subsea to Shore production system

4.3 Description of Main Equipment

4.3.1 Wellhead and X-mas Tree

Two kinds of X-mas tree (XT) can be employed in deep-water fields: dry tree and wet tree. The dry tree is installed on the platform while the wet tree is exposed to the ambient seabed conditions. Globally, more than 70% of deep-water wells are wet tree system (Bai & Bai, 2010). In this thesis, the field is developed with Subsea to Shore concept, so only the wet subsea XT is discussed. Subsea XT can be classified according to the control valve layout as horizontal XT and vertical XT. Horizontal XT can be described as a production adapted base with valves mounted on the lateral sides, allowing well intervention and production column replacement without its removal. The vertical XT comprises separate modules that can be installed independently, and the production and annulus bore pass the XT body vertically. A tubing hanger lands on the wellhead for the vertical XT development, but it is installed in the tree body for the horizontal XT development. This difference requires the tree to be installed onto the wellhead before or after of wellbore completion. Thus, wells that are expected to have many tubing failures or other interventions should be equipped with a horizontal XT, otherwise, a vertical XT is more suitable. In this thesis, frequent interventions are required for the ESP system, so horizontal XT is selected for production and vertical XT is selected for water injection. The main suppliers for subsea XT are FMC technologies, Aker solutions, Onesubsea, and GE Oil&Gas, market share in the same order (Quest Offshore Resources, 2013) Tree type, bore size (3,4,5,7 and 9 in.) and pressure rating (5, 10, and 15 ksi), temperature, water depth, numbers are selected and estimated according to the field conditions by reservoir and drilling engineers. A horizontal X-mas tree is illustrated in Figure 4-6.

Figure 4-6 Horizontal X-mas tree (Courtesy of FMC)

The boundary definition between wellhead and X-mas tree is shown in Figure 4-7. All valves and tree/flowline or tree/manifold connectors are included, while the subsea control system, pressure and temperature sensors and any other detectors mounted on the tree, are outside the boundary (Bai & Bai, 2010). The production master valve (PMV) is manufactured to underwater safety valve (USV) specifications but will only be designated for use as USV if necessary. PMV is the main valve responsible for stopping the flow from well. The subsea tree production wing valve (PWV) is designed as a USV and placed after the PMV. PWV also serves as a redundancy of the PMV, and it is often closed first to allow the PMV to be closed without flow to reduce wear(Wanvik, 2015). The subsea choke valve is used to regulate the flow from the well to the manifold. It has the lowest reliability of the main components of an XT because of exposing to wear due to erosion. For improving system availability, the choke valve is easy to be retrieved. The choke valve can be replaced by just retrieval the worn parts of the valve and without pulling the XT (Wanvik, 2015).

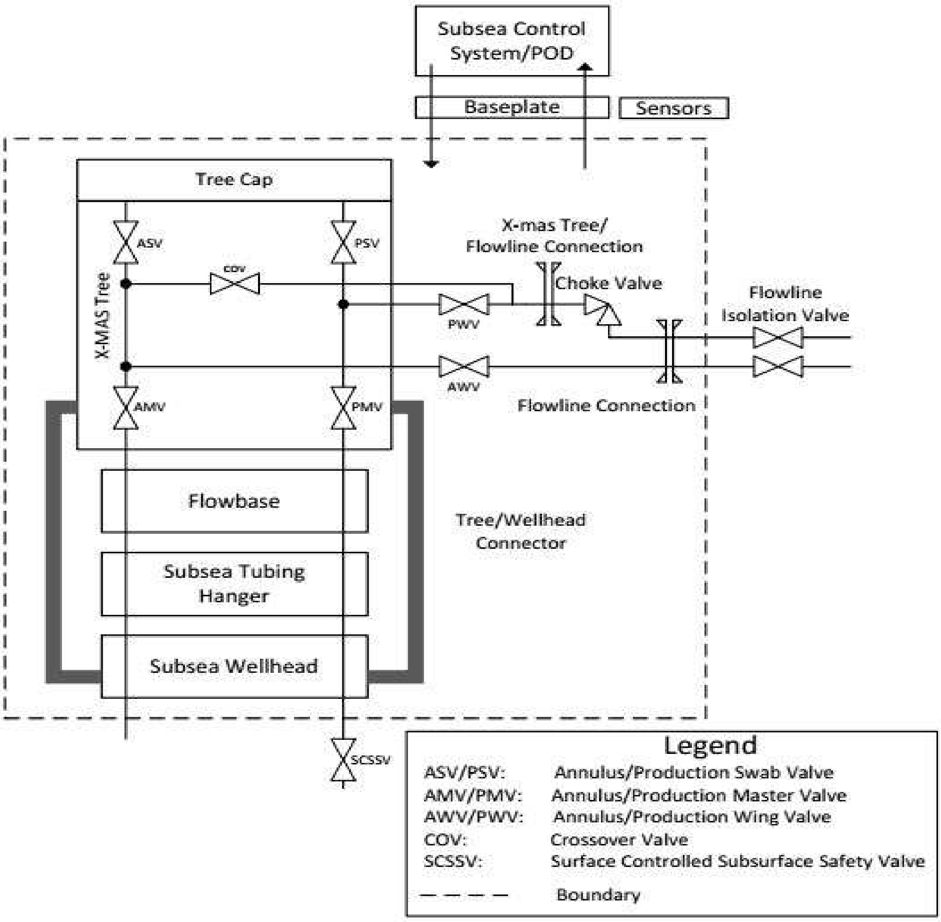


Figure 4-7 Definition of One Well (Wellhead and X-mas tree)

The production swab valve (PSV) and the annulus swab valve (ASV) are open when interventions in the well with wireline or coiled tubing. The crossover valve (COV) is an optional valve. It is normally isolated, when opened, it allows communication between the annulus and production bores so to do well kill operations or to overcome obstructions caused by hydrate formation (Bai & Bai, 2010). The annulus master valve (AMV) and the annulus wing valve (AWV) are the main and secondary annulus barrier valves. They are used to equalize the pressure between the upper space and lower space of the tubing hanger during the normal production. As described by (Bai & Bai, 2010), the production flow coming from the well below passes through the SCSSV, which will shut down when an accident, leak, or overpressure occurring. The subsea control module (SCM) receives electrical power, communication signals, and hydraulic power supplies from the topside or onshore control equipment and provides actuation and monitoring of most of the XT`s functions. In the present work, it is assumed that an X-mas tree has only two working conditions, full production or shutdown.

In OREDA, failure records are classified into severity classes as critical, degraded and incipient. As defined in the database, a critical failure is a failure, which causes immediate and complete loss of an equipment unit's capability of providing its output; a degraded failure prevents the unit from providing its output within specifications; and an incipient failure happens due to an imperfection in the state or condition of an item so that degraded or critical failure can be expected to result if corrective action is not taken. According to (Haugen, Hokstad, & Sandtorv, 1997), "the detection of a so-called degraded failure will result in a preventive maintenance action that could prevent a critical failure to occur". In the present paper, only the critical failures, which causes immediate and complete loss of production, are analyzed. The rate of critical failure is estimated to the number of observed critical failures divided by the exposure time. In OREDA, all the failure events are considered as completely independent, with each corresponding failure rate presented under three categories: lower bound, the best estimate, and upper bound. The standard deviation of the failure rate is provided too. In order to simplify the calculation, only the best estimate failure rates are considered for the reliability assessment. Not every component failure can lead to serious consequences. According to OREDA, eight types of failures are categorized as critical failure modes. Table 4.3 provides the meaning of failure mode abbreviations, while those failure modes and failure rates are indicated in Table 4.4.The choke valve has the worst inherent reliability of the components on an XT. Because of this, the choke valve is designed for easy retrieval for improving system maintenance of unreliable components (Wanvik, 2015).

Table 4.3 Failure mode abbreviations

Failure Mode	Abbreviation
Abnormal wear	ABW
External leakage – process medium	ELP
External leakage – utility medium &	ELU
Fail to close/lock	FTC
Fail to function on demand	FTF
Fail to open/unlock	FTO
Internal leakage - process medium	ILP
Leakage in a closed position	LCP
Other	OTH
Plugged/ choked	PLU
Structural failure	STD

Table 4.4 Critical failure rate data of the Wellhead and the X-mas tree

Component	**Units**	**Failure mode**	**Failure rate per 10^6 hours**
Flow Base	Process isolation valve	ELU / FTC / FTO	0.4
Subsea Wellhead	Annulus seal assemblies	ELP	0.11
	Casing hangers	ELP	0.05
Tubing hanger	Hydraulic coupling	ELU	0.07
	Tubing hanger body	ELP/ILP	0.2
Subsea X-mas tree	Connector	ELP / FTO	0.16
	Hydraulic coupling	ELU / OTH	0.06
	Piping (hard pipe)	PLU	0.21
	Tree cap	STD	0.09
	Choke valve	ABW /ELP / FTC / FTF / PLU / OTH	2
	Process isolation valve	FTC / FTO / LCP / OTH	0.34
	Utility isolation valve	FTC / FTO / LCP / OTH	0.37

4.3.2 Manifold

Subsea manifold, as shown in Figure 4-8, is a set of tubes, valves and monitoring instruments assembled on a metallic structural basis, interconnecting the drainage/flow of several wells to the production unit, thus reducing the number of lines that would be necessary. The manifold is not a safety equipment as the XT because a Manifold is considered as part of the pipe system, favoring the production flow in case of control system failure. Thus, the production blockage valves, operated hydraulically, are fail-safe open. The test blockage valves operated hydraulically as fail-safe close. The cost drivers for a subsea manifold are the number of slots (2,4,6,8,10), pressure rating (5, 10, and 15 ksi), temperature rating, pipe size and material class (Bai & Bai, 2010).

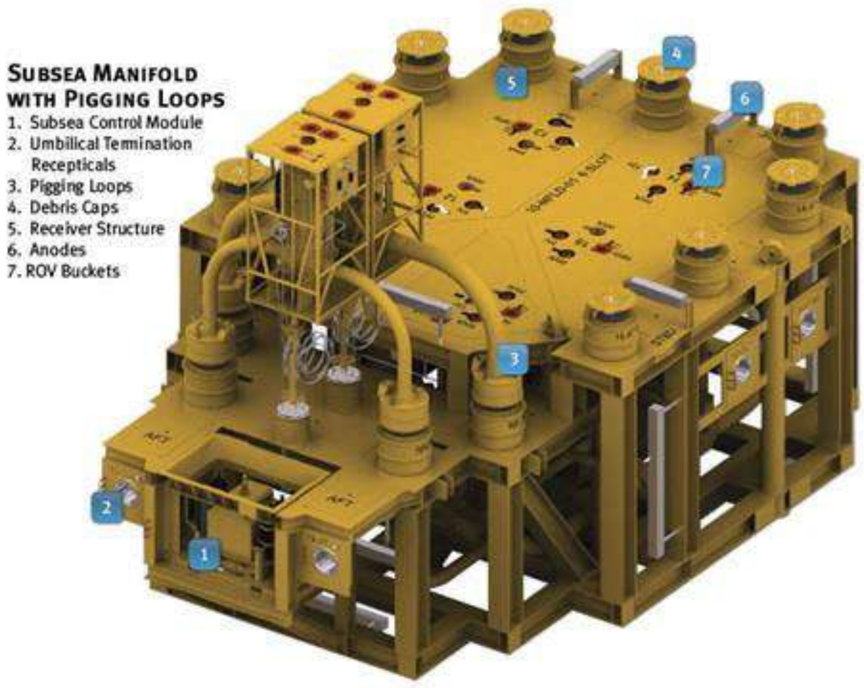


Figure 4-8 Manifold (Courtesy of FMC)

The manifold is an arrangement of piping and valves designed to combine, distribute, control, and often monitor fluid flow. According to the different applications, the manifold ranges from a simple PLET to large structures, such as an entire subsea process system. In the present case, a manifold is connected to four wells by four flexible pipelines. The manifold is comprised of the following: the support structure, control valve, choke valve, pipe connector headers and hard pipes. In this paper, only the basic functions to combine, distribute and provide injections are evaluated. Other functions, such as pigging and metering, are not included. The manifold boundary is presented in Figure 4-9.

