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Production Availability Analysis: Implications on Modelling due to Subsea Conditions

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Reliability, Availability, Maintainability and Safety (RAMS)
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Preface

This Master thesis was carried out during the spring semester of 2017, as part of the Master program Reliability, Availability, Maintainability and Safety (RAMS) at the Norwegian University of Science and Technology (NTNU).

This thesis was conducted in cooperation with DNV GL, Oslo. A study case was proposed based on one of DNV GL's position papers, and an ExtendSim library for reliability modeling was provided. During the master thesis, many suggestions for the case study and help on the use of ExtendSim were given.

As the rapid development of subsea production and processing recent years, the influences on production by implementing subsea systems are of interest for DNV GL. Production availability analysis provides a way to model this issue and predict the related system performance. A set of reliability issues is therefore to be studied and addressed in the model. The main objective of this project is to review the subsea characteristics and the concept of production availability, and demonstrate the modeling process with the use of ExtendSim.

For a better understanding, the reader is assumed to have some background in system reliability, availability and maintenance.

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Tianqi Sun

Acknowledgement

Firstly, I would like to thank Professor Mary Ann Lundteigen, from Department of Mechanical and Industrial Engineering of NTNU. She gave me many feedbacks and suggestions through the weekly meetings, and actively looked up for opportunities of cooperating with DNV GL. I could therefore carry out this thesis with DNV GL, which is a very precious experience and I learn a lot from it.

I would also like to thank Professor Anne Barros and Postdoc. HyungJu Kim, also from Department of Production and Quality Engineering of NTNU. Anne was always available for discussions and suggestions, while HyungJu gave me many valuable feedbacks through the weekly meetings and during the writing of the report. I appreciate their efforts on contributing to my thesis.

I am grateful to my supervisor Siegfried Eisinger in DNV GL. He gave me great help on the modeling and the use of ExtendSim. Besides, Andreas Hafver and Tore Myhrvold from DNV GL proposed the study case and gave me valuable suggestions on what I should include in my study. They are all very helpful during my thesis. I appreciate their efforts on contributing to my thesis.

It is a pleasure to thank my friends and colleagues in my office, Renny Arismendi, Florian Müller and Mariska Putri, for the wonderful time we shared. They were always ready for discussions and suggestions, and made the process of master thesis full of great memories. My gratitude also goes to all my friends in Trondheim, for giving me such a wonderful experience.

Last, but not the least, a big thank you to my parents, for all the love and support. Thank you for encouraging me to follow my dreams and giving me guidance.

T.S.

Abstract

Subsea production and processing systems have become a hot topic among research institutes and industries. While highlighting the advantages on production and economy, the reliability issues show a different picture with limited access, difficulty of maintenance and possibly lower availability. The influence of these issues on the system performance is thus to be studied, to evaluate the benefit of subsea systems.

A literature review was carried out to prepare the background knowledge of the subsea system and its features. The main elements in subsea systems were introduced. Since the study case was about implementing a subsea separator, a more detailed introduction on subsea separation was provided. The drivers and challenges for subsea were also discussed, together with considerations for reliability modeling.

Production availability analysis was selected as the approach for analysis. By conducting such an analysis, the system performance can be predicted and the critical components can be identified for system optimization.

Two different types of approaches, the analytical approach and the simulation approach, were discussed in this thesis. The analytical approaches have restricted use and provide less precise results, but require less effort. The simulation approaches are more flexible and can provide more detailed predictions, but are rather time and cost consuming, and a solid mathematical and programming basis is often needed. A set of software tools were developed to simplify this approach. Since this thesis was done in collaboration with DNV GL, ExtendSim is suggested for the case study. The basic principles of Discrete Event Simulation, especially of ExtendSim, was introduced for a better understanding of how simulation is performed in these tools.

After all preparations were ready, a case study was carried out to demonstrate the analysis process. Two difference cases, namely a reference case (with all separation on FPSO) and a subsea case (with the use of subsea separator), were modeled in ExtendSim based on a library from DNV GL. The modeling process was demonstrated in detail. The production availability and loss contributors for the two cases were derived from simulations.

A discussion was then carried out on the model and the potential use of the results. Recommendations for future work were included at the end of this thesis.

Contents

Chapter 1.
Introduction

1.1 Background

As a new trend in the oil and gas industry, the subsea production and processing systems adopt advanced technologies and have gained extensive attention among the research institutions, because of its benefits against offshore platforms or Floating Production, Storage and Offloading (FPSO). Due to the reduced exposure to production facilities, subsea systems are safer in terms of personnel risk (Kim et al., 2016). Besides, the use of subsea systems facilitates increased and/or accelerated production, a prolonged lifetime of the field and reduced cost for fixed installations (Davies et al., 2010; Mogseth, 2016). It also enables the production in harsher environments where conventional solutions are not applicable.

In spite of the advantages of subsea systems, the harsh operating environment and the immaturity of related technologies give rise to a set of reliability issues (such as corrosion and component degradation) and ask for more maintenance, while the long distance from shore and surface greatly increase its difficulty and cost, which hinder frequent intervention. Besides, the long distance itself also leads to issues with flow assurance. These issues might lead to less production, since systems could often run in a degraded state due to lack of maintenance, and experience long production stops during maintenance. It is therefore hard to judge the overall influence on performance by implementing subsea equipment.

Production availability analysis, which has shown its potential in performance prediction and system optimization (Brissaud et al., 2012; Chang et al., 2010), provides a solution for this problem. By conducting such an analysis, the system production availability can be predicted and the potential defects of the design can be identified. Therefore, the performance of different alternatives can be compared and a system optimization can be carried out in a cost-effective way.

Two main approaches, namely an analytical approach and a simulation approach, are used for such analysis (Kawauchi et al., 2002). The analytical approaches have restricted use and provide less precise results but require less effort. The simulation approaches are more flexible and can provide predictions that are more accurate. It also demonstrates the case in a more visualized way and thus easier to understand and communicate. However, this process is rather time-consuming and requires solid mathematical and programming basis.

To simplify the modeling process of the simulation approach and promote its use in industry, a set of commercial software based on Monte-Carlo simulation is developed. This allows the analyzers to focus more on the reliability issues instead of programming. In collaboration with DNV GL, this thesis selects ExtendSim as the simulation tool to carry out a production availability analysis.

1.2 Literature Review

The literature review for this thesis can be divided into two parts. The first part is about subsea systems, especially the subsea processing systems. This is to prepare the background knowledge of subsea systems and issues to be noticed in the reliability analysis. A better understanding of the study case is achieved in this process. The second part is about the concept and procedures of production availability analysis, which provides numerical results for performance prediction in the case study.

- **Subsea Systems and Challenges**

Due to its potential benefits for a more profitable and safer solution, subsea systems have gained many attentions among both research institutes and industries. Studies on various subsea technologies are carried out and many operators have started to develop their own applications.

Some researchers and organizations reviewed the status of subsea systems and identified the technology gaps for the next goal. The comparison between subsea and topside systems was also performed to investigate the benefit of subsea systems. OG21 (2006) gave an overview of challenges and technology gaps regarding subsea processing, downhole processing and well stream transport, and proposed the technology target for subsea processing and transport. Ruud et al. (2015) introduced the All Subsea Vision (subsea-to-market solution) and discussed how it can be implemented, based on the status and gaps of technologies. Brandt (2004) presented benefits and challenges of implementing subsea processing and conducted a comparative risk assessment of subsea versus surface processing.

Besides, some leading companies presented the existing subsea systems and their current development. Davies et al. (2010) provided an overview of Statoil's practice in subsea boosting (LuFeng and Tordis field as the example) and subsea separation (Troll Pilot and Tordis fields as the example), and summarized the undergoing gas compression projects. Nilsen (2015) summarized TOTAL's practice in subsea processing and presented its ongoing technology development programs on subsea systems.

In order to fill the technology gap, researchers reviewed the existing technologies and proposed new promising solutions. Khoi Vu et al. (2009) gave a more detailed overview of the subsea separation system with current practices and compared the potential of different technologies for a more efficient separator. Prescott et al. (2016) summarized the existing subsea separators (installed, operating and inactive) and explored two novel linear pipe designs that are more efficient.

- **Production Availability Analysis**

Production availability analysis has been developed for many decades and is a rather mature field. Plenty of studies have been carried out, both on methods development and on applications based on commercial software.

For methods development, Kawauchi et al. (2002) developed an analytical approach based on Markov modeling and a rule-based method to assess production availability in the petrochemical industry. Chang et al. (2010) presented a practical application of the Monte-Carlo simulation using Visual BASIC in the evaluation of production availability of the offshore facilities, considering the realistic aspects of system behavior. Brissaud et al. (2012) gave an overview of the production availability concepts and presented a procedure to perform such an analysis based on their project experience and the general framework in ISO 20815.

For applications based on commercial software, Sneve (2015) conducted a case study of Reliability Availability and Maintainability (RAM) analysis for availability improvement in mining industry based on BlockSim and developed a framework of data collection including influence factors. Wang (2012) combined the RAM analysis and LCC analysis to facilitate the trade-off between maximum production and minimum expenditure, using MIRIAM Regina and excel spreadsheet to demonstrate this process. G. Rausand (2005) introduced the approaches of including uncertainty in system modeling with the use of MIRIAM Regina. I. Choi et al. (2013) studied the production availability using the commercial tool Maros for a new subsea concept with seabed storage tanks. Corvaro et al. (2016) reviewed the relevant aspects and findings of RAM analysis and carried out a case study on a reciprocating compressor with Maros.

1.3 Objectives

The main objective of this master thesis is to investigate the influence on system performance by implementing subsea separator. Production availability analysis serves as the methods to produce desired indicators. While modeling for the topside system is studied by Kawauchi et al. (2002), Chang et al. (2010), Wang (2012) and so on, new reliability issues come from the subsea conditions. For this purpose, this thesis has a focus on reliability modeling of subsea systems. To achieve this goal, several tasks are defined:

1. Give an overview of the subsea system, especially subsea processing system.
2. Explore the features of subsea systems compared to topside systems.
3. Discuss the concept of production availability analysis and the approaches to perform such analysis.
4. Review existing simulation tools for production availability analysis.
5. Introduce the principle of Discrete Event Simulation, especially of ExtendSim.
6. Perform a case study to demonstrate the simulation approach for production availability analysis, and explore the modeling process for subsea systems in ExtendSim.

1.4 Research Approach

The first three chapters of this thesis are established based on literature review and former lecture notes, which prepares the background knowledge of the case study. A regular meeting with Professor Mary Ann Lundteigen and Postdoc. HyungJu Kim is carried out every two weeks and discussions are carried out with Professor Anne Barros.

This thesis is conducted in collaboration with DNV GL. An ExtendSim library including a set of blocks for reliability modeling is provided, and Siegfried Eisinger from DNV GL provides great help on the modeling in ExtendSim. Besides, Andreas Hafver and Tore Myhrvold give valuable inputs for the case study. Figure 1.1 gives an overview of this approach.

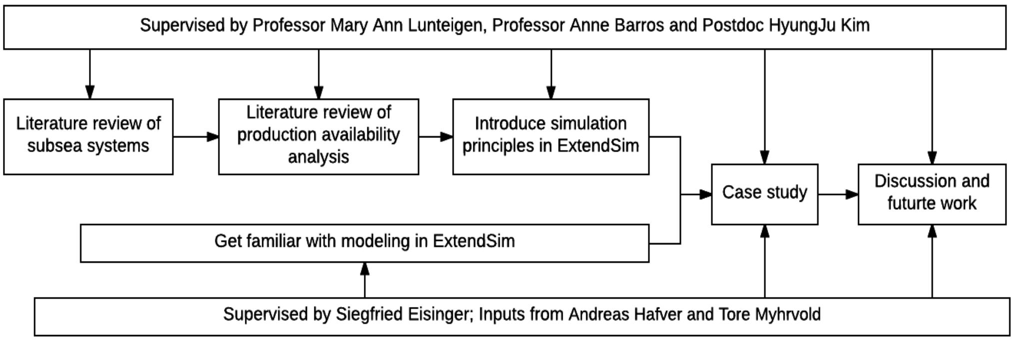


Figure 1.1 Research approach

1.5 Limitations

This project is carried out based on a synthetic case considering subsea separation instead of topside one. Simulation models are built in ExtendSim based on a library from DNV GL to predict the production availability of two different cases.

The models are simplified representations of the system and reflect the influence of component failures on system performance. The process is simplified and only the basic functions are modeled. Since the project is still at the conceptual design phase, no detailed design is available and the topside and subsea facilities are assumed with same configurations. The current models can be easily updated once the real system configuration is available.

In the production availability analysis, one big limitation is the lack of data. The data for topside facilities is from DNV GL and that for the subsea system is from OREDA-15 (2015). The data for subsea components is rather few and therefore some data for subsea components is adjusted from topside. A correction factor based on expert judgment is used. Although the exponential distribution is not enough for subsea application, due to the lack of data, the lifetimes of subsea components are still assumed to follow exponential distributions.

1.6 Structure of the Report

The remaining report of this thesis will be organized as follows.

Chapter 2 introduces the subsea systems, especially the subsea boosting and separation systems. The motivation of going subsea and challenges are also described.

Chapter 3 presents the concepts and approaches of production availability analysis. Several commercial tools for simulation approaches are introduced.

Chapter 4 describe the basic principles of Discrete Event Simulation (DES) software. Detailed illustrations based on an example in ExtendSim are given.

Chapter 5 demonstrates the modeling process for a reference case with all separation equipment on FPSO and a subsea case with the use of a subsea separator.

Chapter 6 presents the results from the models and carries out a discussion.

Chapter 7 summarizes what have been done in the thesis with discussions and recommendations for future work.

Chapter 2.

Subsea System

In recent years, the global energy requirements have continuously increased and around 34% of them are met by oil (Vedachalam et al., 2015). As the oil industry running out of oils that are "easy" to produce, there is a new trend of moving from onshore and shallow waters to deep-water and more remote locations. In the foreseeable future, deep-water oil and gas production is expected to become a major contributor to the global requirements (I. Choi et al., 2013). To cope with this challenge and seize the opportunity, many companies have started to develop their own subsea technology and a concept of "All Subsea Vision" is regarded as the future of this industry (Ruud et al., 2015).

In addition to the ability to produce in the areas where conventional solutions are not feasible or not economically profitable, subsea production and processing systems also facilitate accelerated production, increased hydrocarbon recovery, reduced capital expenditure (CAPEX) and operational expenditure (OPEX), and health, safety and environment (HSE) benefits (Davies et al., 2010).

2.1 Introduction to Subsea Systems

A subsea system is a complex seabed system, designed for the production of hydrocarbons in deep water and served as a supplement to conventional systems like fixed platforms and FPSO. Figure 2.1 shows an illustration of a typical subsea system.