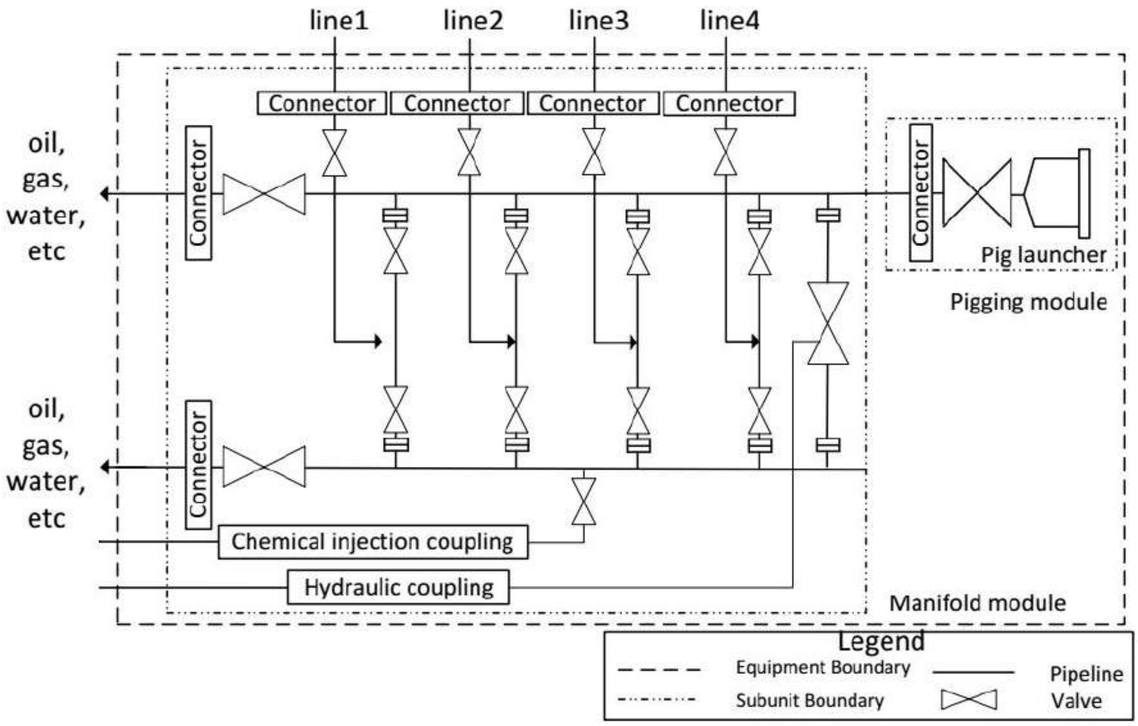


Figure 4-9 Manifold system boundary definition

The common failure modes of a manifold include external leakage, internal leakage, failure to close, fails to open, being plugged, leakage in a closed position and spurious operation. According to OREDA, the connector, piping and process isolation valve has records of critical failure. The failure mode abbreviations are presented in Table 4.5, while the failure rate data are presented in Table 4.6. In this design, the PLEM is identical to the manifold. A PLET comprised by one valve and one connector in series. The failure rate data of these components are the same as those components of Manifold.

Table 4.5 Failure mode abbreviations

Failure Mode	Abbreviation
Combined/common cause	COM
External leakage – process medium	ELP
External leakage – utility medium	ELU
Failure to close/lock	FTC
Failure to open/unlock	FTO
Leakage in closed position	LCP
Spurious operation	SPO
Other	OTH
Being plugged/ choked	PLU

Table 4.6 Critical failure rate data of Manifold

Component	Failure mode	Failure rate per 106 hours
Connector	ELP	0.1093
Process isolation valve	ELP/FTC/FTO/LCP/SPO/OTH	0.8313

4.3.3 Flowline and Pipeline

Offshore pipelines can be classified as flowlines, infield pipelines and export pipeline. Flowlines transporting oil and/or gas from satellite subsea wells to subsea manifolds or from subsea manifold to production facility platform or transporting water or chemicals from the production facility, through the subsea injection manifold, to injection wellheads; Infield flowlines transporting oil and/or gas between the production facility platform; Export pipelines transporting oil and/or gas from production facility platform to shore (Guo et al., 2005). A complete pipeline design includes pipeline sizing (Diameter and wall thickness), material grade selection, hydrodynamic stability, span, thermal insulation, and corrosion. Thermal design predicts the temperature profile along the pipeline and provides information for pipeline analyses, including expansion analysis, upheaval or lateral buckling, corrosion protection, hydrate prediction, and wax deposition analysis. Daily operations for pipeline include flow assurance and pigging operations to maintain the pipeline under good conditions. Subsea flowlines and subsea pipelines may be made of flexible pipe or rigid pipe. The pipelines normally operating at pressures between 7 and 11 MPa (Mott, 2003).

The hazards associated with operating offshore pipelines include leakage, rupture and even bursts that result in an interruption of transportation and production of hydrocarbons, require clean-up operations, and can cause catastrophic health, environment, and safety accidents. Historical data (Mott, 2003) illustrate that a large number of accidents to offshore pipelines were caused by impact, ship anchoring, and corrosion, as shown in Figure 4-10. According to OREDA (OREDA, 2002), the boundary definition for flowline is presented in Figure 4-11.

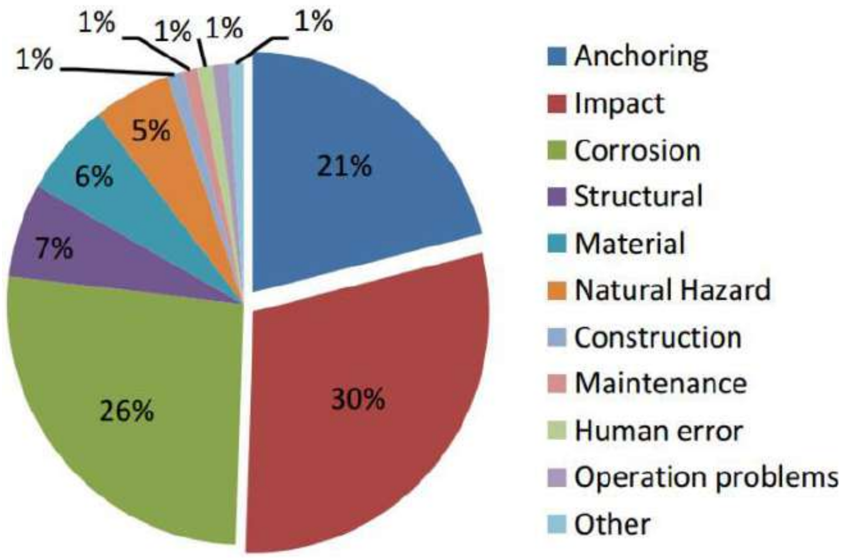


Figure 4-10 Pipeline failure modes

The failure mode abbreviations are presented in Table 4.7, while the failure rate data are presented in

Table 4.8.

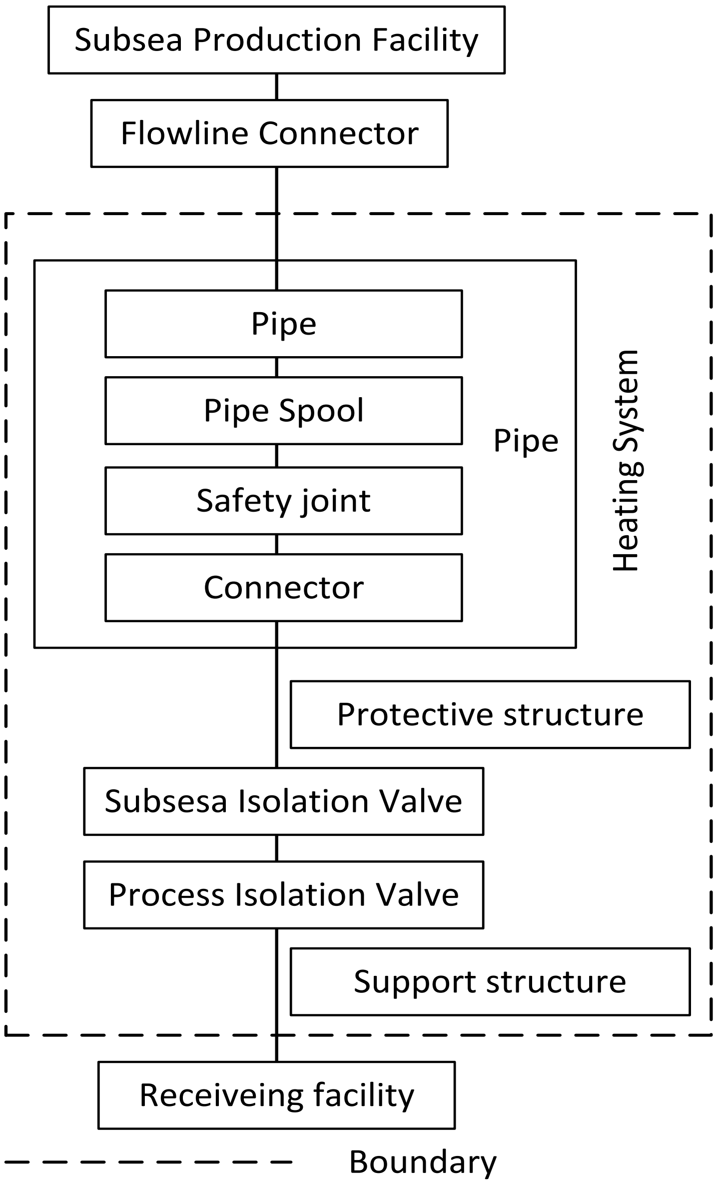


Figure 4-11 Flowline boundary definition

Table 4.7 Failure mode abbreviations

Failure Mode	Abbreviation
External leakage- utility medium	ELU
Fail to close/lock	FTC

Table 4.8 Critical failure rate data of Flowline

Component	Failure mode	Failure rate (per 10^6 hrs)	**Active time(hrs)**
External leakage/Plugged	ELU	0.16	**96.0**
Flexible pipe external leakage	FTC	0.29	**2.0**

4.3.4 Separator

The main objective for using separator is to optimize the cost of transportation. By re-injecting the isolated water into the reservoir, it thus directly reduces the volume of water to be sent to onshore facilities and save a pipeline from the shore to subsea for water injection. The equipment separates oil, gas, and water, and then re-injects the water to the reservoir. Generally, the separated water has to be pressure-boosted by a circuit induction motor. A choke valve is organized in series with the booster pump in order to introduce a variable flow resistance needed for certain operating conditions in order to improve the stability of the closed control loop of the separator. A separation station employed in the Troll C field is presented in Figure 4-12. This Subsea Separation and Injection System (SUBBIS) from ABB, with a total budget of more than US$ 10 million, is the world's first subsea separation and injection system (Strømquist & Gustafson, 1999).

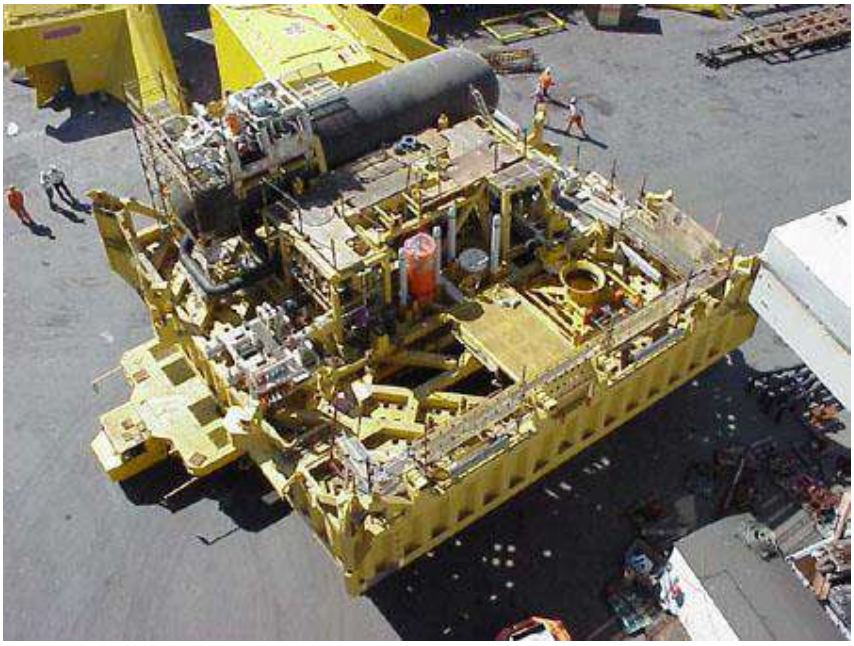


Figure 4-12 A three phase separator (Strømquist & Gustafson, 1999)

Using subsea three-phase separation, with re-injection of water and fluid flow boosting, is a considerable potential for increasing recovery, which is one of the key concerns to improving the economics of subsea field over their life circle. In recent years, there has been a rapidly accelerating shift from traditional surface processing operations to subsea processing operations. At present, there are two primary technologies being used for subsea processing: subsea multiphase pumping (pressure boosting) and subsea separation (Grieb et al., 2008). The locations that where the subsea processing system has been implemented are summarized in Table 4.9.

Table 4.9 Sites utilizing subsea processing technologies

Field Name	Year Installed	Location	Water Depth(m)	Subsea Processing Type	Production (bopd)
Draugen	1994	North Sea	280	Multiphase Boosting	-
Lufeng	1997	South China Sea	330	Multiphase Boosting	-
Topacio	1999	West Africa	488	Multiphase Boosting	-
Marimbá	2001	Brazil	395	VASPS-Subsea Separation	-
Troll C	2001	North Sea	340	Subsea Separation	-

Ceiba	2002	West Africa	800	Multiphase Boosting	16000/3
Lyell	2005	North Sea	145	Multiphase Boosting	150,000
Tordis	2007	North Sea	200	Subsea Separation, Boosting, Reinjection	80,000
BC-10	2009	Brazil	2000	VASPS-Subsea Separation	-
Marlim	2007	Brazil	650	Multiphase Boosting	75,000
Pazflor	2011	Angola	800	Vertical Separator	
Congro	2012	Brazil	-	VASPS-Subsea Separation	-
Malhado	2012	Brazil	-	VASPS-Subsea Separation	-
Corvina	2012	Brazil	-	VASPS-Subsea Separation	-

- Unknown Data

Two main types of subsea processing technology are currently being implemented in deep waters, multiphase pumps and partial separation with pumping. Both of them are proven technologies, but the latter is a new technology and have seen limited use. The multiphase pumping is the most basic subsea processing technology. The unprocessed production that includes water and sands are pumped to the processing facility. The partial separation with pumping systems provides partial separation of the crude petroleum fluids. These systems typically combine some sort of separator unit with a multiphase pumping system or gas compression system to pump the separated liquid and gas to the surface. These systems are the most technologically advanced systems currently applied in subsea processing. The separator system could be either a two-phase (gas/liquid) or three-phase (oil/gas/water) separation process. For the field has a lot of water produced, it will be greatly increased the cost if only a multiphase pumping system is employed, mainly because of the long distance between the field and the coast. By re-injecting the isolated water into the reservoir, it thus directly reduces the volume of water to be sent to onshore facilities. The equipment separates oil, gas, and water and then re-injects the water to the reservoir. In the last phase, the separated gas and oil are recombined at the common outlet from the separator and directed to the pipeline. The water depth is about 500m. Thus a simple gravity separator, utilizing the same principles as applied to a separator on the platform deck, is selected. Based on previous experience, the oil/water separation would be of major consideration in view of the high oil viscosity. Thus, it is concluded that a horizontal separator, allowing a maximum of oil/water interface area, would offer the best performance.