According to Clarin (2013) and Gjersvik (2016), the installation cost for subsea systems is almost independent of water depth, which is a huge advantage against conventional platforms when it goes to deep water. Besides, the drilling for subsea systems requires mobile drilling units, which leads to a rapid increase of drilling cost with more wells. This makes the subsea systems suitable for a small number of wells. Figure 2.2 gives an intuitive description of this idea.

Generally, subsea systems can be classified into two categories: subsea production systems and subsea processing systems. This chapter gives an introduction of the main elements in both systems.

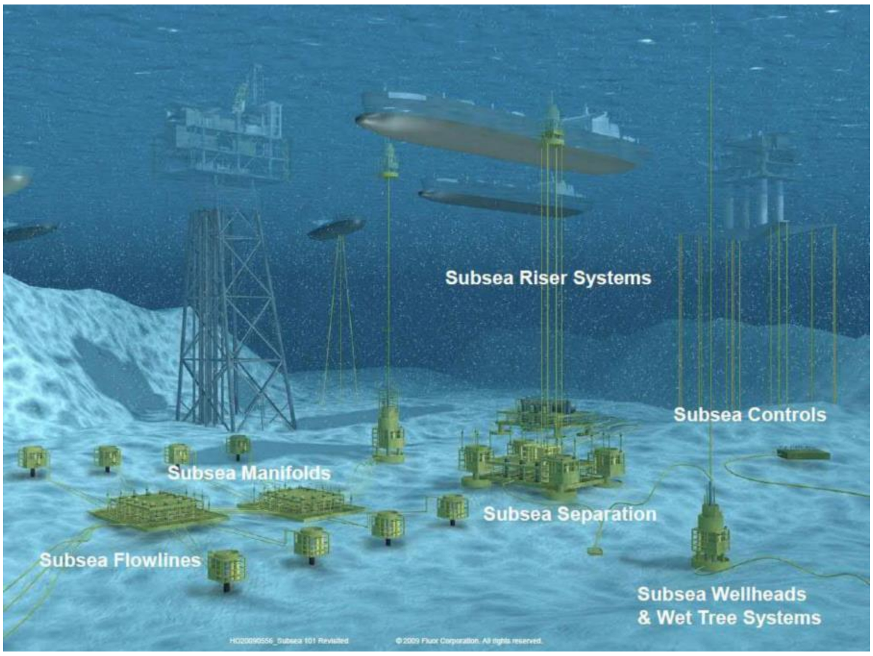


Figure 2.1 Illustration of subsea facilities (Prescott et al., 2016)

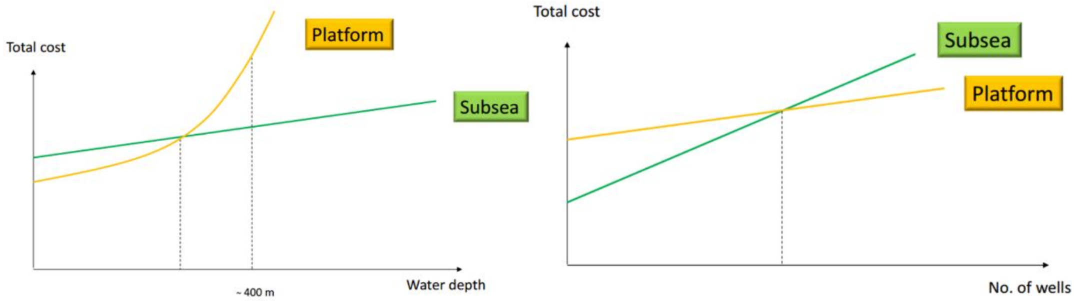


Figure 2.2 Cost changes for platform and subsea with water depth and number of wells (Gjersvik, 2016)

2.1.1 Subsea Production System

Subsea production system refers to the essential facilities for subsea production such as subsea Christmas tree and wellhead system, pipeline and flowline system, subsea manifold and jumper system, which extract oil from the reservoir and transfer to offshore or onshore facilities. The description of each system is based on a paper from I. Choi et al. (2013), the thesis from Clarin (2013) and the lecture notes from Gjersvik et al. (2016).

- **Wellhead & Christmas Tree**

Subsea wellhead is installed at the top of a well as the infrastructure for hanging the production tubing, and installing the Christmas tree and surface flow control facilities. The purpose is to regulate and monitor the hydrocarbon flow from the well, preventing leakage and preventing blowout due to high pressure.

A Christmas tree consists of a set of valves, pressure sensors and chokes. It is connected to the top of the wellhead to control the production. The Christmas tree can be used for production wells, water/gas injection wells, and other types of wells.

- **Subsea Flowlines**

Subsea flowlines are installed to transport the fluids (hydrocarbons, injection water, and other chemicals) between two different facilities. Depending on its purpose, the diameter and length of the flowline vary a lot. Considering the low temperature subsea and the potential of hydrate or wax, insulation is often required to avoid the cooling down of fluids when transported along the seabed.

- **Subsea Manifold**

Subsea manifolds are designed to merge well streams from different wells into one or more flow lines and control flow back. The purpose is to minimize the requirement of flowlines and optimize the flows in the system. A set of high-pressure valves and piping with at least two adjustable chokes are normally used, which allows the isolation and repair of single choke without interrupting the production. Subsea manifolds can be installed either as a stand-alone structure or as an integrated part of the well template.

- **Subsea Control Module**

The subsea control module receives signals and electrical power from the control center topside through an umbilical. It is installed to realize the control of subsea systems during their operation.

- **Production Riser and Umbilical**

A production riser is a flowline that stretches the subsea system to the platforms or floating facilities and realizes the transportation of well streams. Some production risers are equipped with a subsea isolation valve capable of stopping the hydrocarbon flow.

The umbilical is an arrangement of tubing, piping and electrical conductors extending through an armored casing, stretching from the host facility to the subsea equipment. It is installed to supply electric power and transmit signals to communicate with and control the subsea systems. In addition, the injection chemicals such as glycol can also be transported through the umbilical.

2.1.2 Subsea Processing System

The subsea processing system treats the produced hydrocarbons prior to reaching the receiving facility (Bai et al., 2012). It involves one or more combinations of fluid conditioning and pressure boosting of well stream fluids and water at the seabed, where conditioning includes separation of water, gas and sand, fluid cooling (or heating) and chemical injection (Davies et al., 2010).

This thesis will focus on the subsea processing system, especially the subsea separation system. The next section gives a detailed introduction.

2.2 Subsea Processing

For deep-water oil production, a major challenge is the transportation of hydrocarbons, where energy requirements increase greatly due to long tiebacks (Brandt, 2004). The purpose of subsea processing is to boost the well fluid to an adjacent topside facility or directly to onshore facilities. This is achieved by adopting multiphase pumps or by adopting a combination of subsea separation and subsea boosting. An increased oil recovery rate and accelerated production could be obtained from this process.

A set of related novel technologies such as subsea multiphase boosting, subsea separation and gas compression become the hot topic in the past decades, and several subsea processing facilities, especially subsea booster pumps, are currently in service all over the world. Figure 2.3 shows a map of the existing subsea processing systems up to February 2015. Up to Feb 2017, there are in total 20 subsea boosting systems, four subsea water injection systems, six subsea separation systems and only one subsea compression system in operation (Magazine, 2017). Besides, several subsea systems including the second phase of the Åsgard gas compressor are under development.

Figure 2.3 worldwide locations for subsea processing systems (Magazine, 2015)

2.2.1 Subsea Boosting

Subsea boosting refers to the process of pressurizing the well stream through pumps, compressors or a combination of them on the seabed (Gyllenhammar, 2012). It is developed to handle the issue in which the pressure of the reservoir is insufficient to maintain a required production rate. Since the 1980s, subsea boosting technologies have gained rapid development and are getting wider and wider use due to its potential benefits (Davies et al., 2010).

For the production of any field, a certain pressure is required to transfer the well stream from reservoir to the topside. In the beginning, the reservoir has its highest pressure, which will drop along with the production. At some point, the pressure could be below the lower limit and the field starts to produce at a lower flow rate. This could make the production become economically infeasible.

Traditionally this is done by installing a boosting module on the topside system prior to the processing facilities. It allows to produce with low reservoir pressure and thus achieve higher recovery rate. The benefits of implementing subsea boosting are even bigger. According to Gyllenhammar (2012), some of the benefits are listed below:

- More tie-ins to existing installations from saved space topside
- Increased recovery rate.
- Higher production rate.

Subsea boosters usually fall under two different categories, namely multiphase pumping and wet gas compression. The multiphase pumping has been commercially available since 1993 and is considered as a rather mature technology (Ruud et al., 2015). However, further developments are needed for longer distance and increased water depth. This calls for higher pressure boost, increased capacity, and the ability to handle fluids with higher viscosity (OG21, 2006).

2.2.2 Subsea Separation

The well stream from the reservoir is usually a multiphase fluid, consisting of oil, gas, water and solids (e.g. sand). It is thus essential to separate them in order to extract the oil and/or gas, treat/re-inject the water, dispose of the sand, etc. To achieve this, separation is typically the first step of processing. Multiple levels of separation are commonly used to step down the fluid pressure (Prescott et al., 2016). The downstream processes such as compression and boosting highly rely on the performance of separation. Therefore, separation is of vital importance for stable hydrocarbon processing and transportation.

Traditionally, separation has occurred topside on the offshore installations. However, in the later production phase of a field, the infrastructure is typically constrained by excess production of associated well fluids, which is usually presented by water cut and gas breakthrough in the reservoir (Brandt, 2004). The transportation originally used for hydrocarbons will then be partly utilized for other fluids, and a production reduction will happen due to the limited capacity of flowlines and processing facilities.

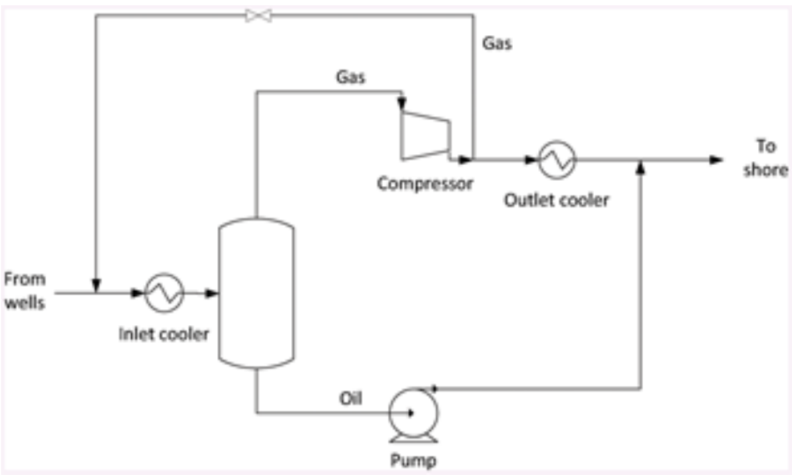


Figure 2.4 Separation and boosting (Ruud, Idrac et al. 2015)

A subsea separator is thus needed to increase and/or accelerate production. It is usually used in combination with subsea boosting to enhance production flow. By removing the water from the pipeline and reinjecting it into the reservoir, less energy will be wasted on water transportation and the reduction of reservoir pressure will be much slower. Meanwhile, the use of a three-phase subsea separator enables the use of single-phase boosting equipment such as oil pumps and gas compressors, which usually have a higher efficiency than multiphase pumps and thus results in higher system efficiency. A sketch of such a system is shown in Figure 2.4. It should also be noted that separation on warm well stream subsea is easier than on cooled well stream topside.

Furthermore, subsea separation also allows for a better flow control and mitigation of a range of flow assurance issues related to multiphase flow. The potential of slugging, hydrate formation, pressure loss and internal corrosion due to the presence of water and gas could be reduced.

Regardless of the benefits it brings, the novelty of technology and lack of experience in subsea make operators hesitate to be the first users of subsea separation systems (Brandt, 2004). Up to February 2015, 13 subsea separators have been installed and operated worldwide. Instead of using traditional gravity separators, researchers are actively exploring the opportunities to apply other principles of separation such as centrifugal force based compact equipment and other sophisticated separation methods.

- **Subsea Separators**

Subsea separators often fall under the categories of two-phase and three-phase separation (Prescott et al., 2016). The former one separates gas from liquid, while the later one separates gas, oil and water. Typically, more phases mean higher complexity and higher cost of the separator.

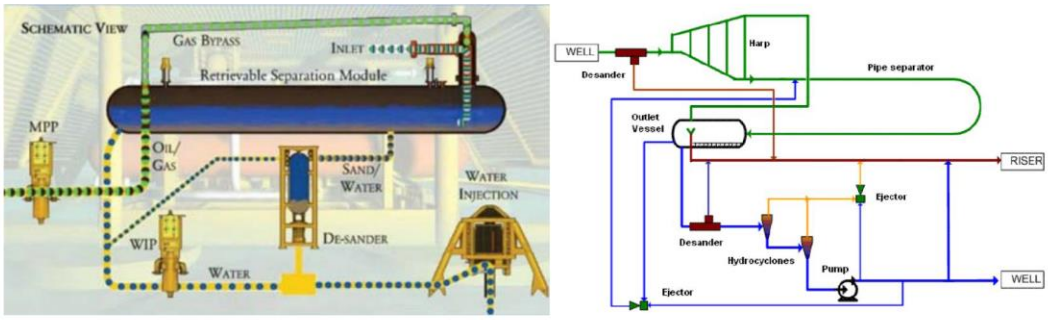


Figure 2.5 Subsea separator for Tordis SSBI (left) and for Marlim SSAO (right) (Shaiek et al., 2015)

According to Prescott et al. (2016), three main configurations, namely vertical, horizontal, and spherical, are used for subsea separators. Vertical separators have small footprints while they are difficult to install and sensitive to vortex-induced vibration (VIV). Horizontal separators are more stable due to the lower center of mass but have a larger footprint. Spherical separators are mostly conceptual now and the knowledge about this technology is limited.

Huge horizontal gravity separators have gradually become the standard application for topside separation. However, it is only suitable for shallow or moderate water depths. For deep-water applications, the required wall thickness becomes very large.

Considering the capacity of installation vessels, this restricts the inside diameter greatly and make such designs with a very low separation efficiency. Therefore, more compact designs are required for deep water separation. A set of different separation technologies are being developed and qualified recent years. Each one with their own pros and cons. A comparison of major subsea separation technologies is shown in Table 2.1 (Khoi Vu et al., 2009).