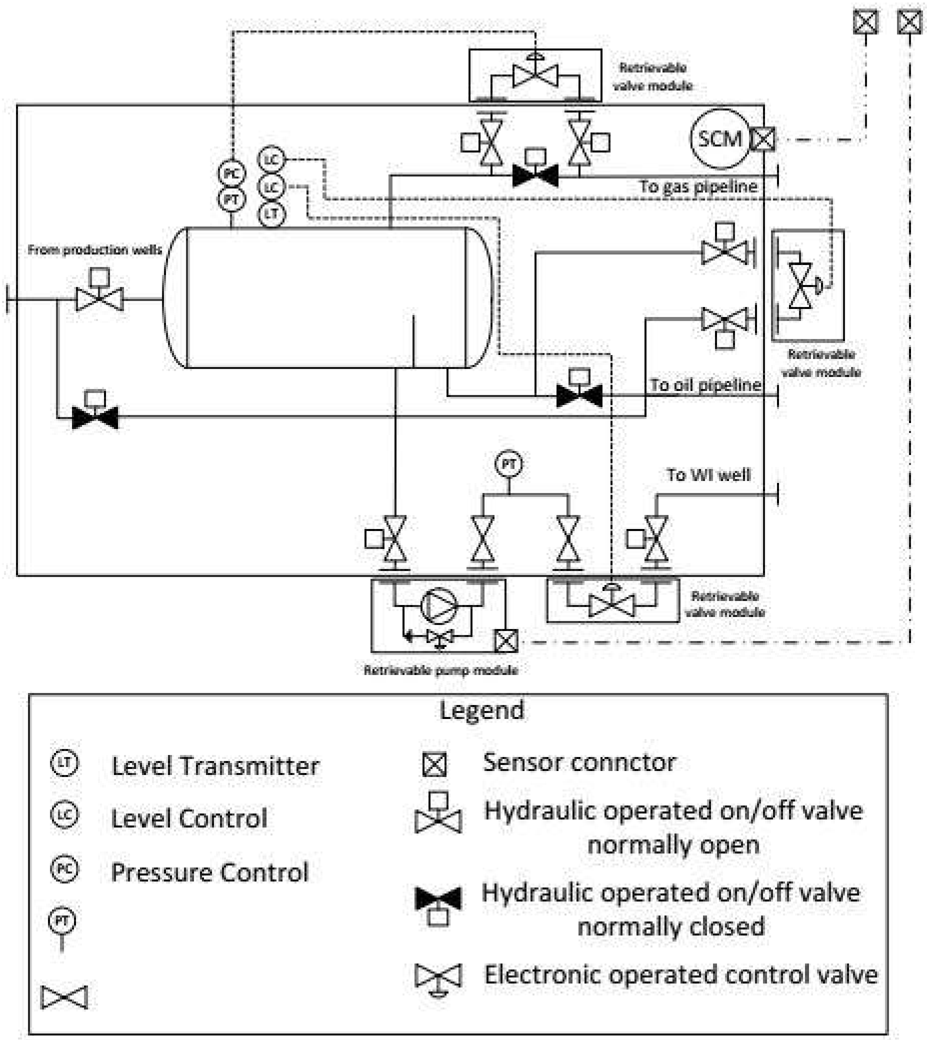


Figure 4-13 Separator boundary definition

4.3.5 Control System

An example of Subsea to Shore control system is the Snohvit system in the Barents Sea. This system is a milestone in subsea oil and gas development, with a record-breaking offset of 145km (Acworth, 2006). All technology has been qualified to 220km. The control system uses a hybrid electrical and optical communications system, electrical and hydraulic power to control the subsea facilities via main umbilical connected between shore-based topsides control system and the subsea system. All connection between the subsea system and the onshore components of the control system is via a single main continuous 144km main umbilical with no intermediate connections or booster stations. The main umbilical connects between the onshore termination equipment and the subsea Central Distribution Unit CDU1. The main umbilical comprises of electrical, optical and hydraulic power transmission lines as well as chemical lines and a spare hydraulic line. All HP supplies are generated by the Subsea Control Module (SCM) by means of High-Pressure Intensifier units located within each SCM. The hydraulic system is of the open loop vent-to-sea type and uses an environmentally friendly control fluid. One of the main challenges for the control system is the length of the main umbilical. Long-range communication without repeaters and relatively high data requirements dictate that a fibre-optic link is used as the principal means of communication in the umbilical. In the event of failure of the umbilical optical system, a backup comms on power system (COPD) is available—operating using the main umbilical high voltage power conductors at a reduced comms rate. According to OREDA, the boundary definition of the subsea control system is presented in Figure 4-14. The failure mode abbreviations are presented in Table 4.10, while the failure rate data are presented in Table 4.11.

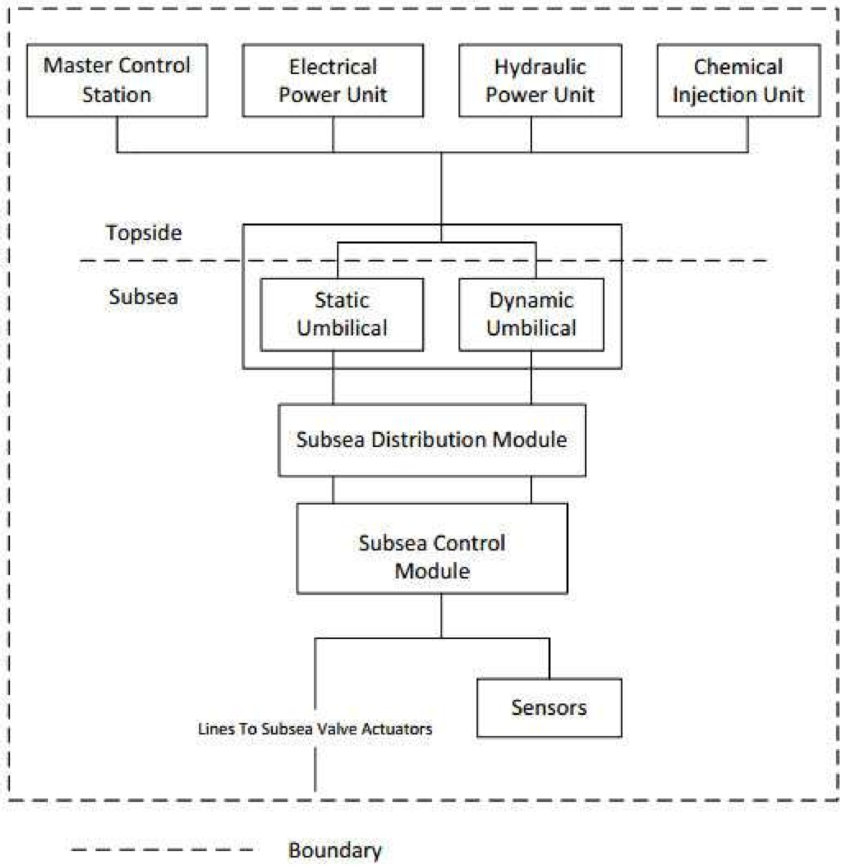


Figure 4-14 Control system boundary definition

Table 4.10 Failure mode abbreviations for control system

ABW Abnormal Wear	LOR Loss of redundancy
AIR Abnormal instrument reading	NON No immediate effect
BRD Breakdown	OCI Open circuit
COM Combined/common cause	OTH Other
ELP External leakage-process medium	PLU Plugged/choked
ELU External leakage-utility medium	POW Insufficient power
ERO Erratic output	SCI Short circuit
FTC Fail to close/lock	SIG Control/signal failure
FTF Fail to function on demand	SPO Spurious operation
FWR Fail while running	STD Structural failure
ILP Internal leakage- process medium	STK Stuck
ILU Internal leakage-utility medium	TRF Transmission failure
INF Insulation failure	UNK Unknown
LCP Loss of barrier	VIB Vibration
LOO Low output	

Table 4.11 Critical failure rate data of Control system

Failure mode	Failure rate (per 10^6 hours)	Active time(hrs)
Abnormal instrument reading	0.46	4.0
External leakage-utility medium	0.44	19.0
Fail to function on demand	2.89	31.2
Internal leakage-utility medium	0.39	6.0
Spurious operation	1.93	1.47
Other failure modes	0.34	-

4.4 System Maintenance

Subsea operating conditions in the deep water can cause hydrate or wax formation in the flowlines; the main equipment has been provided with chemical injection facilities to enable methanol or other chemicals to be injected into pipework and wellheads. This injection capability is for use primarily during start-ups and shutdowns.

Chapter 5.

System Reliability Analysis

5.1 System Describe

In this work, the production reliability and system reliability are obtained using the universal generation function. To perform the analysis, the system is split into three levels, as shown in Figure 5-1.

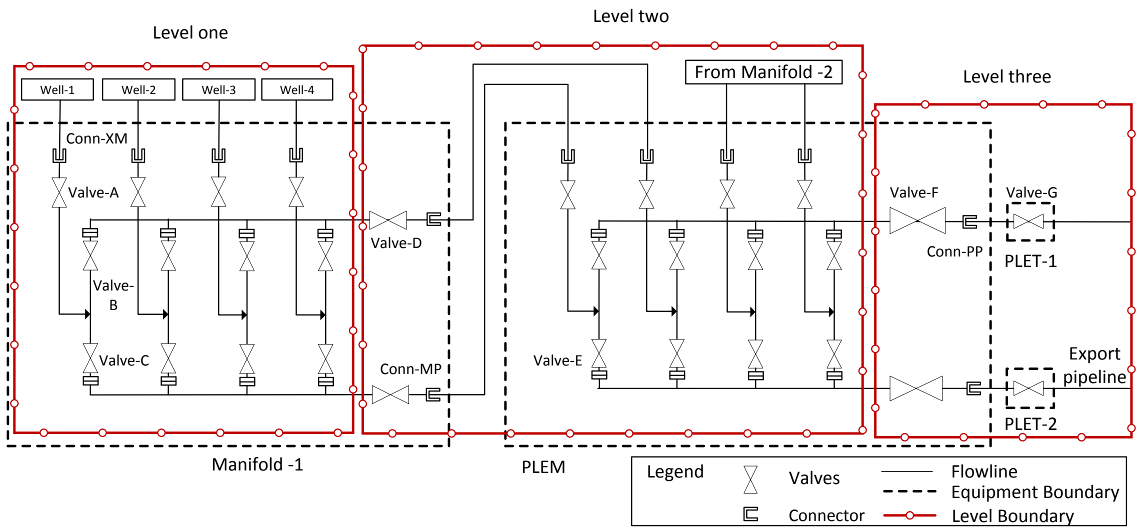


Figure 5-1 System level definition

In level one, four X-mas trees are connected to Manifold-1 and another four are connected to Manifold 2. The latter group is omitted in Figure 5-1. In level two, four pipelines, two of them from Manifold-1 and another two from Manifold-2, are connected to the PLEM in parallel. In level three, two export flow paths, each one comprising one valve, one connector, one PLET and a pipeline, transport the production to shore in parallel. Either Conn-XM or Valve-A in level one fails, then 1/8 of the production (one X-mas tree from the total eight X-mas trees) will be lost. Next to valve A are Valve-B and Valve-C, in pairs. One-eighth production loss occurs only when Valve-B and Valve-C fail together. Two flowlines transport the production from Manifold-1 to PLEM. One flowline cannot take responsibility for the total production of Manifold-1due to diameter or pressure limitations.

5.2 Level One Calculation

Level one is comprised of eight X-mas trees, in which each tree directs the production flow through one connector, one valve and two valves in parallel.

Let Y_{xm} represents the state for one X-mas tree, and then the structure function for X-mas can be expressed as:

$$Y_{xm} = \phi\ (X_1, X_2, ..., X_n) = min(X_1, X_2, ..., X_n) \tag{5.1}$$

where $X_1, X_2, ..., X_n$ represent the states for all the items. Then the Level production can be calculated as the same process of the second case study in Chapter 3. The production loss probability, production probability and reliability for level one are shown in Figure 5-2 and Figure 5-3, respectively. The probability of the production loss of four or more X-mas trees is too low to be represented in Figure 5-2.

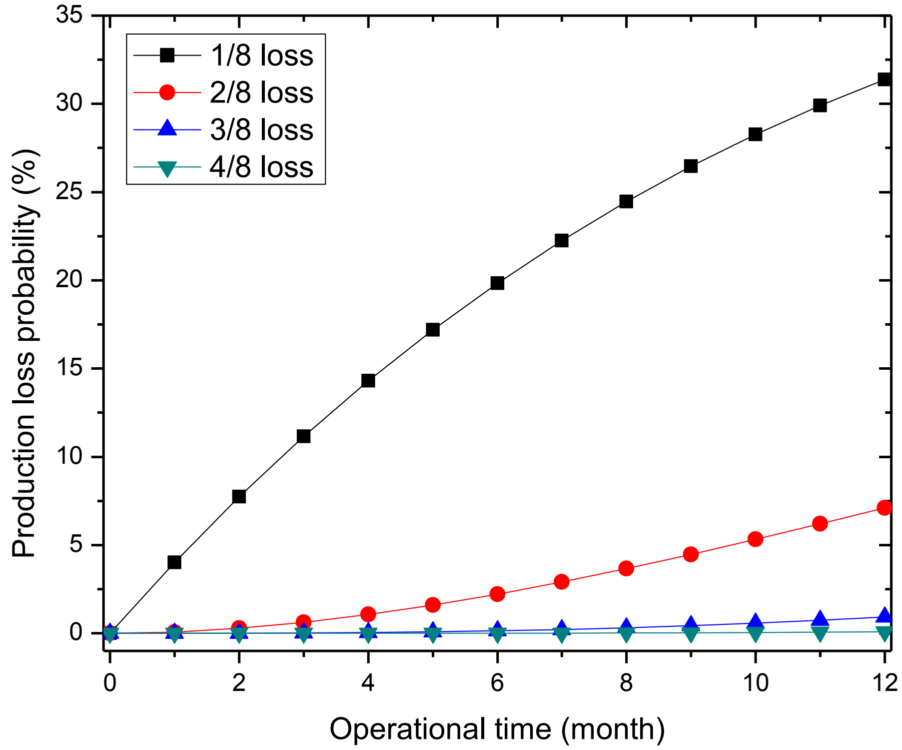


Figure 5-2 Production loss probability for level one

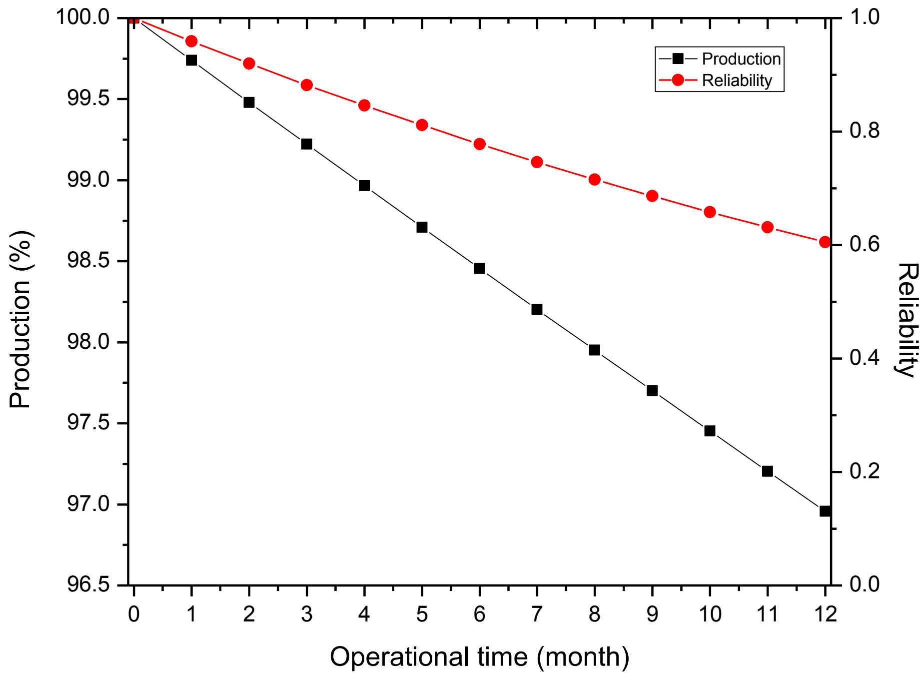


Figure 5-3 Production probability for level one

5.3 Level Two Calculation

Four lines lead the production from level one to level two. The probability of production loss for level two can be calculated in two steps. First, calculate the joint probability of production of two pipelines from Manifold 1, and then calculate the joint probability of production of Manifold 1 and Manifold 2. The results of the production loss probability and the production probability and reliability for level two are shown in Figure 5-4 and Figure 5-5, respectively. The probability of production loss of six or more X-mas trees is too low to be identified in Figure 5-4.

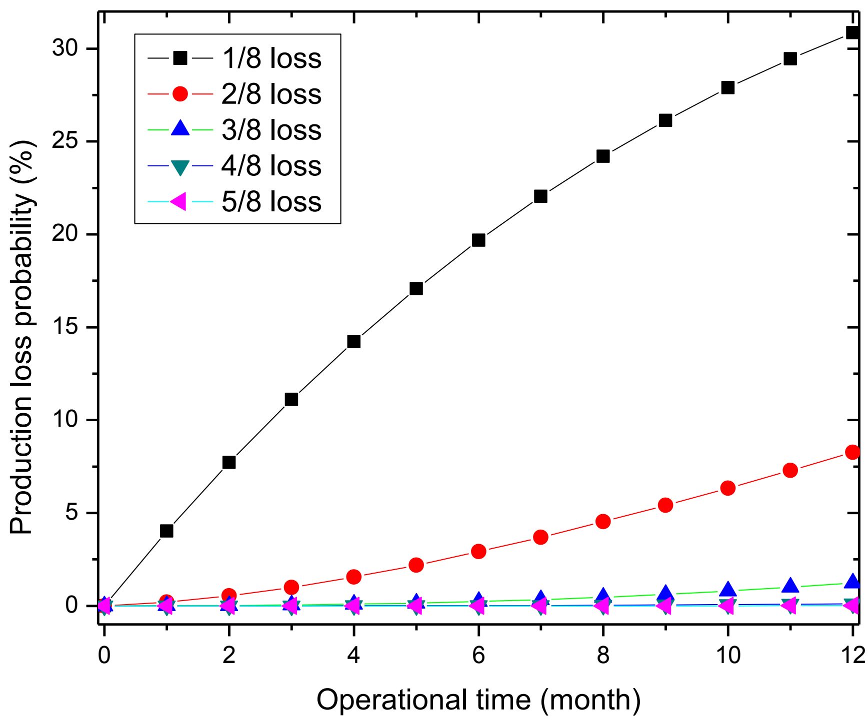


Figure 5-4 Production loss probability for level two

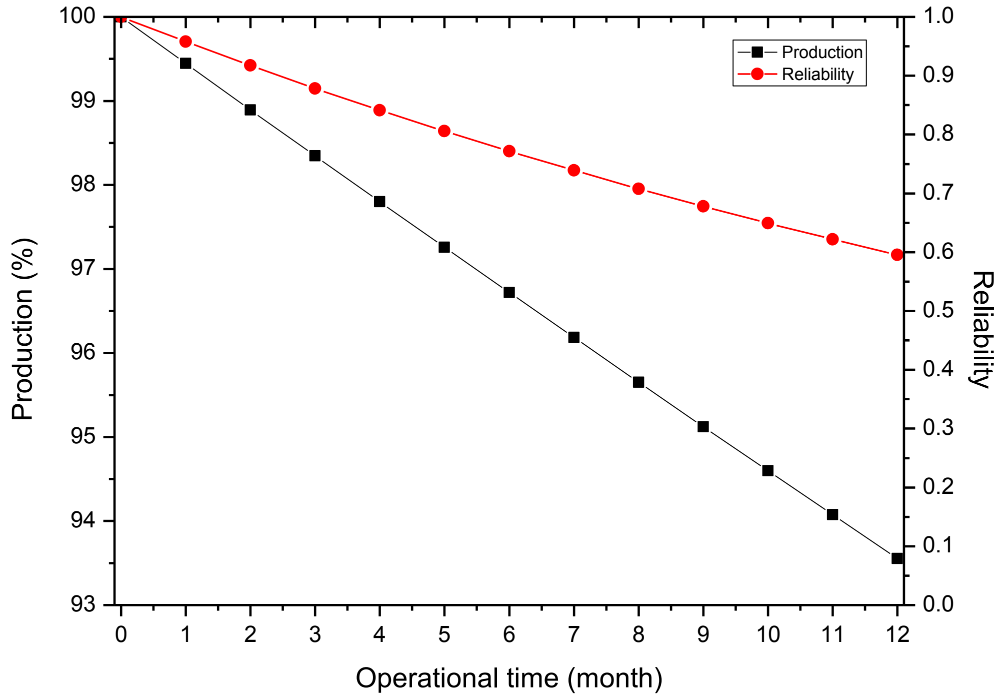


Figure 5-5 Production probability for level two

5.4 Level Three Calculation

The flow from level two will be exported to shore by level three. The production loss probability, production probability and reliability for level three are associated with the performance parameters of the system because these parameters are based on the joint probabilities for levels one, two and three. The results are shown in Figure 5-6 and Figure 5-7.

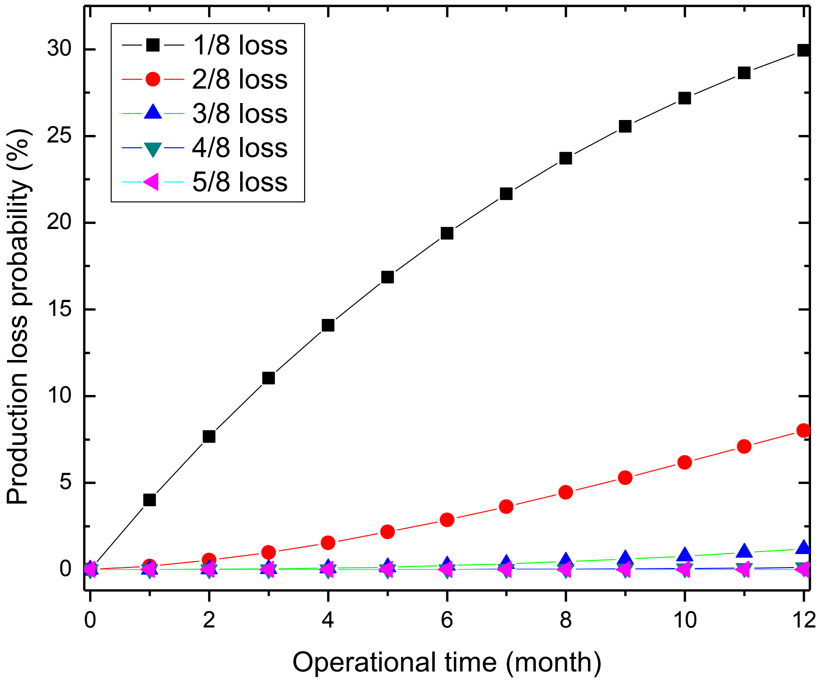


Figure 5-6 Production loss probability for level three

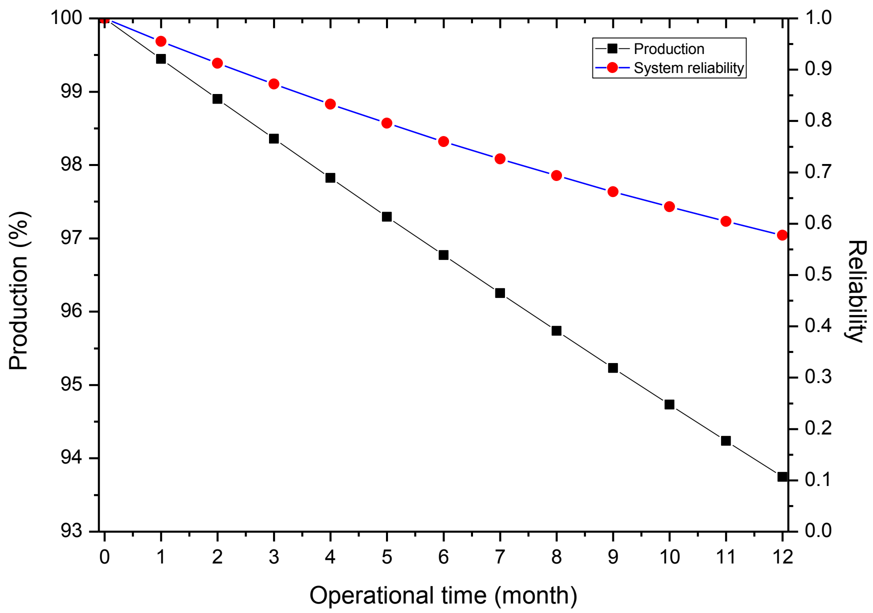


Figure 5-7 Production probability for level three

The method presented in this paper provides an accurate production and reliability assessment. The calculation of production probability from level one to level three gradually approaches the true value. Figure 5-8 shows the comparison of the production probability and reliability for the three levels.