Table 2.1 Comparison of different separation technologies (Khoi Vu et al., 2009)

Concept	Pros	Cons
Gravity separation	- Simple concept, widely applied topside - Sand can be separated from the fluid stream.	- Experience from topside is not enough. - Difficult to manufacture and install subsea with large units. - High system cost. - Additional sand removal system needed
Caisson separation	- Applies common subsea technology, Suitable for deep-water application.	- Low capacity for sand handling. - High cost of drilling and preparing dummy well.
Inline separation	- Very compact, suitable for subsea application. - Easy to handle sand. Inline de-sander available for both multiphase, liquid and gas.	- Unable to handle large slugs, needs to be combined with slug catcher. However, when combined with inline equipment, slug catcher cannot be used for separation.
Pipe separation	- Smaller diameter, more suitable for deep water. - Efficient separation with favorable flow conditions, suitable for difficult fluids.	- Unable to handle sand so far. - Overall structure still bulky, only diameter reduction compared to vessel.
Cyclonic separation	- Very compact, suitable for subsea application. - Easy to handle sand. Sand will follow water stream without accumulating in separator	- Pressure drop required for high G-forces. - Challenge to meet requirements for both oil in water and water in oil at the same time.

Among these technologies, liner, pipe-based separator is considered one of most promising technology developed recently. Compared to the vessel-based separator, it requires a much smaller wall thickness at the same operating pressure (Prescott et al., 2016).

2.2.3 Subsea Compression

Compared to other systems, compression systems are relatively complex. When bringing this technology subsea, it is important to focus on overall simplicity, to ensure both low cost and reliable operation through the system lifetime (Fantoft, 2005). Per OG21 (2006), an increasing number of gas fields located far from existing infrastructures and the produced well stream needs to be transported over long distances. Subsea compression is regarded as the solution for them to achieve accelerated production and a prolonged lifetime.

For gas compression, there is a very strict restriction for liquid in the gas. Therefore, an efficient separation is required prior to the compressor. The first subsea compressor was installed in the Åsgard field in the North Sea in September 2015.

2.3 Drivers for Subsea Systems

A paper from Moreno-Trejo et al. (2012) discussed factors influencing the selection of different subsea production systems, in which the business drivers for subsea systems are discussed in three categories: regulatory driver, commercial driver and technical driver. This section adopted this classification and extended on the basis of a brief literature survey.

- **Regulatory Drivers**

The regulatory drivers represent the authorities, legislation, and standards regulating the oil and gas industry. A typical concern is the sustainable development, from the perspective of socio-economy as well as environment. Development of marginal fields and Increased Oil Recovery (IOR) are also considered important since these ask for safer and more environmental-friendly solutions.

The national petroleum authorities set rules for exploring and exploiting activities in their territory while the oil and gas industry must follow the local laws where the fields located. These are of top priority and decisions highly depend on various policies and regulatory.

International standards such as ANSI/API 17 A and ISO 13628 are often used to regulate technical activities such as the operation of subsea production systems. Additional requirements might be implemented in some national standards. In Norway, the NORSOK U-001, which is focused on the subsea production system, is based on ISO 13628 but includes additional requirements that are not covered by ISO 13628. Besides, some international companies also have their own requirements, which, in some cases, are stricter than local specification to ensure high quality and worldwide reputation.

- **Commercial Drivers**

The commercial drivers are about the feasibility of the project, taking the oil price fluctuations as well as the long-term economic profits into account. The costs of subsequent activities are greatly influenced by the selection of development concept. All major costs, including expenses of equipment and expenses of well and surface, need to be addressed.

The implementation of subsea systems avoids the topside processing equipment and thus lead to reduced CAPEX and OPEX. The removal of water on the seabed allows the use of risers with smaller diameter and possibly removal of riser for water injection. In addition, by using tie-back solutions connected to a nearby production installation or subsea system, the development of remote and marginal fields becomes economically viable and an optimized production can be achieved.

The seabed provides huge spaces to place large, heavy processing equipment, moving more equipment from topside to the seabed allows an increased capacity for tiebacks. This makes it possible for operators to exploit longer tiebacks to fields which were previously considered unattainable or unprofitable due to their size, location, low pressure and so on.

- **Technical Drivers**

The technical drivers are related to the possibility of extracting hydrocarbons using the best technical solutions and following the international standards. The suitable solution depends on characteristics of the reservoir and the surrounding environment.

A main challenge of deep-water production is the transportation of hydrocarbons from seabed to customers. Due to the decrease of reservoir pressure, the production typically declines along with time. The use of subsea processing equipment, especially subsea pumps, compensates for the pressure drop and prevents the production reduction. An increased recovery rate and extended lifetime can also be obtained by this.

What's more, the use of subsea processing also has a positive effect on flow assurance, which is a critical issue due to the potential of hydrate formations or wax deposition in the pipeline (Tienhaara, 2015). The use of subsea processing equipment reduces the need for various chemicals and hydrate inhibitors and thus could result in decreased OPEX.

2.4 Subsea Challenges

The performance of system is influenced by many factors that are directly or indirectly linked to how the system degrades, how the system can be brought back to functioning state, and how the system is able to adapt to different operation environment. Despite all the drivers and potential benefits for subsea systems, many challenges due to exposure to subsea environment, immaturity of subsea technology, and limited experience exist, which need to be addressed.

2.4.1 Subsea Environment

Compared to the onshore or offshore production systems, some new influencing factors are introduced by the subsea environment. Besides, the relative importance of existing factors may also change.

For example, subsea systems are characterized with high automation and remote control and therefore the system reliability highly depends on robustness of instrument and quality assurance during installation (M. S. Choi, 2012). A reduction of failures due to human errors could be obtained, while the consequence of instrument failure becomes much more serious and a well-designed monitoring system is needed to speed the failure identification.

- **Seabed Currents**

Subsea equipment experiences dynamic loads created by seabed currents throughout their life. The combination of bottom currents and the furrows formed in the soft clay is a major factor for the location of subsea systems (Moreno-Trejo et al., 2012). The design need to be able to withstand the worst conditions.

- **Cold Temperature, High Pressure**

Deep water is always accompanied by low temperature and high pressure. These are some of the major challenges when it comes to the design of equipment. Subsea environment is regarded as the prevalent and major agents of corrosion and asset degradation.

The higher pressure on the seabed calls for a more robust design of the vessels. Thicker walls are needed, which results in increased weight and cost. Since the overall size of the equipment is restricted by the capacity of installation vessels, it is challenging to achieve a high capacity if the same design as topside is adopted.

2.4.2 Sand Management

Sand production is regarded as a critical factor to both production and flow assurance. The sand can cause erosion, clogging of pipelines and equipment failures. It can act as the surfactant and prohibit coalescing. This will result in a high viscosity fluid and lead to the failure of pumps.

Current subsea equipment is normally designed to handle significant amount of sand production. A relatively low production efficiency is realized, however, due to the existence of sand. This can be settled by removing the sand subsea. According to Tienhaara (2015), a typical removal solution is the vessel based sand jetting system, which can be used together with sand removal cyclones to achieve an optimal performance.

This principle is adopted in Tordis separator and showed satisfactory results for subsea gravity separator. In Tordis, the sand is injected with the separated water. However, this is not suitable for all cases. For deep water cases, different separation solutions than gravity separators are required and thus new desander principles are to be developed and qualified.

2.4.3 High Intervention Cost

To perform maintenance on subsea equipment requires the use of special intervention vessels and remotely operated vehicles (ROV). Besides, due to the remote and deep location, the maintenance of subsea systems usually takes longer time. These all make it more expensive than offshore. Companies tend to have periodical intervention (for example every half year) and let the system run with failures between two interventions. This result in a decreased maintainability and system failure will cause a longer downtime.

2.4.4 Power Supply

According to Ruud et al. (2015), one of the key technology gaps for subsea fields is long-distance (over 200 km) high voltage power supply for rotating equipment. Many different factors such as the load size and step-out length will affect the need for subsea transformers and Variable Speed Drivers (VSD). With a distance over 200 km, both of them are required. Currently, proven transformers for subsea exist, while subsea VSD is still under development and remain a technical gap.

2.4.5 Flow Assurance

Flow assurance refers to the methods and technologies ensuring successful and economical flow of hydrocarbon stream from reservoir to the point of sale (Kak et al., 2017). Deep water subsea development is always characterized with low temperature, high pressure and long-distance tieback. These factors give rise to a number of technical challenges regarding flow assurance. Hydrate formation, wax deposition, slugging, corrosion and flow stability control are some of the major challenges.

According to OG21 (2006), Tienhaara (2015) and Kuhnle et al. (2015), long-distance tiebacks trigger a need for maintaining the temperature of production fluids. This is indispensable for ensuring good flowability of the fluid, especially for well streams with high viscosity. A combination of heat, insulation and chemical inhibitors is typically used in deep-water field development to prevent icy plugs of gas and water from freezing in the subsea flowlines.

The use of subsea processing system will have a positive effect on hydrate formation, slugging, corrosion and so on. For example, the problem of hydration can be prevented by improving the water separation efficiency and reducing water content in oil to the range of 1-2% (Brandt, 2004). However, removing of water in the separator also removes a portion of thermal mass, which results in more rapid cool down.

2.4.6 Maturity of Subsea Processing Technology

Due to the harsh environment and difficult maintenance for subsea systems, the design for topside systems could become insufficient. Thus, requalification of existing technologies and development of new technologies are both required.

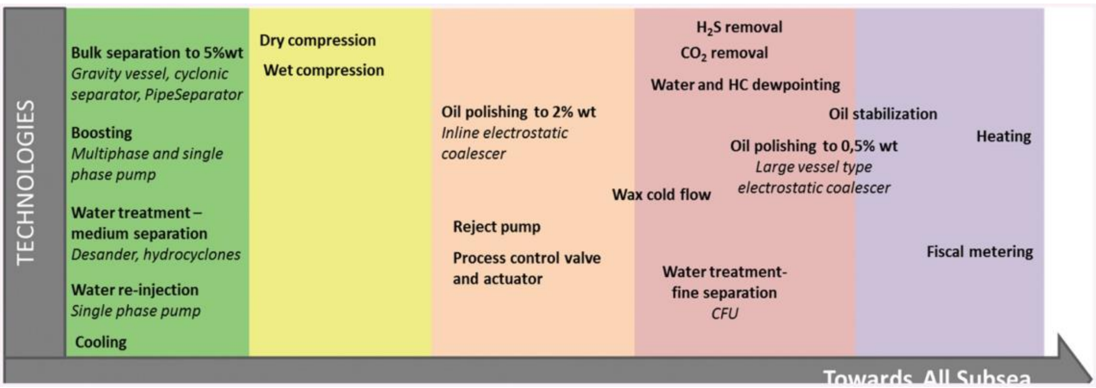


Figure 2.6 Maturity status of subsea processing technologies(Ruud et al., 2015)

Per Ruud et al. (2015), the status of some subsea processing technologies are shown in Figure 2.6. This is arranged according to their current maturity. The horizontal axis represents the gaps to subsea commercial use, from field proven technologies on the left, to no identified concept on the right.

2.4.7 Reliability Considerations

In reliability analysis, the lifetime of items is usually assumed to follow exponential distribution, which means that the items are always in an "as good as new" condition during operation. This is not the case for subsea systems. The high intervention costs and difficulty of performing it make operators prefer to carry out the maintenance during periodical intervention, usually every half year. Besides, the harsh environment subsea and other technical challenges also speed up the degradation of equipment. Therefore, many items are running in a degraded condition, instead of "as good as new". A more accurate failure model is thus needed.

However, a more complicated model does not mean better results. Limited by the number of existing subsea systems, only a small amount of data is available for subsea components. A more complicated model requires more data to obtain a good-enough estimation, while this is still not available. A set of realistic assumptions could provide a solution for this, but this will introduce more uncertainty. Therefore, exponential distribution is still the most common used assumption and will be used in this thesis.

According to OREDA-15 (2015), failures are classified into three categories: critical, degraded and incipient. Table 2.2 gives the description of each category (OREDA-15, 2015).

Table 2.2 Meaning of different failure mode category (OREDA-15, 2015)

Critical failure	Desired function is not obtained (e.g. fail to start).
Degraded failure	Specific function lost or outside accepted operational limits (spurious stop, high output).
Incipient failure	A failure indication is observed, but there is no immediate and critical impact on equipment unit function. These are typical non-critical failures related to some degradation or incipient fault condition (e.g. initial wear).

For the topside system, the incipient and degraded failures can be regarded negligible due to the opportunity to repair and only the critical failures are considered. However, for subsea systems, interventions are mainly carried out when failures that are either critical to safety or could lead to production stop or unacceptable production reduction take place. The mobilization time can be significant due to the demand of specific vessels and resources. For the degraded failures or incipient failures, operators may prefer to wait until the next intervention and thus many components are running in degraded conditions. Therefore, all three failure modes need to be considered for subsea systems.

Besides, the abruption in production is more critical subsea due to the potential of hydrate formation and clogging following the stop in flow and the medium being cooled down. For this reason, it is not desired to have untimely stops, except those required in response to abnormal events. This can sometimes be a challenge in relation to installation of safety measures. Their ability to respond is improved with increasing number of sensors, controllers, and actuating devices like valves. At the same time, more equipment leads to more failures over time and some spurious activations due to such failures may be expected.

Chapter 3.

Production Availability Analysis

The performance of the system depends on the availability of components, which is usually represented with binomial states (either up state or down state). Per IEC60050 (2001), availability is defined as the ability of an item to be in a state to perform a required function under given conditions at a given instant of time, or in average over a given time interval, assuming the required external resources are provided. For oil and gas facilities, the performance can be continuously ranging from no production to full production and thus it is assumed to be at up state when the production is above a reference level. However, this is not accurate enough since it does not distinguish whether a failure is slightly below the reference level or highly below it. This can have a big influence on the production and need to be addressed during the evaluation of system performance.

Production availability is introduced in this situation by NORSOK_Z-016 (1998) and then adopted by ISO20815 (2008). Per ISO20815 (2008), production availability is defined as the ratio of production to planned production, or any other reference level, over a specified period of time. Compared to the availability defined in IEC60050 (2001), this is volume-based instead of state-based.

Production availability analysis is an important part of the production assurance, which is defined as the activities implemented to achieve and maintain a performance that is at its optimum in terms of the overall economy (ISO20815, 2008). It is especially suitable for projects with medium to high technical risk, and during the first life-cycle phases (feasibility, conceptual design, and engineering) (Brissaud et al., 2012).

The output from production availability analysis can be used to:

- Predict performance of the system, and verify per objectives and requirements specified in the production-assurance program (ISO20815, 2008);
- Identify critical subsystems and equipment, and address the potential defects to achieve improved performance;
- Compare alternative solutions to optimize the system configuration and maintenance strategies.

3.1 Study Basis

3.1.1 System Performance Measurement

For the performance of a system, the production availability is usually calculated as an indicator. As described above, production availability is a ratio of real production to a reference level. This reference level can vary in different project phases. In the early project phase, the designed maximum rate that the system can handle is often used due to the lack of detailed production information. In later phases, more information such as contracted production rate can be available and need to be taken into account. The production volume without downtime is often used in this case.

3.1.2 Procedure for Analysis

Per Corvaro et al. (2016) and Brissaud et al. (2012), a procedure for production availability analysis is proposed, which is shown in Figure 3.1. Prior to system modeling, a set of preparations including specification of study scope, and system description is required.

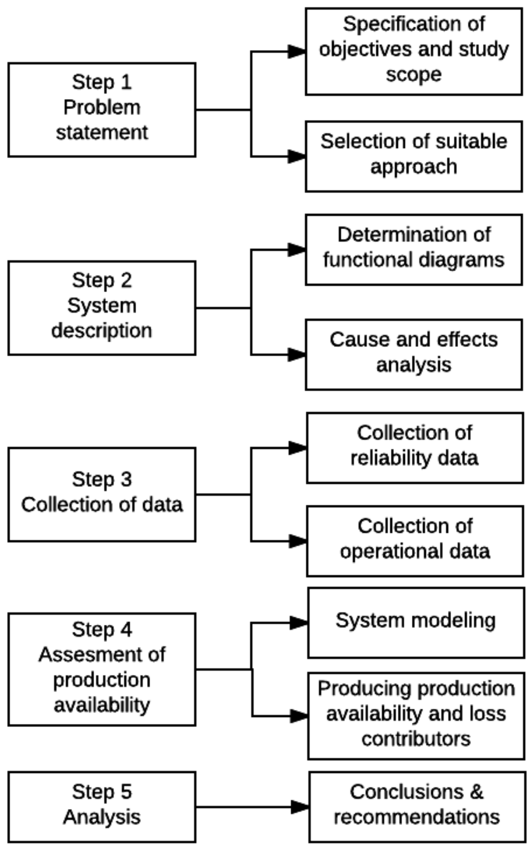


Figure 3.1 Procedure for production availability analysis

- **Scope of Study**

The scope of study defines what is included and excluded in the analysis. Some examples could be system failure, failure of production equipment, failure of safety system, preventive/corrective maintenance, and catastrophic events. All these issues need to be classified in the beginning of the project.

- **System Description**

The system description consists of system definition regarding the system boundaries and the production information including design rate, production profile and lifetime, operating condition and so on. A detailed description of equipment included should also be provided. This should be consistent with the failure mode and effect analyses (FMEA) related to the equipment.

- **Reliability/Maintenance Data**

In order to evaluate the system performance for a certain configuration, a set of reliability and maintenance data is needed as the input. Some of these data is listed in Table 3.1. The environment and operation conditions can have an influence on some of the data. For example, equipment might have a lower failure rate when running with a reduced load and in a good environment. In practice, the failure is assumed negligible when equipment is idle.

Table 3.1 Reliability/maintenance data (Brissaud et al., 2012)

Reliability data	Failure rates of individual items.
	Rates of common cause failure.
	Probabilities that spare parts fail to activate on demand.
Maintenance data	Time to repair individual items
	Number of maintenance crew
	Time periods where maintenance can be performed
	Delay due to logistic
	Number of spare parts required for maintenance
	Frequency and duration of preventive maintenance (for each item and for the whole system)

It is preferred to use the data from the same application (same environment, same operation condition, same equipment) when they are sufficient. However, this is usually not the case. There is always insufficient data if only the same application considered. Therefore, some reliability data handbooks are produced. For example, OREDA collects and analyzes reliability data from offshore oil and gas activities, and PDS data handbook provides data dossier for safety-instrumented systems, mainly used in the process and offshore oil and gas industry (M. Rausand, 2014). Some of the data sources are listed in Table 3.2 (Lundteigen, 2016).

When using these handbooks, analysts need to pay attention to the condition and system definition where these data are collected (the operation and maintenance condition, the configuration and type of the equipment, the failure modes, and so on). Therefore, corrective coefficients based on expert judgment are often required to take all the influencing factors into account.

Table 3.2 Some commonly used data sources

Standards	General	Offshore/Process industry
IEC 61709 IEC TR 62380 ISO 13849-1	MIL-HDBK-217F NPRD-2011 (RIAC) FIDES Siemens SN29500	OREDA PDS data handbook Exida

3.2 Approaches for Production Availability Analysis

Performance analyses approaches are mainly categorized into two different types: analytical approaches and simulation approaches (Kawauchi et al., 2002).

3.2.1 Analytical Approaches

The analytical approaches use some predefined formulas to evaluate the availability performance and capacity performance of a system. For example, if the mean time to failure (MTTF) and mean time to repair (MTTR) of a component is known, the availability of the component can be approximated by

$$Availability = \frac{MTTF}{MTTF + MTTR}$$

In general, the use of analytical approaches is usually more restricted and can only provide a rough prediction. However, less effort (time and cost) is required to perform the analysis and thus the analyzer can easily conduct the evaluation of a variety of alternatives, for example, various configuration of the system or the choosing of components with different failure rates, repair rates and so on.

Many analytical approaches have been developed in the past decades based on either one single conventional reliability analysis approach such as the Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Markov model, or Petri Net, or a combination of two or more approaches (Kawauchi et al., 2002).

The approaches based on reliability block diagram or fault tree are easy to use and able to provide an average availability of the system. However, each component can only have two states, functioning and fail, and the system ability is modeled as a static process. Therefore, they are not suitable for modeling the system with complex maintenance strategies.

Markov models are maybe the most popular conventional reliability analysis approaches in the development of analytical approaches. All components, maintenance strategies, and various system configurations can be modeled with Markov models. By building an intuitive diagram, it is easy to communicate with engineers or researchers from different areas. However, in order to fulfill the Markov property, lifetimes of all components are assumed to have an exponential distribution, which is not realistic in many cases. Besides, the model will expand exponentially with the increase of the size and complexity of the system. Although some simplifications of the model can be made to refine and eliminate states with low probability, the model can easily become too cumbersome and thus Markov models are suitable only for systems with limited size and complexity. A brief introduction to a Markov-based model is given in the following section.

Petri nets is a very flexible reliability analysis approach and can be used to analyze complex systems with maintenance. Since simulation is often needed to solve the equations, some consider the approaches based on Petri net as simulation approaches.

Due to its time-saving and effort-saving in the application, some companies use the analytical approaches in the feasibility studies or early conceptual design phase to have a quick overview of the whole project. For example, Aker Solutions built their own Excel spreadsheet and used this approach in many of their projects (Wang, 2012).

Despite its advantages, the limitation of the conventional reliability analysis will also become the limitation of the analytical approach for production availability analysis. For example, in the Markovian analytical approach mentioned in the next section, the constant failure rates and repair rates, and an immediate conduction of maintenance work are assumed due to the use of Markov model.

3.2.1.1 Markov for production availability

Kawauchi et al. (2002) presented an analytical approach based on Markov modeling and a rule-based approach to measure the production availability of the system. A probability distribution of throughput capacity (PDC) with the consideration of maintenance strategies can be calculated. A structure of this approach is presented in Figure 3.2.

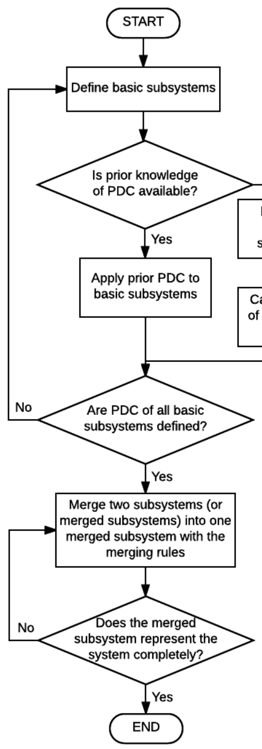


Figure 3.2 Analytical approach for production availability (Kawauchi et al., 2002)

In this approach, the production system is modeled in three levels: components, basic subsystems, and merged subsystems, which is inspired by the software package UNIRAM. In the components level, the failure and repair data is collected and applied, and possible states of each component are defined. Then, one or more components aggregated to the basic subsystems with distinct PDCs. Specific resources are assigned to each basic subsystem. The merged subsystems are generated by aggregating basic subsystems or other merged subsystems. A rule based merging approach is using here. An illustration of the structure of this approach is shown in Figure 3.3.

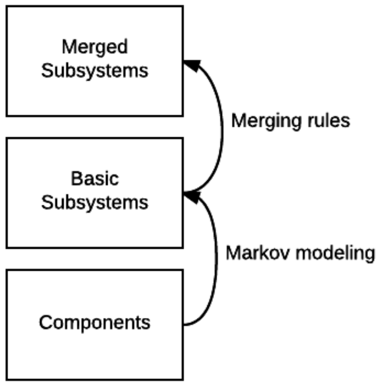


Figure 3.3 Structure of three levels and two modeling approaches (Kawauchi et al., 2002)

The throughput capacity of each basic subsystem, or merged subsystem, can be calculated by the throughput volume of the subsystem divided by a fixed throughput volume(Kawauchi et al., 2002). The expected throughput of a system in normal operating condition is recommended as this fixed volume. A probability distribution of all possible throughput capacity levels will be generated as a result. An example of discrete PDC is shown in Figure 3.4.

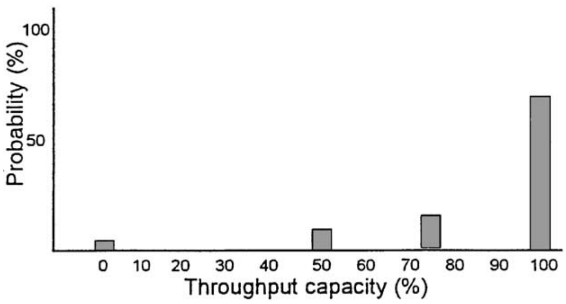


Figure 3.4 Example of a discrete PDC (Kawauchi et al., 2002)

In this approach, the innovative work is on the merging rules, which are developed to derive the PDC for a merged subsystem and avoid the using of Markov modeling for the whole system, and there is nothing special for Markov modeling in components level. Therefore, the focus of this section is on the introduction of merging rules and no detailed introduction to Markov will be presented. Two different rules for the series structure and parallel structure respectively will be introduced.

- **Merging Rule for Series Structure**

This rule is suitable to derive the PDC of a merged subsystem containing two subsystems in series. An illustration of this rule is shown in Figure 3.5.

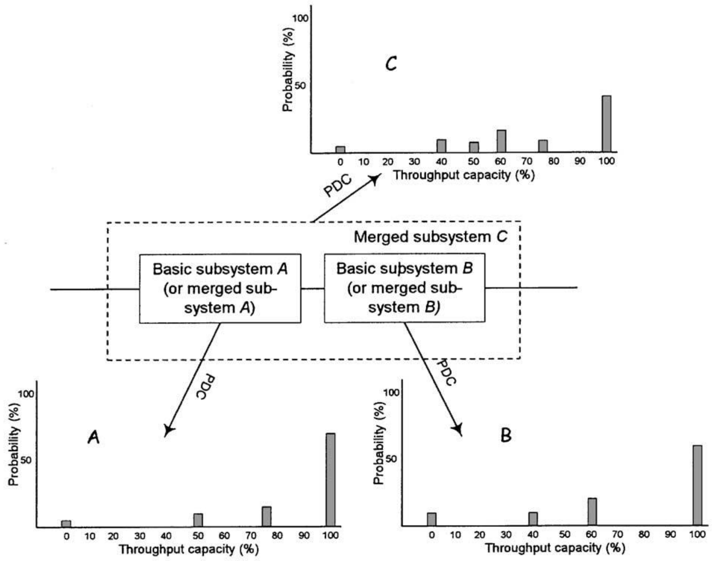


Figure 3.5 Merging rule for two subsystems in series (Kawauchi et al., 2002)

Let X and Y denote the throughput capacity of subsystem A and B, respectively. The throughput capacity of merged system Z is equal to the minimum of X and Y. According to Kawauchi et al. (2002), for systems with discrete PDC, if system A and B are independent, the probability that system C has throughput capacity z is:

$$Pr\ (Z = z) = Pr(X = z)\, Pr(Y \geq z) + Pr(Y = z)\, Pr(X > z)$$

While for systems with continuous PDC, the probability that system C has throughput capacity z becomes:

$$h(z) = f(z) \int_{z}^{y_{max}} g(y)dy + g(z) \int_{z}^{x_{max}} f(x)dx$$

for $\min(x_{min}, y_{min}) \leq z \leq \min(x_{max}, y_{max})$

where $f(x)$, $g(y)$, and $h(z)$ represent the probability density functions of X, Y, and Z, respectively.

- **Merging Rule for Parallel Structure**

This rule is suitable to derive the PDC of a merged subsystem containing two subsystems in parallel. An illustration of this rule is shown in Figure 3.6. In this case, the throughput capacity of merged system Z is equal to the sum of X and Y.

Similar to the derivation of merging rule for series structure, for systems with discrete PDC, the probability that system C has throughput capacity z is:

$$Pr\ (Z = z) = Pr(X + Y = z) = \sum_{x,y;x+y=z} (\Pr(X = x) \Pr(Y = y))$$

While for systems with continuous PDC, the probability that system C has throughput capacity z becomes:

$$h(z) = \int_{x_{min}}^{z} f(x)g(z - x)dx \qquad \text{for } x_{min} + y_{min} \leq z \leq x_{max} + y_{max}$$

where $f(x)$, $g(y)$, and $h(z)$ represent the probability density functions of X, Y, and Z, respectively.

Through this approach, the probability distribution of system throughput capacity can be derived with the consideration of maintenance.

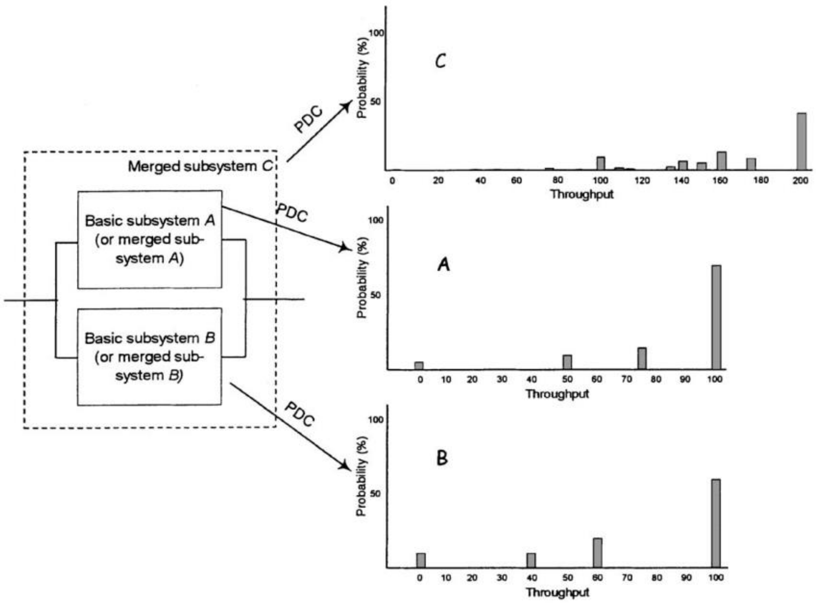


Figure 3.6 Merging rule for two subsystems in parallel (Kawauchi et al., 2002)

3.2.2 Simulation Approaches

Simulation approaches predict the production availability of a system by simulating system behavior at each time node, based on failure rates of each component and various operation rules. Two main categories are proposed: simulation with fixed time increments and simulation with variable time increments, which is so-called next event simulation.