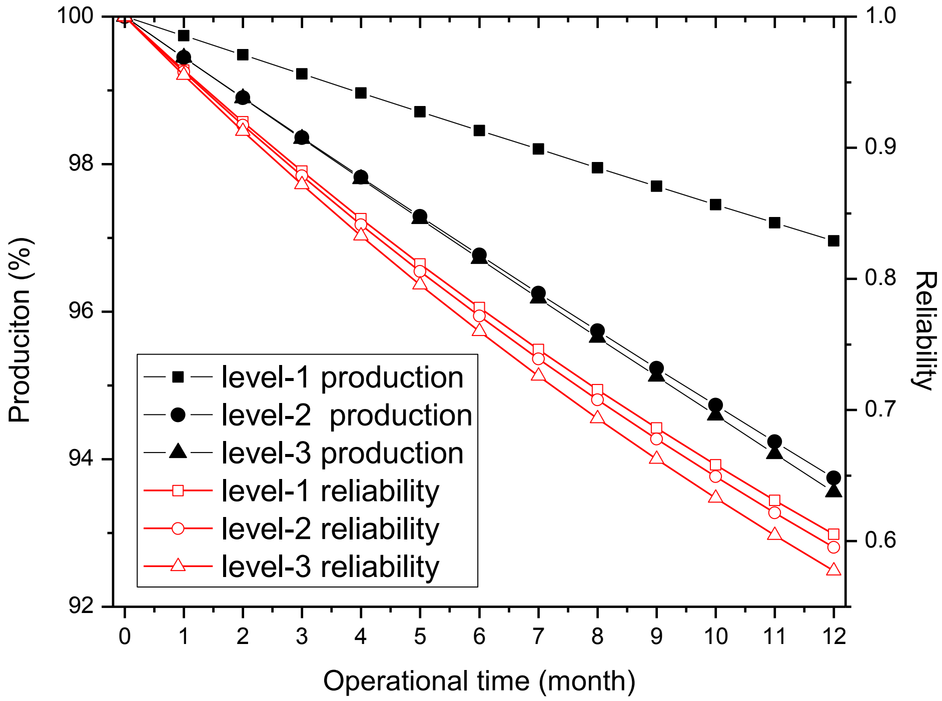


Figure 5-8 Comparison of the production probability and the reliability for different levels

5.5 Importance Measures

The importance measures for the selected components of the system are calculated using Equations (3.51) and (3.52). The result is presented in Table 5.

Table 5 Importance measures of the components

Component ID	IB	IP
Valve-F	4.964E-1	2.970E-4
Con-PP	4.961E-1	2.969E-4
Valve-D	2.482E-1	1.485E-4
Con-MP	2.481E-1	1.484E-4
Choke valve	1.242E-1	1.787E-4
Valve A	1.241E-1	7.425E-5
Flowbase	1.241E-1	3.572E-5
Utility isolation valve	1.241E-1	3.304E-5
Process isolation valve	1.241E-1	3.036E-5
Piping	1.240E-1	1.875E-5
Tubing hanger body	1.240E-1	1.786E-5
Xmas Connector	1.240E-1	1.429E-5
Annulus seal assemblies	1.240E-1	9.823E-6
Con-XM	1.240E-1	9.760E-6
Tree cap	1.240E-1	8.037E-6
Tubing hanger Hydraulic coupling	1.240E-1	6.251E-6
X-mas tree Hydraulic coupling	1.240E-1	5.358E-6
Casing hangers	1.240E-1	4.465E-6
K	2.610E-3	0
Valve-E	1.484E-4	8.881E-8
valve-B	7.421E-5	4.440E-8

The result shows that the Valve-F and Connector PP are the most important components due to their having the highest values of IB and IP. The importance order is almost the same between IB and IP. This result indicates that the most important components measured by IB have more improvement potential for the system productive. Note that the value of K, which representing the marginal transportation capacity for a pipeline, has a very low order of IB in the component list, i.e., the production reliability will not be increased very much by increasing the pipeline diameter.

Chapter 6.

Flow Assurance Analysis

The use of the multiphase system to produce and transport fluids is becoming increasingly common when developing an oil and/or gas field. These fluids, combination of gas, crude/condensate and water have the potential of solid precipitate at certain combinations of pressure and temperature. The precipitated solids are often carried downstream suspending in the fluid; however, in some case, the solid will deposit on the walls of production equipment, which ultimately causes plugging and flow stoppage. Flow assurance, which concerns about the potential of forming and depositing of solids, is a key factor in formulating the design operating plan for a subsea production system. Flow assurance is an engineering analysis process that utilizes the in-depth knowledge of fluid properties and thermal-hydraulic analysis of the system to develop strategies for control of solids including hydrates, wax, asphaltenes, and scale (Kaczmarski & Lorimer, 2001). The precipitated solids are often carried downstream suspending in the fluid; however, in some case, the solid will deposit on the walls of the production equipment, which ultimately causes plugging and flow stoppage. Control of this blockage is the essence of "flow assurance". Solid control strategies involve keeping the system pressure and temperature in a region where the solids are unstable (thermodynamic control) or controlling the conditions of solids formation so that deposits do not form (kinetic control) or allowing solids to deposit, then periodically removing them (mechanical control). For the production system adopted in this work, the pipelines are too long to remove deposits periodically. The best method for flow assurance is keeping the system pressure and temperature in a region where the solids are unstable.

6.1 System Operation Strategy

The basis of operating strategy is that the system could be started up, keeping production and can be recovered from a shutdown without fluid state ever moving into the hydrate and the wax formation region. It means from the wellhead to onshore facility, the temperatures should be above the cloud point for all expected operating conditions. The key point of the operating procedures includes cold start-up, normal production, shut-in and recover from shutdowns. The main procedures and operating strategies are as follows (Berger & McMullen, 2001):

- During cold start ups, electricity heating, and chemical injection, system should be running until an 8 hours cool down time is available for a plan/unplanned production shutdown.
- During shut-ins, no action is necessary to the subsea components and pipelines for 8 hours.
- Recovery from shutdown less than 8 hours permitted restarts the system without additional operations.
- Longer shutdown requires the fluid replacement by dead oil to prevent solid deposition.

The trees, jumpers, manifold, flowlines, separators and pipelines are all insulated to minimize heat loss during production, as well as to extend reaction time to manage solid formation potential following an unplanned shut-in.

6.2 Data Basis

The composition of produced fluid which excludes water content is shown in Table 6.1. Once the gas composition is defined, hydrate formation curve under different combination of pressure and temperature could be obtained. To do that, the software PVTsim (Calsep-A/S, 2005) was employed. PVTsim is a versatile PVT simulation program which allows reservoir engineer, flow assurance specialist and process engineer to combine reliable fluid characterization procedures with robust and efficient regression algorithms to match fluid properties and experimental data. The fluid parameters may be exported to produce high-quality input data for the reservoir, pipeline, and process simulators (Calsep-A/S, 2005). Here, the software OLGA receiving the exported data from PVTsim and to do further flow assurance simulations. Based on the oil and gas composition characteristics and with the help of PVTsim, the hydrate and wax formation curve can be obtained.

Table 6.1 Production composition

Component	Evolved Gas(mol%)	Residual Liquid (mol%)	Total Fluid (wt%)
N2	2.09	-	0.028
CO2	0.571	-	0.012
C1	74.07	0.074	0.57
C2	6.202	0.154	0.101
C3	7.714	0.845	0.26
iC4	2.164	0.551	0.144
nC4	3.055	1.099	0.251
C5	1.157	0.899	0.209
nC5	0.873	1.167	0.25
C6	0.766	1.766	0.412
C7	0.546	2.608	0.66
C8	0.602	3.834	1.062
C9	0.119	4.274	1.299
C10	0.051	3.923	1.377
C11	0.023	3.054	1.175
C12	-	3.133	1.318
C13	-	3.138	1.435
C14	-	3.072	1.525
C15	-	3.564	1.918
C16	-	2.731	1.584
C17	-	2.366	1.465
C18	-	2.833	1.858
C19	-	2.234	1.535
C20	-	2.077	1.492
C21	-	1.011	1.529
C22	-	2.176	1.734
C23	-	1.776	1.475
C24	-	1.772	1.532
C25	-	1.353	1.22
C26	-	1.55	1.454
C27	-	1.437	1.404
C28	-	1.407	1.426
C29	-	1.299	1.364
C30	-	1.591	1.729
C31	-	1.374	1.544
C32	-	0.878	1.019
C33	-	1.764	0.914
C34	-	1.075	1.326
C35	-	0.774	0.982
C36	-	29.367	57.408
Total	100	100	100

The field designed production life is 30 years. Table 6.2 provides the annual production of the field for the whole life.

Table 6.2 Annual Production Data

Year	Oil Mill STB	Gas Mill scf	Water Mill STB	Year	Oil Mill STB	Gas Mill scf	Water Mill STB
1	9.1	614	0.2	17	8.1	563	79.2
2	22.2	1523	6.4	18	7.7	537	82.3
3	29.5	2019	24.7	19	7.3	507	81.2
4	28.8	1952	46.3	20	6.9	481	79.0
5	27.6	1874	59.9	21	6.5	457	78.0
6	25.7	1757	66.3	22	6.2	435	79.2
7	22.5	1553	69.1	23	5.9	413	79.9
8	18.3	1281	68.1	24	5.6	393	80.5
9	16.0	1123	74.2	25	5.3	373	80.3
10	13.0	922	69.2	26	5.1	356	79.7
11	12.0	852	70.4	27	4.8	337	79.8
12	11.3	797	74.3	28	4.6	320	79.3
13	11.1	780	78.9	29	4.4	304	75.8
14	10.1	707	78.8	30	4.1	288	75.8
15	9.2	649	79.2	31	1.1	76	22.0
16	8.6	602	79.0	Cumulative	359	24842	2077

6.3 Solid Deposition

Wax and hydrates are the two major threats to flow assurance that must be assessed by subsea designers.

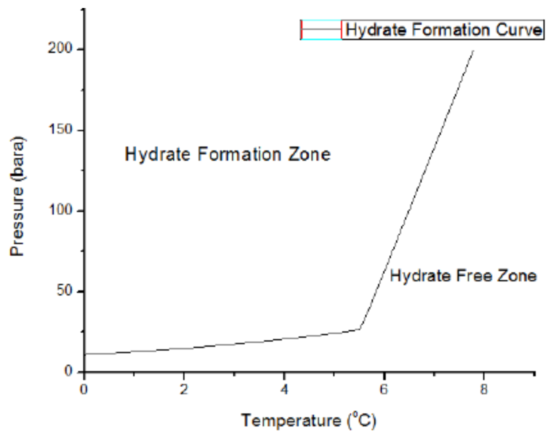
6.3.1 Hydrate Problems

Normally, hydrates start to form around 25°C, depending on the water cut, temperature and pressure in the pipeline. Based on the oil and gas composition characteristics and with the help of PVTsim, the hydrate formation curve was obtained, as illustrated in

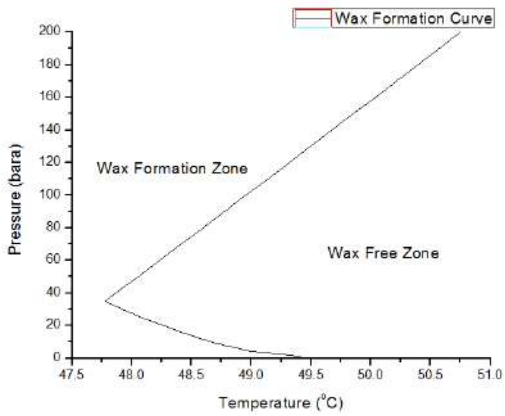
Figure 6-1a. Hydrate formation occurs on the left side of the curve where it is labeled as hydrate formation zone.

6.3.2 Wax Problems

In this work, PVTsim is used to simulate the conditions of solid wax occur. Based on the oil and gas composition characteristics and with the help of PVTsim, the wax formation curve was obtained, as illustrated in Figure 6-1 b. Wax formation occurs on the left side of the curve where it is labeled as wax formation zone.



(a) Hydrate



(b) Wax

Figure 6-1 Hydrate and Wax PT curve of multiphase flow with water-cut 5%

Combining the hydrate formation curve and wax formation curve into one chart, it is easy to get knowledge that under the maximum transportation pressure of 200 bar, the minimum temperature keeping the flow, avoiding hydrate and wax formation is nearly 50°C, as shown in Figure 6-2. In order to have a safety margin of 8°C, the arrival temperature (at the outlet of the onshore pipe) must be above 58℃.

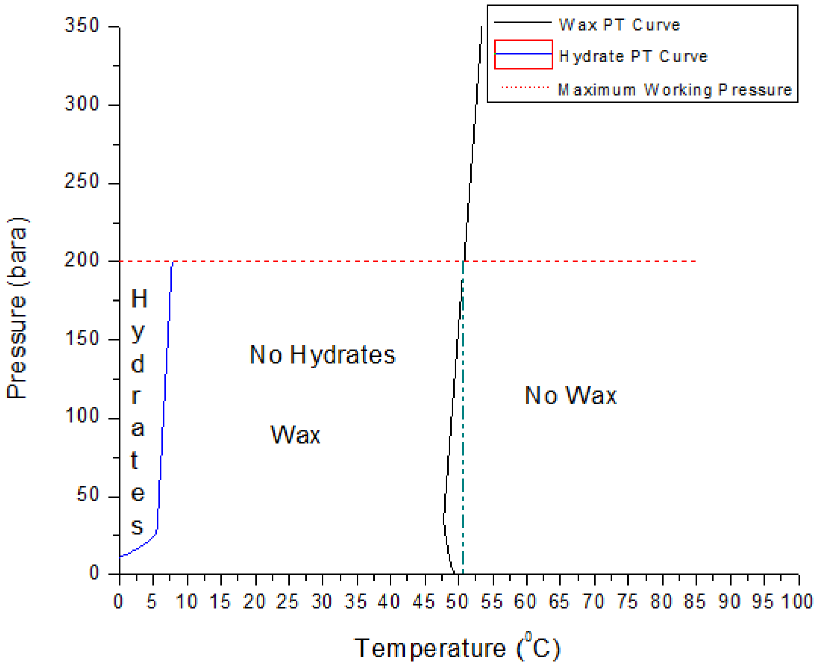


Figure 6-2 Hydrate and Wax PT curve of multiphase flow with water-cut 5%

6.3.3 Steady State Production

In relation to the minimum and maximum production should be paid close attention. The lower flow rate dictates the insulation level required and the highest determines the pipeline inner diameter. In other words, for minimum insulation and steel cost, it is necessary to determine the minimum insulation required at a minimum flow rate and minimum inner pipe diameter allowed at maximum flow rate. When building the OLGA model, the temperature and pressure of subsea wellhead oil are assumed to be 80℃ and 75bar.

The export pipeline is considered as two rigid 14-inch pipes with 100 mm thickness insulation. In order to keep the production rate as 0.18m^3/s, the inlet pressure should be raised to 13.5MPa. Without DEH, the production could be transported without wax formation approximate 35km. Exceeding this distance, the temperature will cool down below 58°C, as shown in Figure 6-3. The flow state crosses the wax formation curve, as shown in Figure 6-4. The red and black curve in Figure 6-3 refers to fluid temperature and pressure profiles along the pipeline. This graphic is used to estimate if the insulation is effective to avoid hydrate and wax formation.

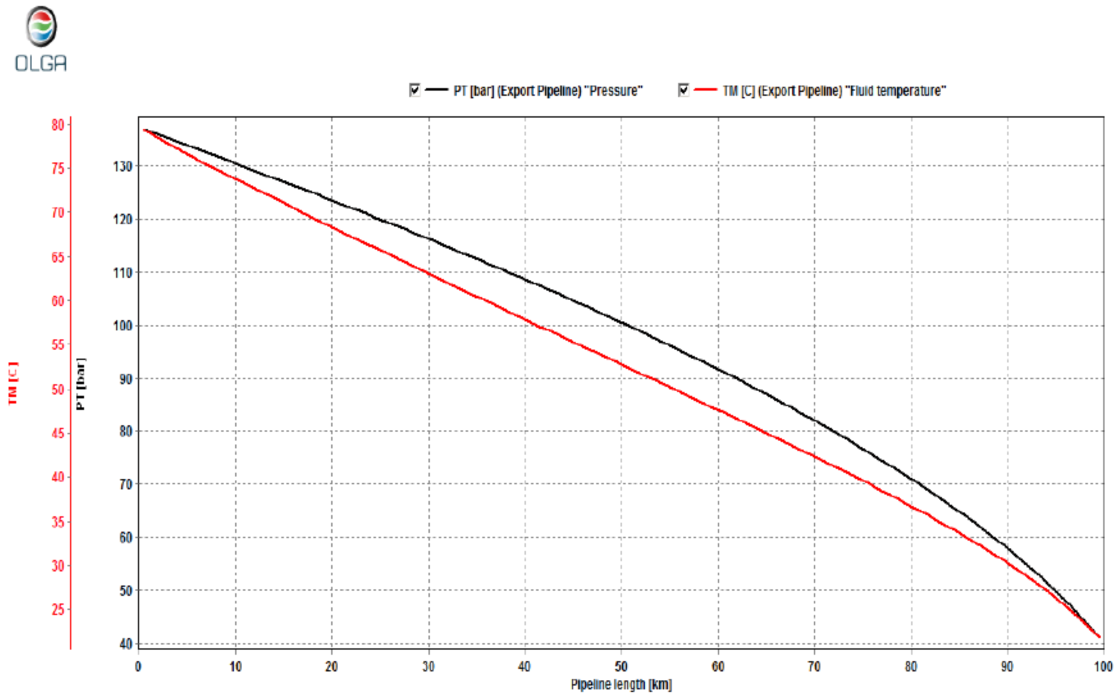


Figure 6-3 Export pipeline (two 14-inch) temperature profile without DEH

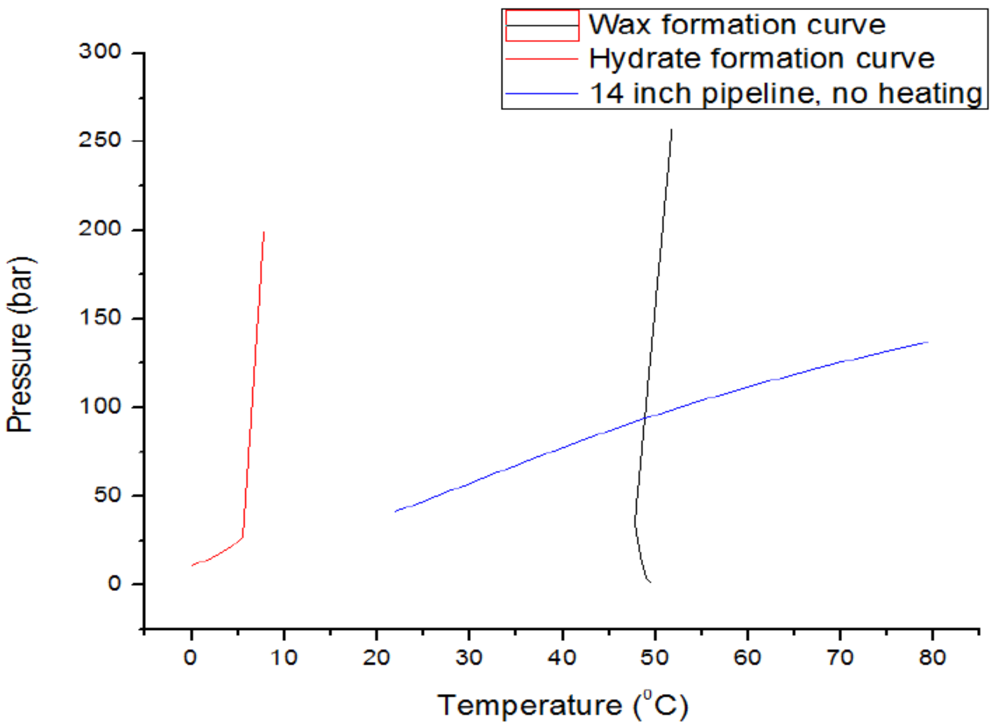


Figure 6-4 Flow thermodynamic state in 14-inch pipelines without heating

When a 14inch export pipeline with a 100 mm insulation and active heating power at 143W/m, the production in the pipeline could flows without wax formatting within a distance of 100km. The temperature profile along the 100 km pipeline will above 58 ℃, as shown in Figure 6-5.

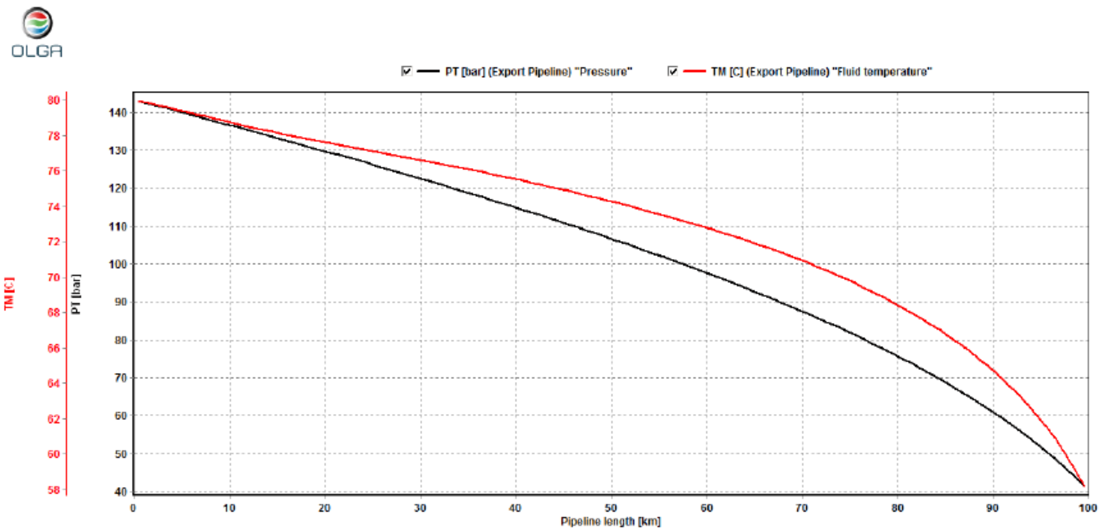


Figure 6-5 Export pipeline pressure profile with active heating power 143W/m

With the temperature and pressure results obtained for the whole pipe, it is guaranteed that the hydrate and wax will not form, as indicated in Figure 6-6.

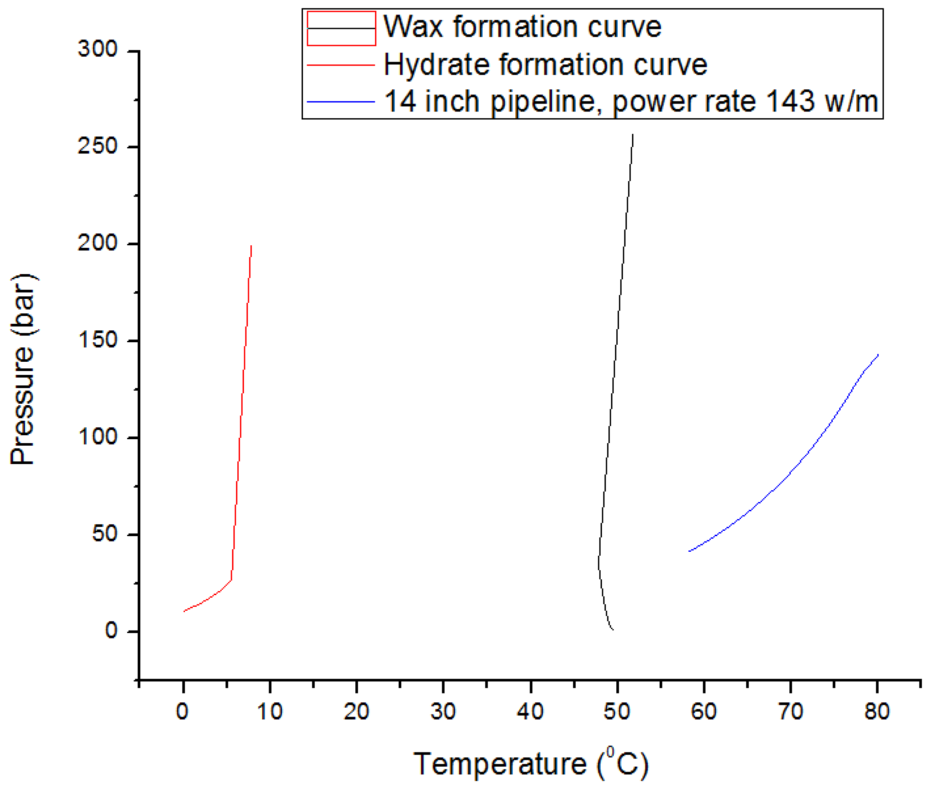


Figure 6-6 Flow thermodynamic state in 14-inch pipelines with heating rate 143w/m

According to the production data, the inlet flow rate of one of the two 14 inch pipelines should be approximate 78 kg/s. The flow rate curve presented in Figure 6-7 shows the flow rate in the middle point of the pipeline.

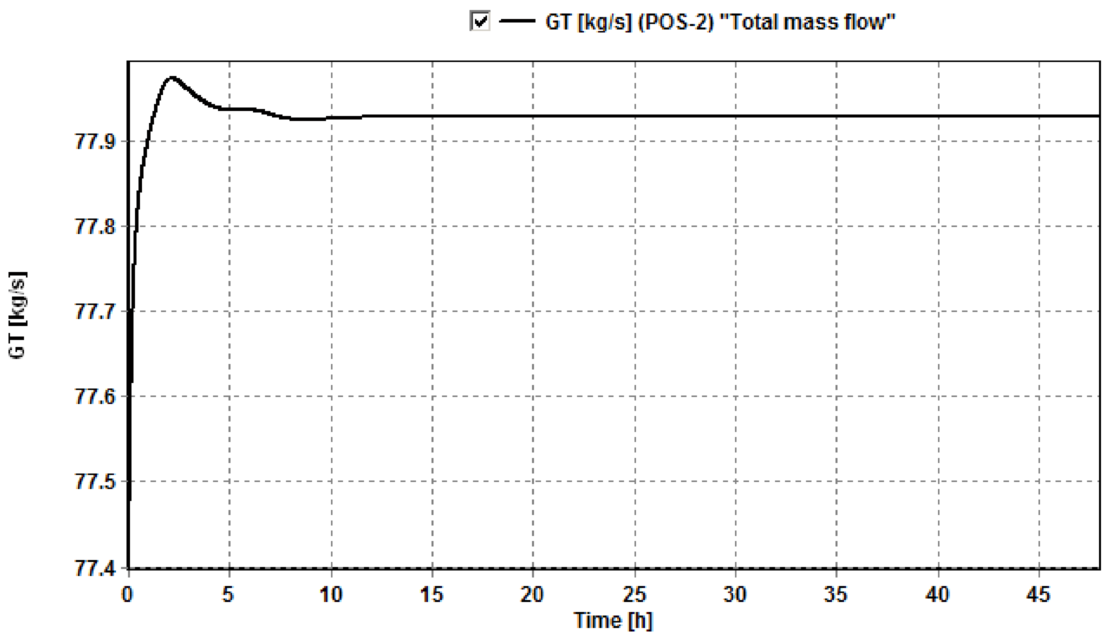


Figure 6-7 Flow rate in one 14 inch pipelines

6.3.4 Shut-in Situation

Run the OLGA model for two hours full production at steady state conditions followed by a 13 hour production shutdown. In this simulation, both inlet and outlet valves in the export pipeline shall be fully open for the first two hours. And then close these two valves simultaneously over a period of 5 minutes to shut down the production. The production flow rate curve is presented in Figure 6-8. With a shut-in period of 13hours, the total simulation time adds up to 15 hours.