Due to its ability to model the realistic maintenance strategies and operational scenarios, Monte-Carlo simulation is increasingly used to predict the production availabilities of complex systems. All kinds of events such as the component failure, preventive maintenance (PM), corrective maintenance (CM) and many other parameters can be generated and recorded during the simulation.

The simulation approaches are more flexible and can provide more accurate predictions for the system performance (Kawauchi et al., 2002). However, this process is rather time and cost consuming, and a solid mathematical and programming background is required, which limited its application in industry.

In practice, the evaluation of system availability by Monte-Carlo simulation is done by performing a virtual observation of a large number of identical stochastic systems, each one having a different behavior due to the stochastic character of the system behavior, and recording the instances in which a failure is found (Chang et al., 2010).

An illustration of the procedure of discrete event simulation is presented in Figure 3.7. All events that happened in the system are recorded in the event list in chronological order. The events could be component failures, maintenance activities, logistic requirements during maintenance and so on. A random number based on the defined distribution is generated as the occurrence time or duration of the events.

Monte-Carlo simulation is a very powerful tool to simulate the real case, especially for complex phenomena, where no analytical approach is available or such a solution is too difficult to establish. It is much cheaper to realize than any physical experiment and the results are easy to reproduce. However, it only provides us a good-enough solution instead of the optimal solution, and sometimes it may be too calculation resource consuming. Furthermore, a very important issue is the checking of models, which is often extremely difficult.

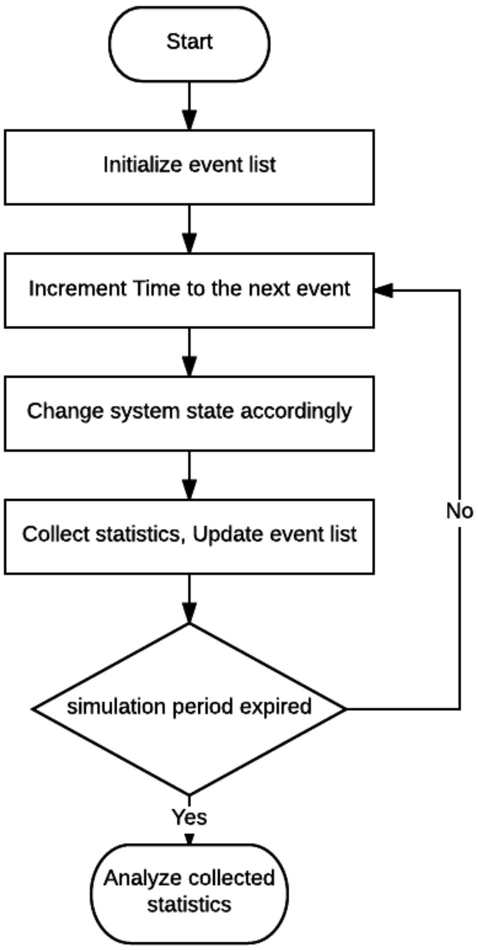


Figure 3.7 A procedure of simulation approaches (Kawauchi et al., 1999)

During the simulation, a set of random values are generated according to the predefined logic and the related calculation is carried out. This can be repeated hundreds or even thousands of times, which is called the number of runs. With only a few runs, the results can vary a lot due to the randomness of Monte-Carlo simulation. In order to overcome this problem, a certain number of runs need to be performed regarding the probability of the observed phenomenon to get a sufficiently large sample size and thus sufficiently accurate results (Rauzy, 2017). For instance, if the failure rate of the equipment is 1.0×10^{-4}, a minimum of 10^6 runs is needed to get some valuable information. The high number of runs is one of the limitations for the Monte-Carlo simulation.

3.2.2.1 Commercial Tools for Simulation Approaches

To make the simulation approaches easier to use and understand for the industry, a set of commercial simulators are built based on Monte-Carlo simulation. All these simulators have similar technical characteristics like flow algorithm. In these tools, many complicated system behaviors and strategies such as production profile, maintenance policy, and logistic delays can be modeled (Chang et al., 2010).

In this section, Maros and Taro, MIRIAM Regina and ExtendSim will be discussed.

- **Maros and Taro**

Maros stands for Maintainability, Availability, Reliability, and Operability Simulation. It was first developed by a British company named Jardine Technology Ltd in 1983. In 2008, the company was bought by Det Norske Veritas (DNV), therefore now DNV-GL is in charge of its development and maintenance.

It was originally developed to evaluate the performance of upstream oil and gas industry, which is sometimes known as the exploration and production (E&P) sector, for example, the offshore installation, subsea systems and floating facilities. However, now it is also used in other sectors such as petrochemical and process industries.

Maros applies a direct simulation algorithm structured on the sampling and scheduling of the next occurring event (Chang et al., 2010). A combination of flow network and Monte-Carlo simulation is used as the basis. Table 3.3 shows the main input and output of Maros.

Table 3.3 Main input and output of Maros (Chang et al., 2010)

Model input	Simulation output
Economics	Production analysis
– unit costs, product pricing	– availability
– CAPEX	– production efficiency
Production	– equipment criticality
– reservoir decline	– contract/production shortfalls
– plant phase-in/out	
Operations	Net product value (NPV) cash flows
– item reliability	
– redundancy	Maintenance analysis
Maintenance	– manpower expenditure
– resources, priority of repair	– mobilization frequency
– work shifts, campaign/opportune	– planned maintenance scheduling
– logistics	– spare/manpower utilization
Transportation	
– round-trip delays	
– weather factors	
– standby/service vessel	

The flow network is a simplified representation of the real system, in which the users can model the individual elements changing over time and reproduce the flow throughout of the system. The changes could be deterministic, due to maintenance and other scheduled changes, or stochastic, characterized by laws of probability theory. The flow network should be able to provide much information such as the system boundary, main components, and the buffers in the system.

Taro (Total Asset Review and Optimization) is another software developed by Jardine/DNV (UK). Compared with Maros, Taro functions in a similar way but focuses more on logistics. The whole supply network can be modeled and analyzed by Taro, with the consideration of production and demand profiles, configurations of the network and of its components.

Compared to other simulation tools, the economics data, such as unit costs, product pricing and CAPEX, can be treated in Maros. Thus, a Life Cycle Cost (LCC) can be performed at the same time of production availability analysis, which enables Maros to provide opportunities for optimizing system availability and achieving the maximum economic return in the decision making.

- **MIRIAM Regina**

MIRIAM Regina is another widely-used RAM simulation tool to evaluate the operational performance in terms of the related equipment availability, throughput capability and required maintenance strategy.

It is based on a former program named Miriam, which was developed to predict the RAM performance for offshore installations by Electronic Data Systems (EDS) Corporation and Statoil. Many new features are added to the new MIRIAM Regina to achieve an improved performance and a much more flexible application. With the new MIRIAM Regina, users are able to model the system from different industries and with different levels of complexity.

Similar to Maros, a flow network and Monte-Carlo simulation are used in MIRIAM Regina. The system structure is modeled by a flow network, as shown in Figure 3.8 (Wang, 2012). Three main compositions are included: boundary points (triangle), process stages (square) and storage units (circle). The boundary points specify where the flow enters and leaves the system, thus at least one entry and one discharge point are needed. The process stages represent the main components of the real system, which can be either a subsystem or a specific item. The storage units usually refer to the buffer in the system.

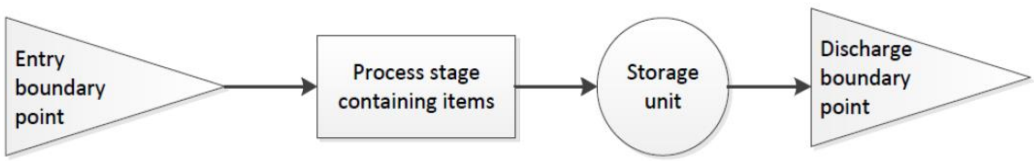


Figure 3.8 Example of MIRIAM Regina flow network (Wang, 2012)

Other information such as the maintenance strategy and production profile can also be included to achieve a more accurate result.

- **ExtendSim**

ExtendSim is a general simulation tool capable of modeling a wide range of systems such as the manufacturing, logistics, oil and gas, and production chain. It is developed by a US company named Imagine That.

A variety of specific architectural features and modeling components are included in ExtendSim to help users model systems with consideration of the reliability factors. It is a “drag and drop” graphical simulation program. The modeling process in ExtendSim is basically to drag the blocks you need to a worksheet, connect them, and input the simulation data.

The source code for each block is available and can be modified to the users, which allow them to create customized blocks based on the existing one or even from scratch. This gives the modeler more freedom and thus a wide range of simulation products are developed on ExtendSim (Krahl et al., 2014).

Another advantage of using ExtendSim is the internal database integrated into the model structure. For the reliability modeling, a large number of data will be produced. ExtendSim provides many modeling components to store and manage data, and the possibility of using the database in the realization of the simulation.

A detailed description of how ExtendSim works will be introduced in Chapter 4.

Chapter 4.

Discrete Event Simulation Software

In this thesis, ExtendSim is used for a case study. The function used is based on Discrete Event Simulation (DES) (or Next Event Simulation). Compared to simulations with fixed time increments, Discrete Event Simulation allows variable time increments until the next event and therefore could achieve a much higher simulation efficiency.

For the learning of discrete-event simulator, a “black box” approach is often taken. Modelers usually focus on the external features of the simulator, while they ignore or only take a quick look at the principle of how it works. This might hinder the modelers from thinking things through when they are faced with the demand of coming up with good solutions to model complex situation, understanding error arising during model development, and verifying whether the complex system is modeled correctly.

This chapter will describe the basic principles of Discrete Event Simulation software especially of ExtendSim and illustrate in detail with a simple example. A set of basic terms are introduced for the illustration of how it works. The terms reserved by ExtendSim are capitalized. The concept in this chapter is based on a paper from Schriber et al. (2011).

4.1 Introduction

Systems in Discrete Event Simulation software are visualized as a set of moving units flowing through the model while competing with each other for the use of scarce resources. The state of model changes at discrete simulated time points, which are called event times.

In a simulation model, several moving units might need to be treated at the same time point and thus the simultaneous movement must be addressed. This is realized by treating them serially at that time point. A problem of processing order in which the related traffic units are to be treated at given time points is then raised. In order to better understand how simulation is performed in the simulators, the principle of resolving these issues need to be clarified.

4.2 Generic Terms

In this section, the generic terms in Discrete Event Simulation software, namely entity, resource, control element, and operation are introduced. A brief example of what each term can represent using subsea separation is shown in Figure 4.1.

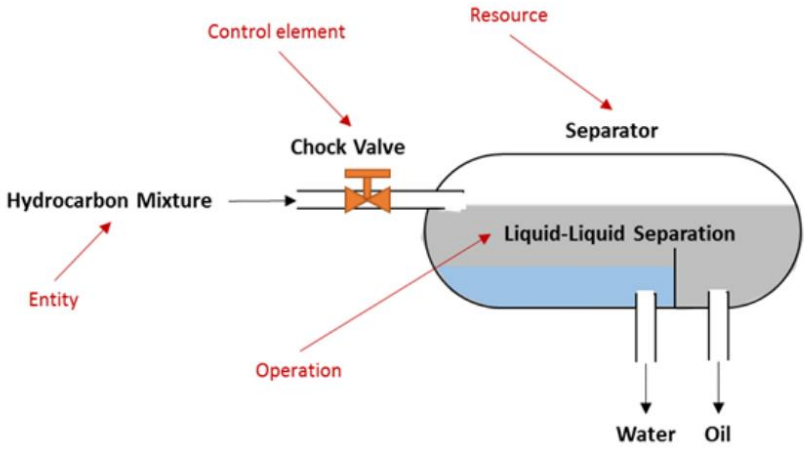


Figure 4.1 Example of different terms with subsea separation

- **Entity**

Here entity is used to denote the unit of traffic or transaction. It triggers and responds to different events. Events are occurrences which alter the state of a model. For instance, in a model of production line, the loading of materials could be simulated by entering entities into the model.

There are two different types of entities, namely internal and external entities. The internal entities are created and treated by the simulation software itself, while the modelers could define the external entities and arrange the flow of them. In some languages, internal entities are used to simulate machine failures, while the external entities are used to simulate their use.

- **Resource**

The term resource denotes the system element that provides service. Their users are entities. Resources usually have limited capacity, and therefore, entities need to compete for their use and have to wait sometimes, experiencing delays.

- **Control Element**

The term control element represents a construct that supports other types of delay or logical alternatives based on a system’s state. It can be a switch, a counter, or user/system data values. Different arithmetic and/or Boolean expressions can be used to model complex control conditions.

- **Operation**

The term operation refers to an activity performed by or executed on an entity while it flows in a system.

4.3 Model Execution

The concept of experiment, replications, and runs and their relationship is introduced in this section. Figure 4.2 gives an overview of how the simulation is carried out.