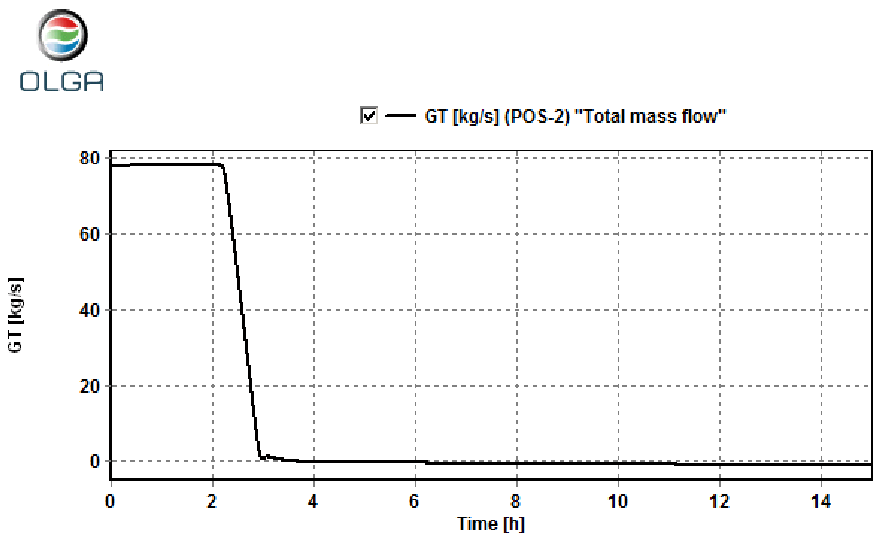
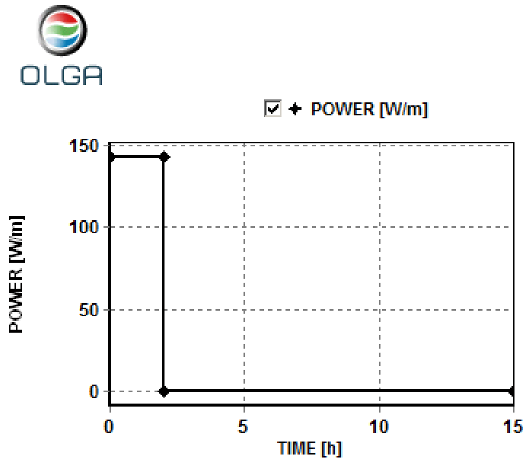
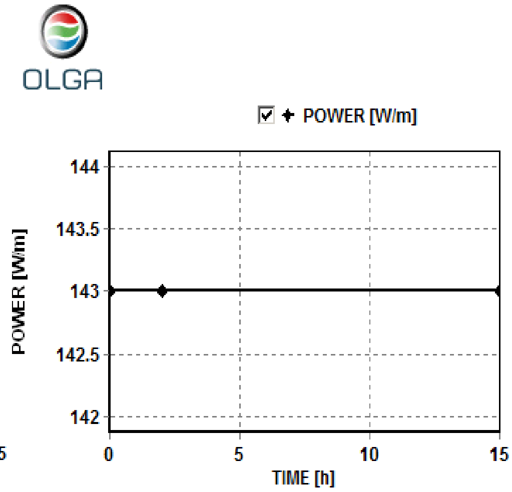


Figure 6-8 Production flow rate versus shut-in time

In order to compare the flow state with and without heating, two simulations with difference power heating states have been done. In the first simulation, the heating power will shut down at the same time of the production shut down. While in the second simulation, the heating power will keep on until the end of 15 hours. These two power forms are shown in Figure 6-9.





(a) (b)

(a) Heating power and production shut down simultaneously

(b) Continuous power supply

Figure 6-9 Heating power rate versus with time

After the production and heating power were shut down at the second hour of simulation, the pressure and temperature at the near end point of the pipeline will rise quickly and followed by a shape reducing. Without DEH, the production could keep above 58°C for approximate 2 hours, after this time, the temperature of the production at the end point of the pipeline will fall below 58°C, as shown in Figure 6-10.

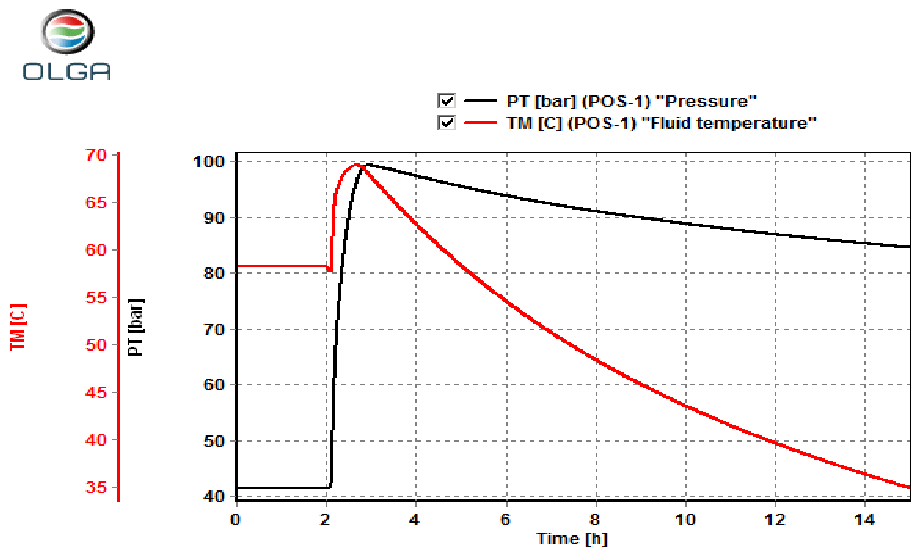


Figure 6-10 Heating power rate versus with time

Keeping the heating power rate at 143 W/m until the end of the simulation, while the valve is closed, the pressure and temperature at the near end point of the pipeline will rise quickly and keep in high level, as shown in Figure 6-11.

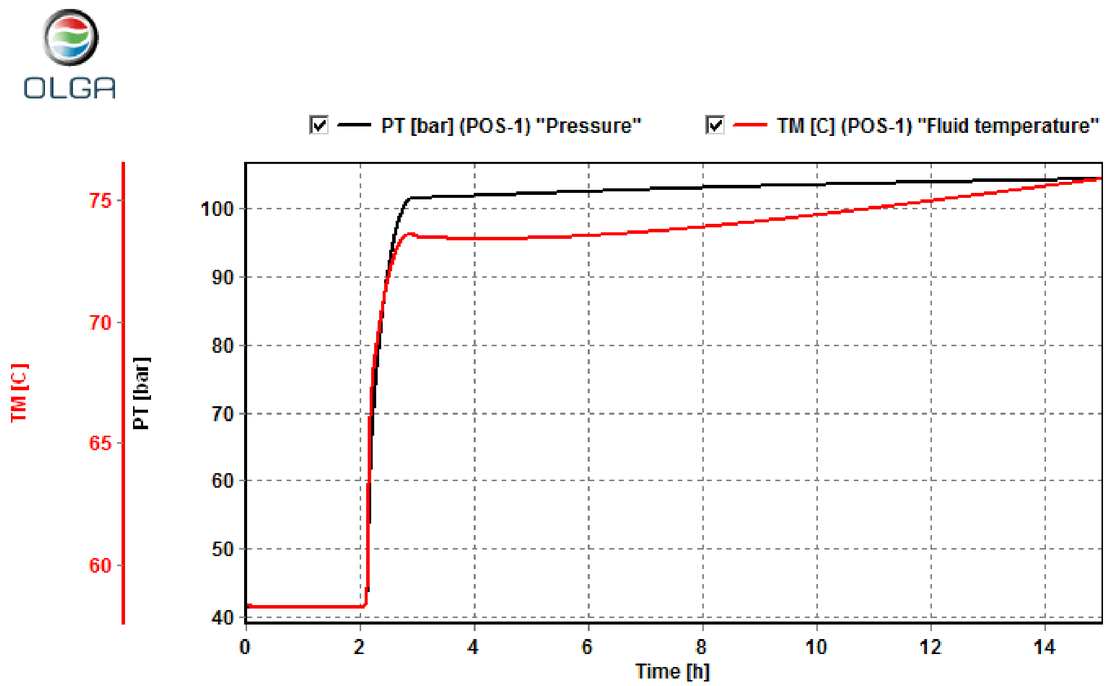


Figure 6-11 Export pipeline shutdown simulation for 15 hours

In order to find a suitable heating power rate, as shown in Figure 6-12, reducing the heating rate to 120 W/m when the production shut down. The pressure and temperature trend curve at the end point of the pipeline are presented in Figure 6-13.

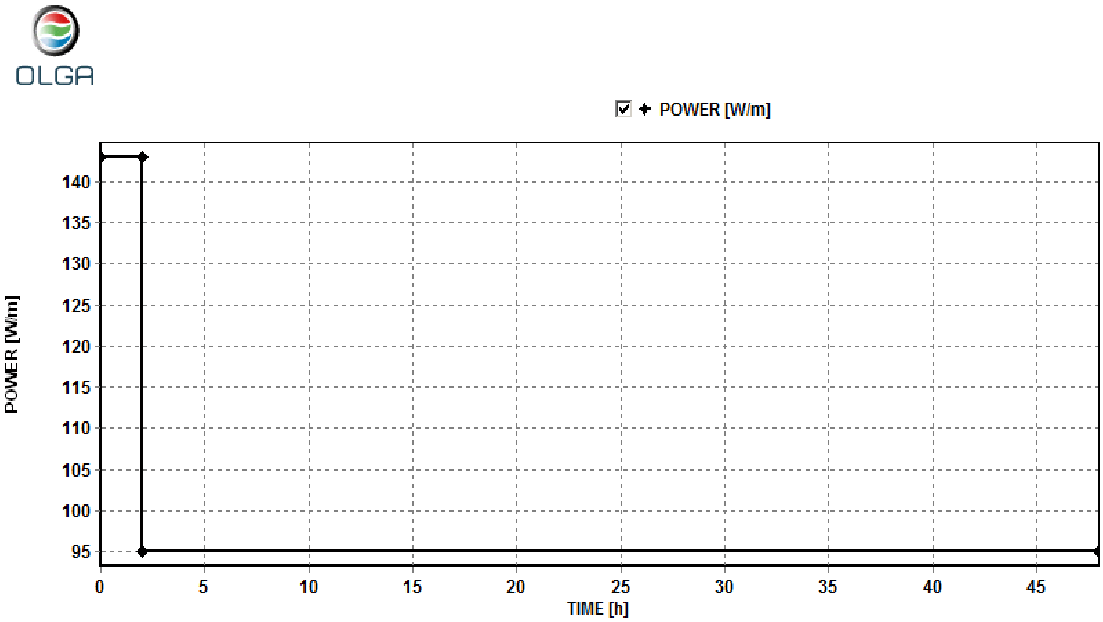


Figure 6-12 Heating power rate versus with time

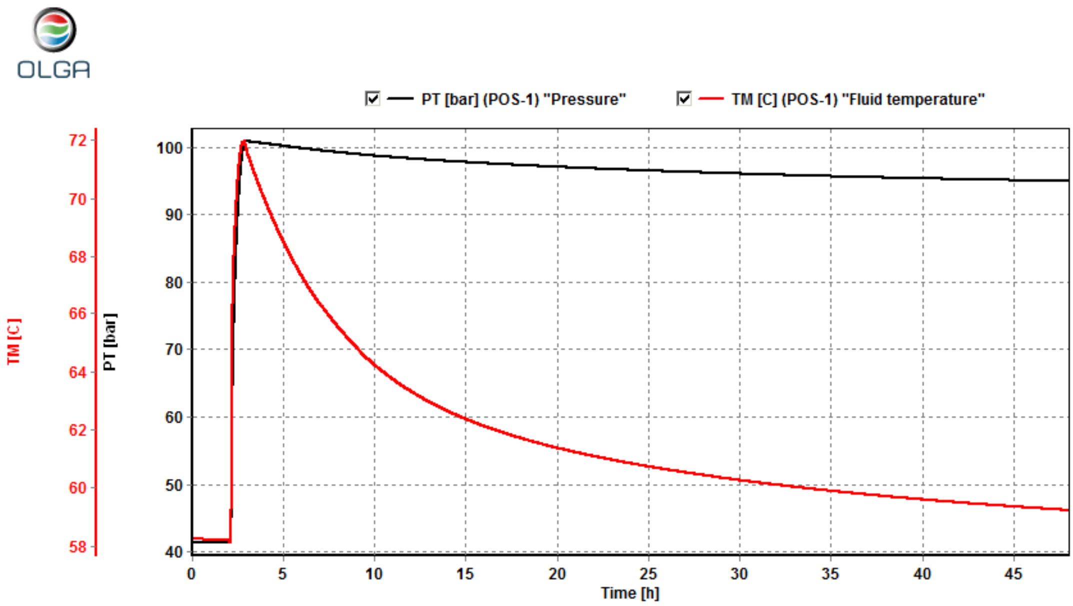


Figure 6-13 Export pipeline shutdown simulation with changed power rate

According to the pressure and temperature profile at the worst condition point (the end of the pipeline), it is possible to conclude: (1) when the heating power shut down at the same time of production shut-in, there will be no hydrate and wax formation for 2 hours; (2) keeping the heating rate at 95 W/m after production shutdown, there will be no hydrate and wax formation for at least 48 hours.