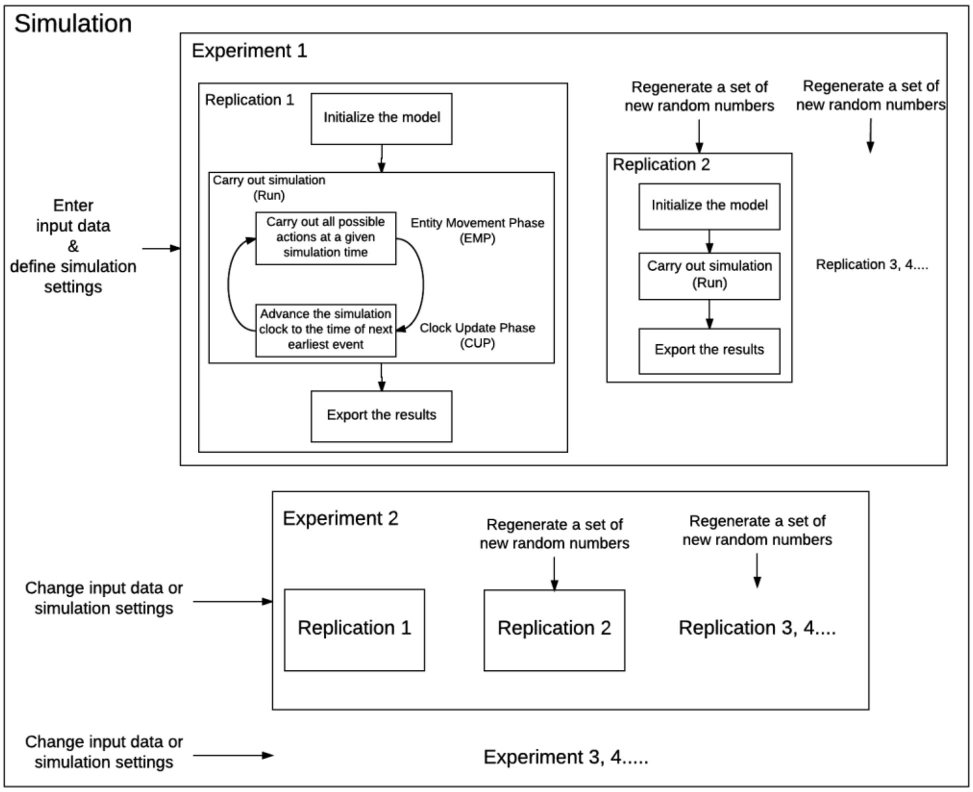


Figure 4.2 Execution of simulations

A simulation consists of one or more experiments. Different experiments are characterized by various logic and/or changing input data. The alternate part-sequencing rule is a common way to try out different alternatives, for example, different redundancy in the system, different input data, different maintenance policy and so on.

Every experiment contains one or more replications. Each replication is one single simulation based on the experiments setting and its unique set of random numbers, and therefore produces unique results that can be analyzed later together with other replications.

A replication is comprised of initializing the model, carrying out the simulation until the ending condition is met, and export the results. The phase of carrying out the simulation is called a run.

During a run, the simulated time is tracked by the simulation clock, which is an internally managed and stored value. The clock advances automatically in discrete steps according to the occurrence time of events.

Essentially, the execution of a run is made up of a two-phase loop, “carry out all possible actions at the current simulation time”, then “advance simulation clock until the next event”. These two phases are called the Entity Movement Phase (EMP) and the Clock Update Phase (CUP) respectively. They are repeated until the ending condition takes place.

4.4 Management of Entities

4.4.1 States of Entities

When moving through the model, entities migrate among five different states. Table 4.1 gives a brief description of these states. The transition between states is described in Figure 4.3.

Table 4.1 Entity states

Entity states	Description
Active State	The currently moving entity is in the Active State. At any instant, only one entity moves. It keeps moving and migrates to an alternative state when encountering a delay or other.
Ready State	In the Entity Movement Phase, two or more entities can be ready to move at the same time, while only one can enter Active State. Entities waiting to migrate to Active State are in the Ready Sate.
Time-delayed State	The entities that will enter the Ready State after a known simulation time are in the state of Time-delayed State.
Condition-delayed State	The entities that will enter the Ready State once some specific condition takes place are in the state of Condition-delayed State.
Dormant State	Entities that cannot automatically migrate to another state in model conditions are in the state of Dormant State. The migration from Dormant State to Ready State rely on modeler-supplied logic. An example of this could be the job-ticket entity. It could be put into Dormant State and migrate to Ready State when it is chosen by the operator entity as the next job.

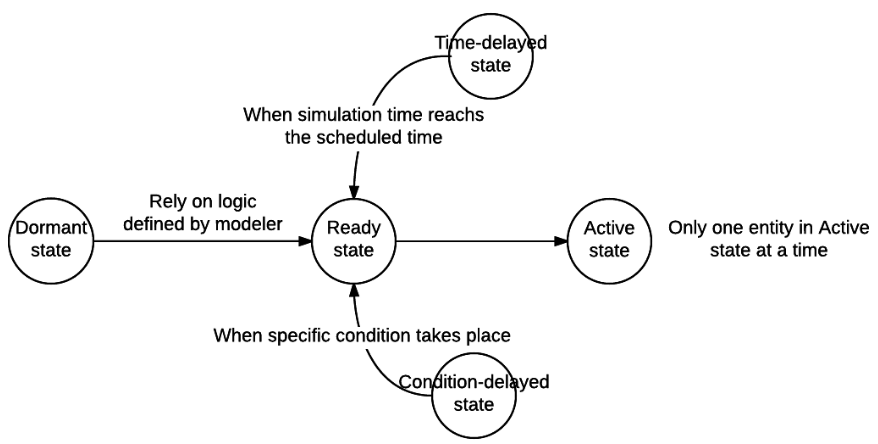


Figure 4.3 State transition

At each time, there can be only one entity at Active State and keep moving, while some are at Ready state and waiting for their turn to move. For the rest, some are waiting for their scheduled time and thus are at Time-delayed State, others are waiting for a certain condition such as the required resources and thus are at Condition-delayed State, the others are constrained by some user-defined logics and are at Dormant State. Entities at all these three states can migrate to Ready State when their delays are resolved.

4.4.2 Entity Lists

During the simulation, entities at different states are stored in different lists. A set of lists are used to organize the entities and manage their behaviors. Figure 4.4 gives a summary of the management structure for these lists.

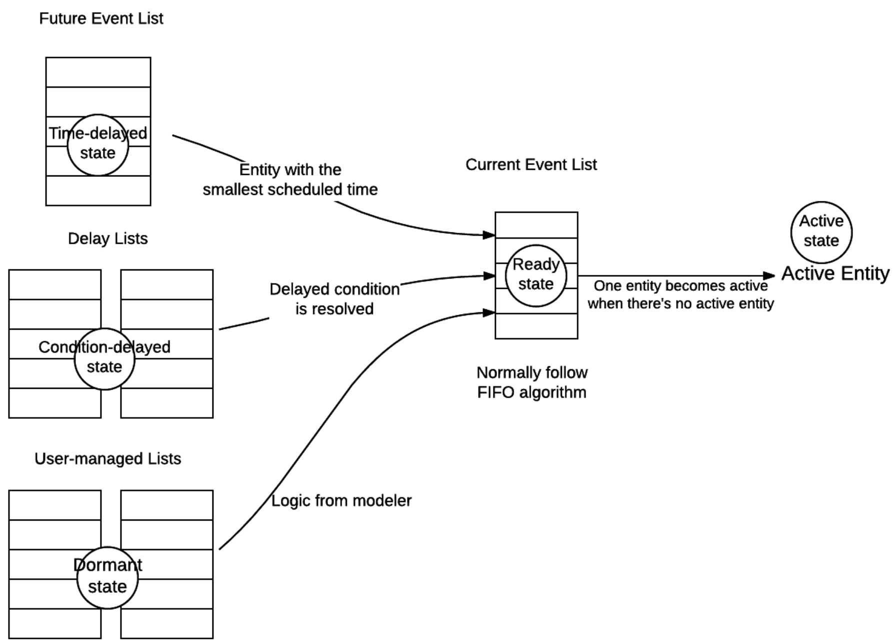


Figure 4.4 Entity management with different lists

- **The Active Entity**

The Active Entity is stored in a list. It keeps moving until encountering an operation which leads to its state migration or removal from the model. An entity in the Ready State will then enter the Active State and start moving. These are repeated until there is no more entity in Ready State. The Entity Movement Phase is then over and the Clock Update Phase starts.

- **The Current Events List (CEL)**

This is a single list of all entities in the Ready State. Entities in CEL are migrated from Future Events List, Delay Lists, and User-managed Lists, which will be discussed below. CEL normally adopts the FIFO (first in, first out) algorithm, while some software provides built-in functions to define priorities.

- **The Future Events List (FEL)**

This is a single list for entities in Time-delayed State. They are inserted when their time-based delays start and ranked ascendingly by their scheduled time to migrate to Ready State. This scheduled time is calculated by adding the duration of entity's time-based delay to its inserted time.

The CUP advances to the time of the first entity in FEL (smallest scheduled time) when EMP ends. This entity is then migrated from Time-delayed State to Ready State, and transferred to CEL. The next EMP starts.

In this process, it is assumed that no two entities have the same scheduled time. In the case of scheduled time ties, some software transfer only one entity at a CUP while the others transfer all of them to CEL during one CUP.

- **Delay Lists**

Entities in Condition-delayed State are stored in Delay Lists (which can be more than one). Related waiting or polled waiting are usually used to manage these lists.

Related waiting is the common approach for managing conditional delays. It can be used for delays easily related to model events that could resolve it. For example, if the status of a machine changes from busy to idle, the related waiting entity can be then removed from the delay list and insert into the CEL.

If it is too hard to relate the delay condition with model events, polled waiting provides another way to manage delays. With polled waiting, software checks periodically whether there is any entity could be transferred from delay lists to CEL. This can be convenient for complex delay conditions.

- **User-managed Lists**

Entities in Dormant State are stored in User-managed Lists (which can be more than one). These lists and the required logic for entity transfer among lists are both created by the modelers.

4.4.3 Representing of a Run with Entity Lists

During an Entity Movement Phase, more than one entity could be ready to move. Since only one entity can be at Active State, the rest will be stored in the Current Event List and waiting for its turn to become Active and start moving. Once the Active Entity migrates to other state or is removed from the model, one entity in the Current Event List becomes the new Active Entity.

During this process, the simulated clock remains unchanged. This is repeated until there is no entity in the Current Event List and the Entity Movement Phase is over. Then the software goes to the Future Event List to find the time for next event. The Clock Update Phase then starts to advance the time to the next event. This is repeated until the end condition for the simulation. Figure 4.5 gives an overview of this process.

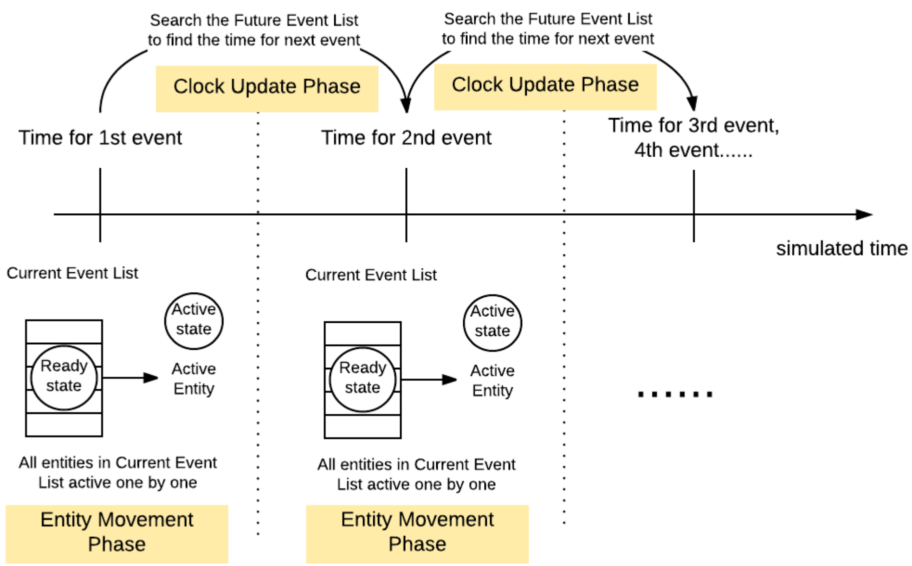


Figure 4.5 State transition of entity during a run

4.5 Principle in Extendsim

ExtendSim adopts a message-based architecture for DES. Various types of messages are used to schedule events, propel Items (Entities) through the model, enforce the logic incorporated into the model, and force computation. Blocks (Operations) are senders as well as receivers of messages, while Executive Block also acts as a master controller. ExtendSim defines a set of its own terms for the simulation elements.

Table 4.2 shows the matchup of generic terms and terms in ExtendSim.

Table 4.2 Terms in ExtendSim (Schriber et al., 2011)

Generic terms	ExtendSim terms
External Entity	Item
Internal Entity	None
Resource	Resource; Resource Pool
Control Element	Block Dialog
Operation	Block
Current Events List (CEL)	Current Events Array and Next Times Array
Future Events List (FEL)	Time Array
Delay list	List of Items resident in a Pre-Programmed Block
User-management list	List of Items resident in a User-Programmed Block
Entity Movement Phase(EMP)	Block Execution Phase (BEP)

ExtendSim schedules the execution of Blocks instead of the activity of entities. The execution of Block will trigger the sending of messages, which propels an Item through its path in the model. This makes ExtendSim have a slightly different structure compared to the general case. A summary of the management structure for different lists is given in Figure 4.6.

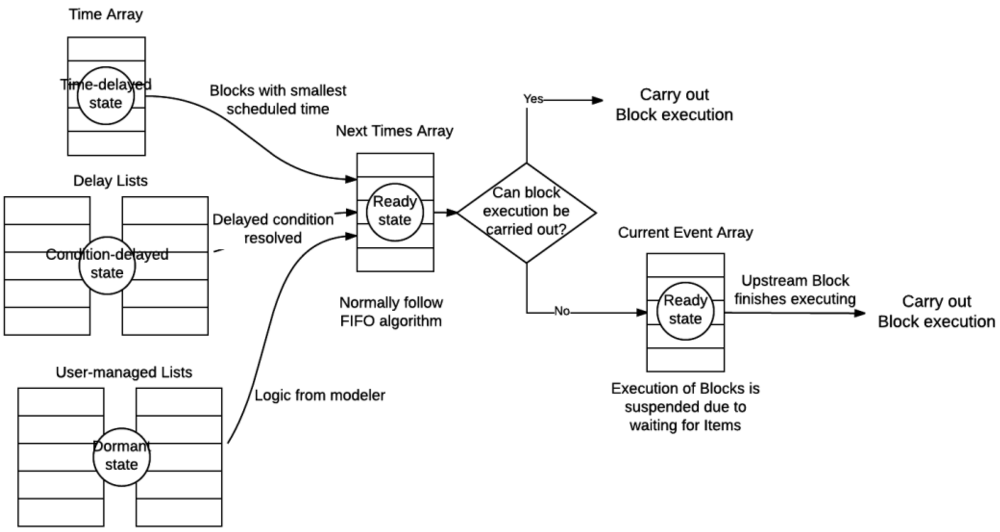


Figure 4.6 Block execution management in ExtendSim

- **Block**

Block is the basic modeling element in ExtendSim. Each block has its own icon, dialog, connectors for message passing and code that defined its behavior. Items can be held in Residence Blocks for specified simulation times to simulate the storage or treating process. A set of pre-programmed blocks are provided from ExtendSim's Block libraries. The source code for them is open and can be modified. Customized blocks can be created from scratch with development tools provided by ExtendSim. These are the user-programmed blocks.