6.3.5 Start-up Situation

At the end of the shutdown, the operator will have two options: to restart production or, in case the production cannot be restarted, to depressurize the pipeline to be sure that the pipeline fluids remain outside hydrate and wax formation conditions. With the help of the DEH system, start-up process will not be a big challenge.

6.4 Relationship Between Reliability and Flow Assurance

When an equipment fails, the associated flow will be reduced or totally shut off will occur. For the export pipeline, reducing the production from seven wells to one well, the temperatures at the end position are presented in Figure 6-14. As discussed previously, when the temperature is below 58^{o}C, there is a risk of wax deposition. For the export pipeline, the probability of total production loss may be quite low; but for the infield flowline, a valve or an X-mas tree fails can cause a total production shutdown of a specific flowline.

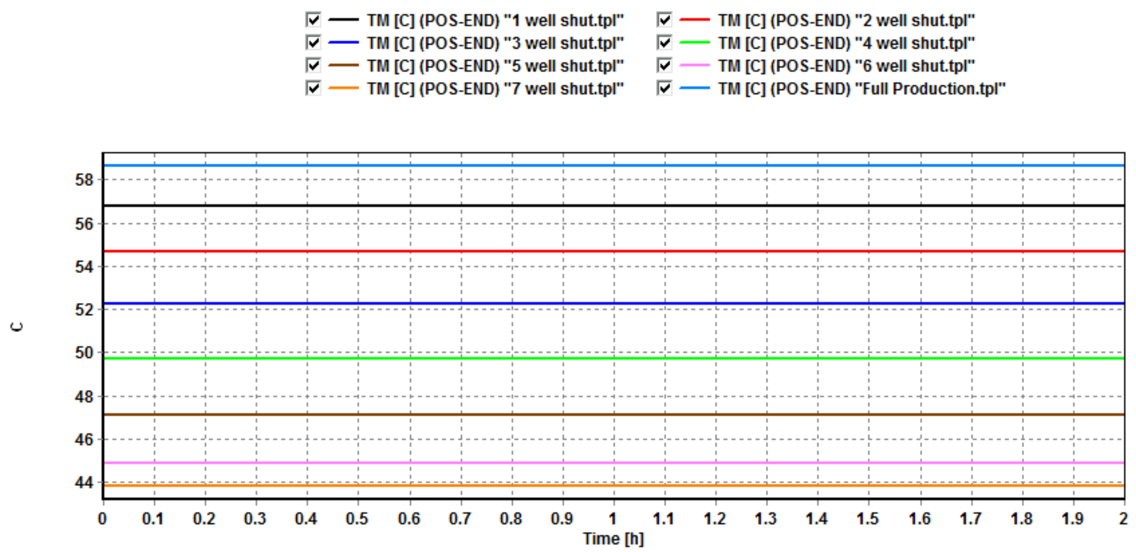


Figure 6-14 Temperature drop when reducing production

The temperature profiles along the export pipeline are presented in Figure 6-15. The maximum safety distance for each scenario (number of shut wells) can be obtained from Figure 6-16.

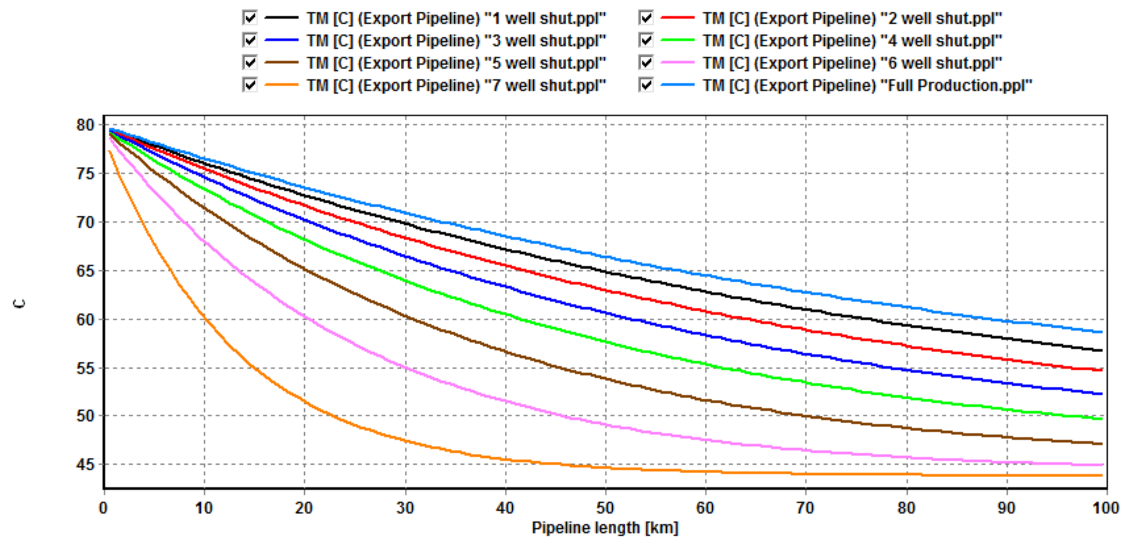


Figure 6-15 Temperature profiles of export pipeline for different number of shut wells

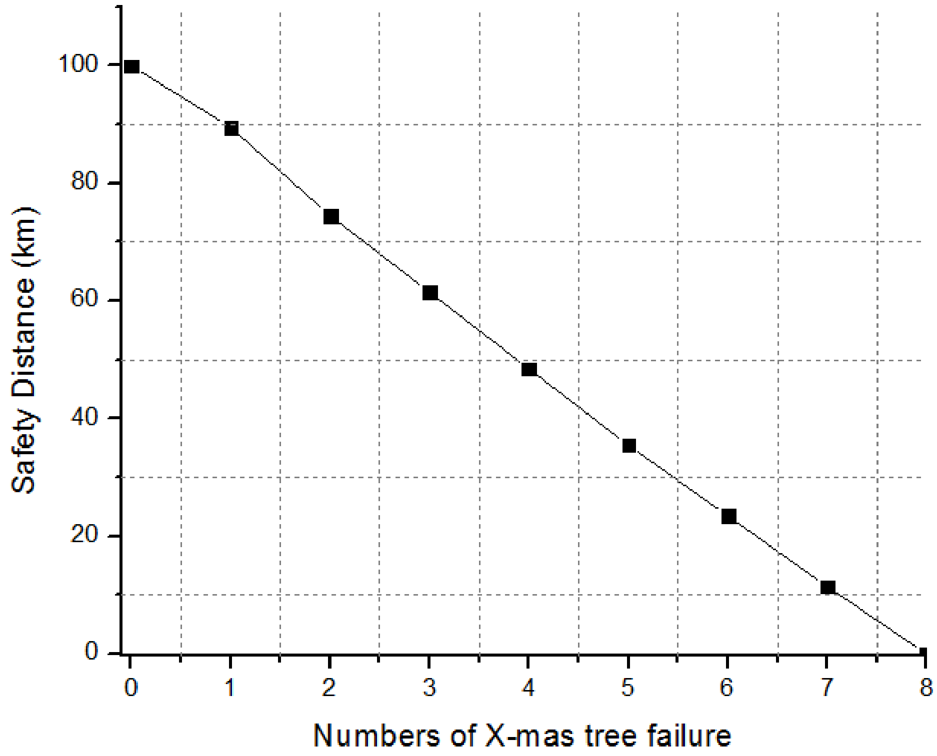


Figure 6-16 Safety distance vs. X-mas tree failure

The reliability of an X-mas tree will influence the flow assurance. When an X-mas tree fails, the safety distance for the export pipeline is about 90 Km. Here, not only the X-mas tree fails, but all the equipment that can influence the flow have the same effect as the X-mas tree failure.

The system production probability is presented in Table 6.3 and Table 6.4, the former presents the data from one to six months, and the latter presents the data from seven to twelve months. These data are obtained by the reliability analysis, in Chapter 5.

Table 6.3 Reliability data from 1 to 6 months

Operational time (months)	1	2	3	4	5	6
1/8 loss	4.01E-02	7.67E-02	1.10E-01	1.41E-01	1.69E-01	1.94E-01
2/8 loss	2.06E-03	5.41E-03	9.89E-03	1.54E-02	2.17E-02	2.87E-02
3/8 loss	3.54E-05	1.68E-04	4.32E-04	8.57E-04	1.47E-03	2.28E-03
4/8 loss	9.52E-07	5.20E-06	1.55E-05	3.55E-05	6.94E-05	1.22E-04
5/8 loss	5.66E-09	5.48E-08	2.25E-07	6.46E-07	1.51E-06	3.09E-06
6/8 loss	1.93E-10	1.85E-09	7.36E-09	2.03E-08	4.60E-08	9.17E-08
Reliability	9.55E-01	9.13E-01	8.72E-01	8.33E-01	7.96E-01	7.60E-01
Production	9.94E-01	9.89E-01	9.84E-01	9.78E-01	9.73E-01	9.68E-01

Table 6.4 Reliability data from 7 to 12 months

Operational time (month)	7	8	9	10	11	12
1/8 loss	2.17E-01	2.37E-01	2.55E-01	2.72E-01	2.86E-01	2.99E-01
2/8 loss	3.63E-02	4.44E-02	5.30E-02	6.18E-02	7.09E-02	8.01E-02
3/8 loss	3.31E-03	4.57E-03	6.06E-03	7.79E-03	9.76E-03	1.20E-02
4/8 loss	1.98E-04	3.03E-04	4.43E-04	6.23E-04	8.49E-04	1.13E-03
5/8 loss	5.73E-06	9.88E-06	1.61E-05	2.49E-05	3.71E-05	5.35E-05
6/8 loss	1.68E-07	2.88E-07	4.70E-07	7.37E-07	1.12E-06	1.65E-06
Reliability	7.26E-01	6.93E-01	6.62E-01	6.33E-01	6.04E-01	5.77E-01
Production	9.63E-01	9.57E-01	9.52E-01	9.47E-01	9.42E-01	9.37E-01

According to the system reliability data and the flow assurance data, the relationship between them can be established. For example, the 1/8 production loss in the end of 12 months is about 29.9%. This failure will reduce the safe export distance to 90 Km (Figure 6-16).

Based on the previous considerations it is clear that equipment reliability and flow assurance are interdependent. Therefore, special attention must be paid for the equipment failure that can cause flow blockage.

Chapter 7.

Conclusion

7.1 Summary

This work considered an approach for the production reliability assessment of an innovative subsea production system, Subsea to Shore. The calculation method is based on universal generation function techniques. The probabilities for the production loss ratios are obtained using the proposed method. The approach has the advantage of avoiding the complex process of constructing multi-fault trees or programming a Monte Carlo Simulation, which is usually performed to simulate a multi-state system. This method not only represents an accurate procedure for calculating reliability, but also can provide more information associated with different production loss ratios than the traditional method.

Flow assurance has been evaluated using the software OLGA. It is important to notice that the analyzed oil is a heavy oil with API grade 13^{o}. It means that the present research focused on an extreme condition for flow assurance in which passive insulation and chemical injection must be combined with electrical heating.

As already discussed, equipment failure associated with unsatisfactory reliability level can have a detrimental effect on the flow assurance and consequently blockage of the subsea lines. As reliability data were based on OREDA data bank, it is important to note that the equipment considered can be relatively old and do not reflect the technology evolution of the mechanical and electrical components of new equipment.

7.2 Conclusion

The research conducted in the thesis established a Subsea to Shore concept for an offshore field with eight wells. The reason for this was to define a satisfactory number of wells not small enough to justify tie-backs or too big that could bring difficulties for the research.

The proposed subsea to shore system reliability is approximately 0.58 after one year of operation. It should be noted that this number is obtained under the condition of no maintenance work performed for the entire year. For a complex system, it is very difficult to maintain high system reliability. Note that even for low system reliability, the operator will make a judgment about the risks involved and take the decision about the maintenance strategy, considering that production reliability is a different concept from system reliability. In many cases, the occurrence of failure equipment does not mean production loss.

In the present work, the production reliability is approximately 0.93, which means that the production yields 93% of the production target by the end of the first year. The production loss reduces both temperature and pressure in the pipeline, which means an increased probability of solid formation and deposition along the pipelines. Even when the production yields approximately 93% of the production target, the probability of production loss for one shut well is 30%. It means that at the end of the first year of operation the export pipeline has a safety distance of only 90 km with a probability of 30%.

Based on the simulations presented in the thesis, it is recommended a comprehensive flow assurance and reliability analyses during the conceptual design of subsea production systems, in particular, the evaluation of the production loss associated with the flow assurance problems caused by equipment failure or the decrease of production along the field life cycle. As a result of these analyses, the insulation thickness can have a safety margin to prevent the line blockage.

The ranking of the importance measures of the components of the entire production system was also determined. Redundant components can be considered to improve both production and system reliability.

The method used in this thesis is easy for applying to other systems. The essence of the objectives of this thesis is to find a method to assess a production system that may be used when designing a system or comparing different systems.

7.3 Suggestions for Further Work

The study conducted in this work opens up several questions on how to calculate the reliability of a subsea production system. The following areas of research are recommended for the progress of the activities focused in the thesis.

System maintenance: Strategy for the maintenance of Subsea to Shore system should be considered in terms of equipment replacement and logistics to attend emergency failures.

Repair time. Productivity must be considered in relation to the repair time and possible contingency factors to reduce it.

Electrical Heating system: Reliability techniques should be considered for the electrical system associated with flow assurance constraints and costs in the long export pipeline. This technology associated with insulated pipes, in particular, the new concept of sandwich pipe with insulation properties of the annular material, can be a promising solution for Subsea to Shore production systems.

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