- **Time Array**

Time Array is used in ExtendSim to schedule Block executions. For every Block, one or more elements can be included in the Time Array. Each element records a scheduled execution time for that Block.

Blocks which have not been scheduled currently are assigned with large time values in the Time Array.

Residence Blocks capable of holding several Items sort the related event times internally and keep only the earliest one in the Time Array.

Because there are a constant number of Blocks in a certain model, the size of Time Array is fixed and not so big. Therefore, ExtendSim searches the Time Array to find the next event time instead of keeping them in order. This makes the modification of Blocks' event time more straightforward, no rearrangement in the Time Array is needed.

- **Current Events Array and Next Times Array**

The scheduled execution of Blocks is managed with the Next Times Array. During Clock Update Phase (CUP), the Time Array is searched to find the next scheduled time for Block execution. The identifiers for related Block(s) are then inserted to the Next Times Array. Then Block Execution Phase starts with the execution of the first Block in the Next Times Array.

The Current Events Array is used to manage Blocks whose execution is temporarily suspended during a BEP. Suppose a Block sends a message while still in execution. The receiving Block replies but cannot start because the Item has not arrived yet. This Block will then be added to the Current Events Array. After the execution of sending Block is over, the Executive (a Block controls and schedules event in ExtendSim) sends a message to the first Block in the Current Events Array to start its execution. In the end, the Current Events Array becomes empty and Executive turns to the Next Times Array for the next Block.

When both the Next Times Array and the Current Times Array are empty, the BEP is over and the CUP starts. This process is repeated until the ending condition takes place.

- **Delay Lists**

In Residence Blocks, Items could be delayed while waiting to enter their next Blocks. These Items are stored in Delay lists. ExtendSim adopts related waiting for Delay lists and provides different algorithms such as LIFO (last in, first out), Priority, and Attribute in addition to FIFO. This is realized by combining Blocks and exploiting ExtendSim's message-based architecture. Polled waiting is available in ExtendSim, but generally is not used.

4.6 Example Illustration

In this section, the principle of Discrete Event Simulation in ExtendSim is illustrated with a simple example. This example is inspired by a paper from Eisinger (1997).

4.6.1 Example Setup

The example system consists of three components: component A, B and C. Component A and B are connected in parallel, while component C is connected in series with them. A block diagram of the system is shown in Figure 4.7.

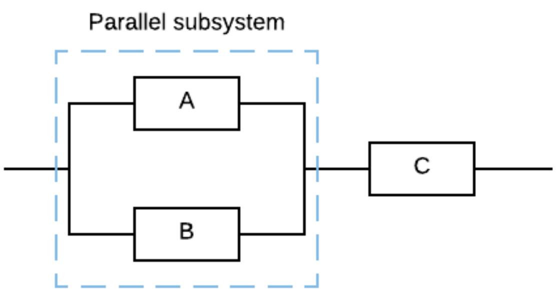


Figure 4.7 Block diagram of example system

Parallel indicates that the system is functioning as long as one of the components is functioning, which is logically equal to an "OR" gate. Series indicates that all components have to work to make the system work, which is logically equal to an "AND" gate.

Corresponding ExtendSim model is shown in Figure 4.8. Considering the terms discussed above, a resource block representing the maintenance crew is added to give a more comprehensive illustration of the principle of ExtendSim. Table 4.3 provides an example of how these terms reflected in the model.

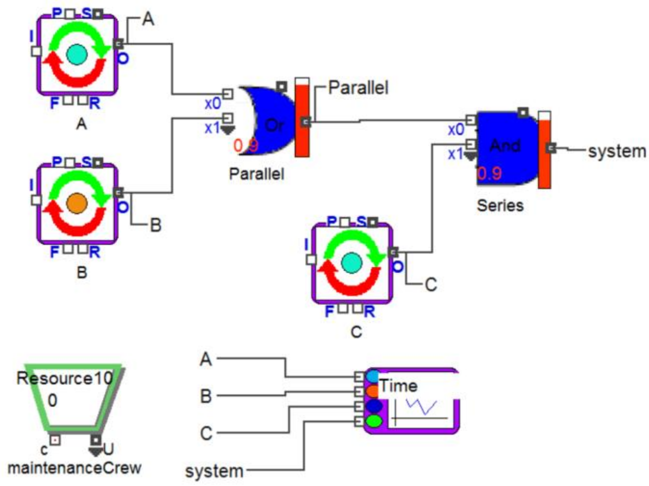


Figure 4.8 ExtendSim model of the example

Table 4.3 Different terms reflected in the example

General term	ExtendSim term	Example
Entity	Item	Failure of component
Resource	Resource Block	Maintenance crew
Control element	Block dialog	Logic gates (“OR”, “AND”)
Operation	Block	Component A, B, C

The failure of all components is assumed to follow the exponential distribution, with mean time to failure (MTTF) equal to one year. The mean time to repair (MTTR) is assumed to be constant. When a failure happens, related maintenance work is assumed to start immediately. The number of maintenance crew is set to be one, so only one maintenance work can be carried out at a time. Once two failures happen at the same time, one need to wait until the maintenance crew finishes repairing the other component. Different priorities of maintenance are assigned to the components. The parameters of all components are shown in Table 4.4.

Table 4.4 Parameters for components

	MTTF (year)	MTTR (year)	Priority for maintenance
Component A	1	0.1	2
Component B	1	0.1	3
Component C	1	0.01	1

4.6.2 Discrete Event Simulation

- **One Replication**

The event-time plot of the first 3 years from a single replication is shown in Figure 4.9. In this plot, the x-axis represents the simulated time, while the y-axis represents the availability of components and system. For each curve, the larger value represents that the component or system is functioning, and the smaller value represents that a failure happened and the component or system is down, either being maintained or waiting for the maintenance resource.

In the beginning, all components are functioning and thus the system is up. Random failures are then generated for each component based on its distribution. These are stored in the Time Array and searched during the Clock Update Phase to find the first event.

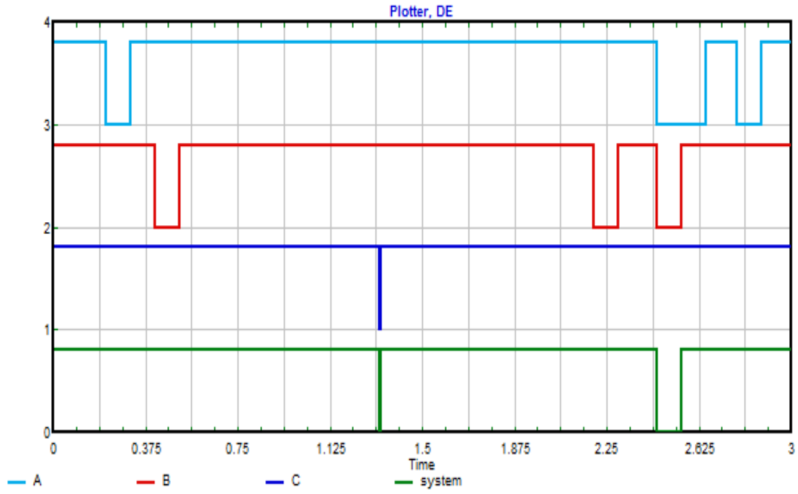


Figure 4.9 Event history plot

In this replication, the first event is at 0.21 years when component A experiences a failure. Therefore, the simulated clock is first advanced to 0.21 years and the Block Execution Phase starts, all possible actions at year 0.21 are carried out. The state change (state of component A changes from TRUE = up to FALSE = down) is then reported to the connected blocks. The change of block values will pass through predefined actions based on its connections and dialog settings. In this case, component A is connected to the system with "OR" gate, thus the state of the system will not change.

After all possible actions at 0.21 years are carried out, the Block Execution Phase is over and the Clock Update Phase starts again. ExtendSim searches the Time Array again to find the next event, which is the (constant) time to repair of 0.1 years in this case. The simulation clock is then advanced to the next event, which is 0.21 plus the duration of repair. The state of component A is then restored to TRUE = up during the Block Execution Phase.

Once again, ExtendSim searched the Time Array during the Clock Update Phase and found that the next event is the failure of component B, which lead the simulation clock advanced to 0.42 years. Similarly, it is then repaired within 0.1 years.

Next event will be the failure of component C at 1.32 year. Based on the logic defined in this case, this will lead to a state change of the system. The simulation clock is then advanced to that time and the repair is triggered. This process will be repeated until the simulation clock reaches 3 years.

Since there is only one maintenance crew in this example, components need to compete for this scarce resource when two of them failed at the same time. At 2.45 year, component B failed and the maintenance started immediately. Shortly after, at 2.46 year, a failure also happened to component A. The repair for component A cannot be carried out until that for component B is finished.

- **One Experiment**

All details of the model at any time of the simulation are recorded and shown in the plots of one replication. However, these plots are fully randomized with very high uncertainty, which is not sufficient for reliability studies. Mean values are often desired to reduce the randomness of the results. Two ways are normally used to obtain statistical estimates from the results of stochastic simulation:

1. Derive the time average of "working" state and "failed" state for a sufficient large simulation time. This is the way used by most analytical approaches.
2. Produce stochastically independent replications of the same parameters and derive the averages at every time point. This approach can produce time-dependent results, while requires longer calculation time.

By running the simulation for 10,000 years and calculating the time average of "working" state and "failed" state, the following availabilities are obtained:

$$A_{parallel} = 0.991, \qquad A_{system} = 0.972$$

$$where\ A_{parallel}\ denotes\ the\ availability\ of\ the\ parallel\ subsystem,$$

$$A_{system}\ denotes\ the\ availability\ of\ the\ whole\ system$$

The simulation time is determined based on the lowest failure rate. The lowest failure rate is that of component C, which is 0.01 per year. This means that in theory component C fails once a hundred years. The minimum simulation time should be 100 times than this, therefore, it is set to be 10,000 years.

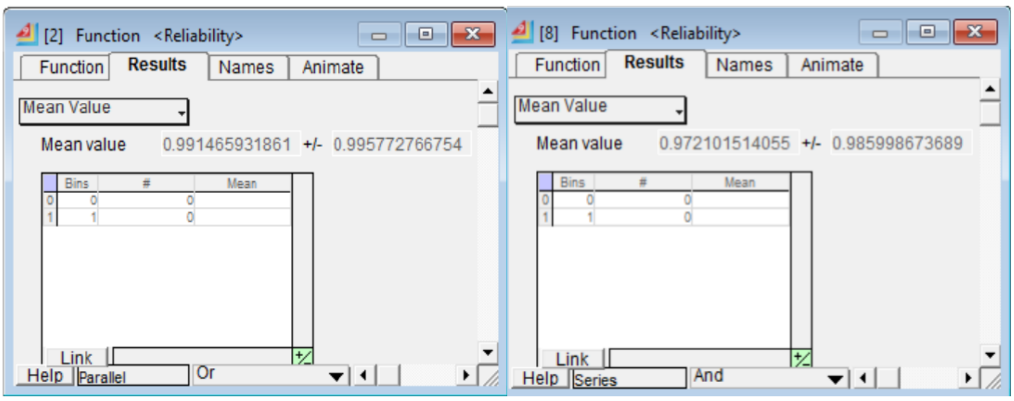


Figure 4.10 Screenshot of results tab in ExtendSim

A screen shot of the result tab in ExtendSim is shown in Figure 4.10. The confidence intervals of mean availabilities for the parallel and series structure can be read from the tab.

By producing a number of stochastically independent replications of the same parameters and deriving the averages at every time point, a time-dependent result can be obtained. Similar to the simulation time mentioned above, the minimum number of replications is also based on the failure rate of component C. The minimum number of replications that can produce valid results is around

$$\frac{10000\ (the\ total\ simulation\ time\ required)}{3\ (the\ simulation\ time\ for\ a\ single\ replication)} = 3500.$$

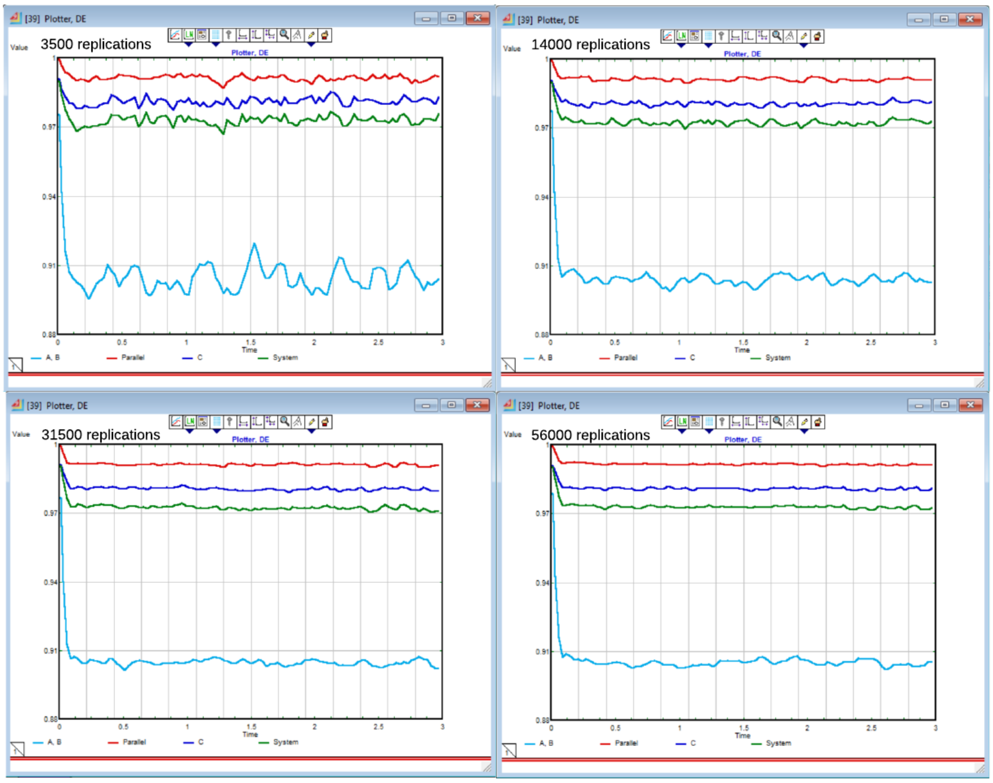


Figure 4.11 Time-dependent results

The accuracy of Monte-Carlo simulation is proportional to the square root of its number of runs (G. Rausand, 2005). If we want to improve the accuracy by two times, the number of replications should be $3500 \times 4 = 14000$. Similarly, the number of replications should be 31500 and 56000 if we want to improve the accuracy by three or four times respectively. The results of experiments with different replications are shown in Figure 4.11. It is obvious that the results are more stable and closer to a certain value with the increasing of replications. However, this also means much longer running time for the simulation. Therefore, analysts need to find a balance between the accuracy and the simulation time. In this example, the results for 31500 or 14000 replications are good enough for our purpose and thus there is no need for more simulations.

When not considering the competing for maintenance resources, the results can be easily checked by analytical approaches.

$$A_{parallel} = 1 - (1 - P_A)(1 - P_B) = 1 - (1 - 0.9091)(1 - 0.9091) = 0.992$$

$$A_{system} = A_{parallel} \cdot P_C = 0.992 \times 0.9901 = 0.982$$

In the model, this is done by assigning three maintenance teams, thus there is sufficient maintenance crew and the maintenance can be carried out right after failure. By running the simulation for 10,000 years and calculating the time average of "working" state and "failed" state, the following availabilities are obtained:

$$A_{parallel} = 0.992, \qquad A_{system} = 0.982$$

This is consistent with results from the analytical approach. Since the analytical approaches have normally been proved to be correct, comparing the results from simulation and results from analytical approaches can help modelers discover some errors in the model, which can be regarded as a simple model checking.

Chapter 5.
Case Study

Previous chapters give a whole picture of the subsea system (especially subsea processing system), production availability analysis and the simulation principle in ExtendSim. This chapter then shows a practical application of production availability analysis as a case study.

The objective of this thesis is to investigate the influence on production by implementing subsea separation, while production availability serves as the indicator for production performance. In cooperation with DNV GL, the study case comes from one of their position paper by Kuhnle et al. (2015) and ExtendSim is suggested as the tool for such an analysis. In response to the emerging subsea separation, a case with topside separation and another with subsea separation are proposed as the study case.

The whole case is still in the conceptual design phase and thus no detailed design is available. Still, DNV GL provides many inputs regarding the system configuration, general operation data and reliability data. This chapter demonstrates the procedure of production availability analysis and gives a detailed illustration of the modeling process in ExtendSim. An ExtendSim library from DNV GL is used.

5.1 System Description

The study case is a turret-moored FPSO field development concept located at a synthetic deep-water field from DNV GL. Two different production alternatives are proposed for the field development: a reference case and a subsea separation case. The objective is thus to model the two cases and compare the corresponding system performance.

The reference case is a conventional FPSO-based development concept. This is the currently preferred practice for water depth over 200 meters. Figure 5.1 shows an overview of this concept. The produced well streams are treated preliminarily on the FPSO before sent onshore. All the processing facilities are on the topside while only production wells and injection wells on the seabed.

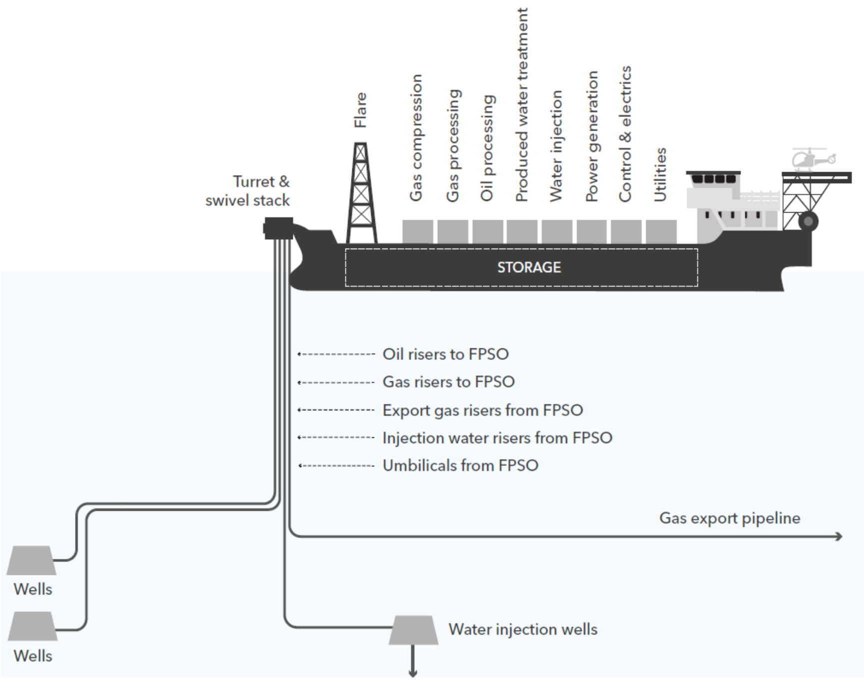


Figure 5.1 Conventional FPSO-based development concept (Kuhnle et al., 2015)

The alternative case is a subsea separation concept, where a subsea separation system is adopted and all the produced water will be separated and injected on the seabed, without transporting to the topside. The oil and gas are then sent to the FPSO through one riser to avoid extra cost. Although there is still a technology gap for the subsea separator, the idea is to demonstrate the influence of adopting subsea separation. A future subsea separator capable of removing all the water is assumed to be used. Figure 5.2 gives an overview of this concept.

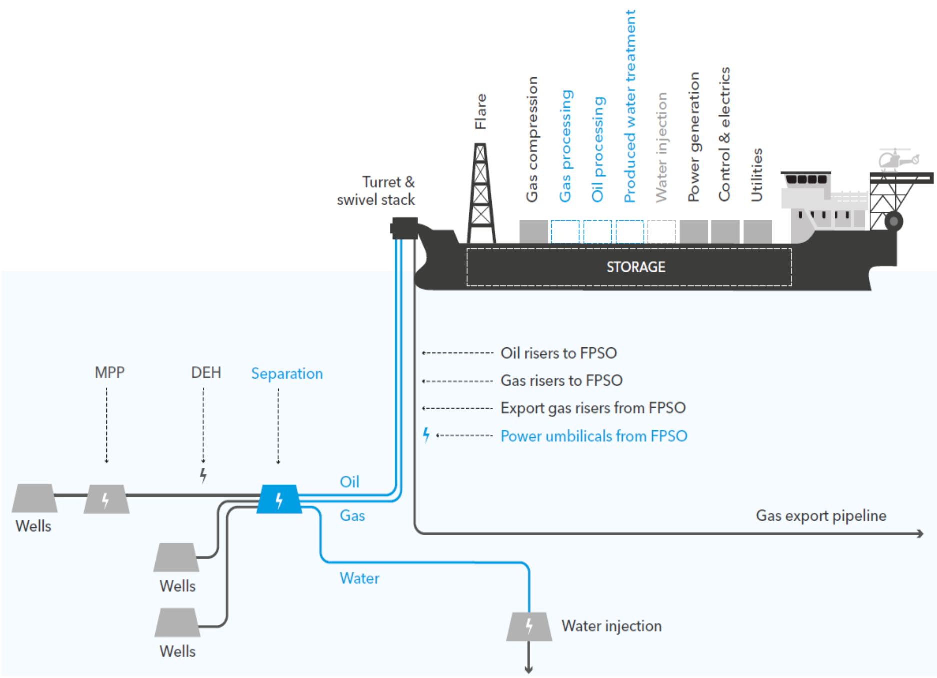


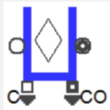
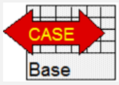
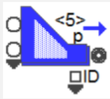
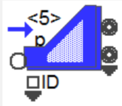
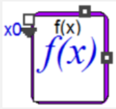
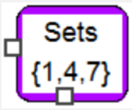
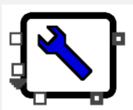
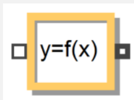
Figure 5.2 Development concept with subsea separation (Kuhnle et al., 2015)

5.2 Blocks Used in the Model

ExtendSim adopts the “drag and drop” approach. The model can be built by dragging the required blocks to the worksheet, connecting them, and entering the simulation data. Blocks are the basic modeling construct in ExtendSim. Each block has its own icon, dialog, message-passing connectors and behavior-defining code.

According to the ExtendSim Manual and “HELP” function for each block, the main blocks used in the system modeling are listed in Table 5.1 together with their icons. A brief introduction is given in this section.

Table 5.1 Blocks used in the modeling

Block	Icon	Block	Icon
Executive		Tank	
Case Study		Merge	
Component		Diverge	
Function		Valve	
Sets		Get	
Maintenance Manager		Equation	

5.2.1 Executive and Case Study

Executive Block controls and does event scheduling for discrete event and discrete rate models. This must be included and put at the top left corner in the discrete event model.

Case Study enables the link between ExtendSim and Excel. Cases with different inputs and parameter settings can be defined and managed in Excel. The results can be outputted into a separate tab in Excel.

5.2.2 Blocks for Reliability Modeling

DNV GL created an ExtendSim library named Reliability, which includes a set of customized blocks providing functions related to reliability modeling. Several blocks used for reliability modeling is introduced in this section.

Component is used to model maintainable items. In the model in this thesis, only the "State Out" connector on the right is used. A binary output of TRUE/FALSE will be sent to the Blocks connected. The initial state, up value, down value, MTTF, MTTR, their distribution and maintenance-related parameters such as MTTPM (Mean Time to Preventive Maintenance), repair quality can be defined for components.

Sets finds the sets of components or single components whose failure will cause a certain system performance. Based on the sets and their corresponding system performance, the total number of system failure, the accumulated time for system failure, the system performance when all components in a certain set failed and so on.

Maintenance Manager can define various maintenance management tasks such as preventive maintenance for the whole system. A function of group maintenance can be used to realize the modularization of subsea systems.

5.2.3 Blocks for System Flow

ExtendSim provides a set of blocks for the flow control, which can be used to simulate the production process. The flow blocks used for process modeling is described in this section.

Tank block is a type of residence block, which could hold a certain amount of flows when time advances. It is usually used as a source (no inflow connection), an intermediate storage or sink (no out flow connection). The contents of a tank could be a predefined initial quantity or received from an upstream source. In the model of production systems, all three ways are used in different part.

Merge block realizes the function of merging several flows into one single flow. Seven different rule-based options that define how the inflow will be merged are defined, of which includes proportional, priority of flow, select one flow, distributional and so on. This is used in the case study to model the merge of production flow from two wells, which simulate the process in the manifold.

Diverge block realizes an opposite function of the Merge block. It distributes the input flow into two or more outputs based on the same seven ruled-based options. This is the fundamental block for the separation process, which distributes the well flow into different phases based on their percentage.

Valve block is used to control, monitor and transfer flow. This block limits the maximum rate of flow passing through. Different functions can be connected to define and change this rate.

Get block gets the flow attributes value from one or more parts of the model. The retrieved values are shown in the dialog and reported on the value output connectors. These values can be retrieved in two different ways:

1. Several attributes from one single location
2. One attribute from several different locations

In this model, we mainly used the first way by defining four attributes for the well flow, namely production rate, oil%, water%, and gas%.

5.2.4 Blocks for Algorithm

Both the original ExtendSim library and the library from DNV GL provide the blocks that can define different algorithms. The Function block and the Equation block are introduced in this section.

Function defines a set of fixed functions such as sum, min, max, and, or and koon. In addition, a “General” option allows users to define their own function. The output is the calculated result or a given value defined by the user.

Equation block uses the set of input variables and the user defined equation to update the set of output variables. This is one of the main blocks in the realization of the separation process.

5.3 Input Data

- **Well Profile**

The production of each well is assumed constant during a year, with constant maximum flow rate, a percentage of gas, oil and water, and changes in different years. This to some extent simulates the dynamic production curve without adding too much complexity to the simulation. The data is provided by DNV GL. Table 5.2 gives an example of Well 1 in the first five years. The full well profile is shown in

Appendix B. Well profile. The maximum production rates of two wells are shown in Figure 5.3 while Figure 5.4 shows the trend of oil, water percentage over 20 years.

Table 5.2 Production profile for Well 1 in first five years

Year	Flow rate (t/year)	(Max) Rate (t/h)	% gas	% oil	% water
2016	4120000	470	0.16	98.84	1
2017	4740000	540	0.16	90.84	9
2018	3800000	600	0.14	77.86	22
2019	3800000	630	0.1	46.9	53
2020	3800000	600	0.08	24.92	75

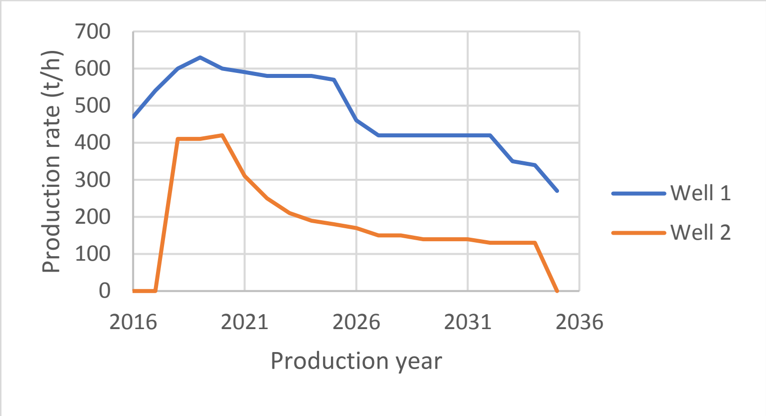


Figure 5.3 Production rate over years for two wells

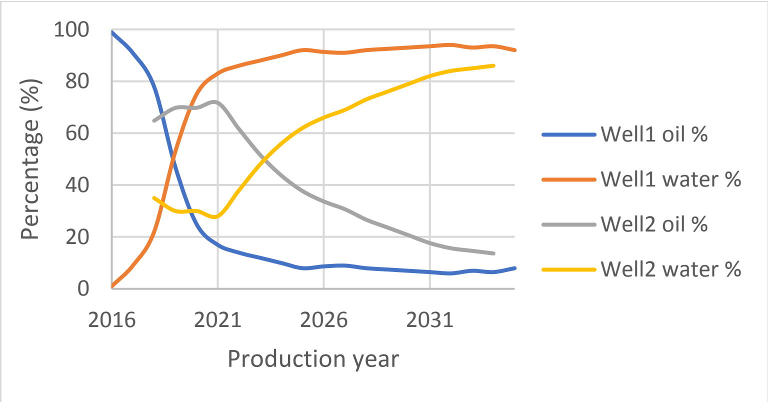


Figure 5.4 Oil water percentage over years

- **Reliability Data**

In this model, all the components are modeled as maintainable items with the Component block. Their failures are assumed to follow the exponential distribution, while the repair time is assumed to be constant. The reliability data for topside facilities are typical data, as included in the OREDA handbook.

The reliability data for subsea facilities is derived from OREDA-15 (2015). In the OREDA book, the failure modes are classified into three categories: critical, degraded and incipient. As discussed in section 2.4.7, for subsea facilities, failures in all three categories need to be considered due to the lack of maintenance. However, the models in this thesis simulate the system performance as functioning or failed. Degradation of components is not modeled. Therefore, only the critical failures are considered for the subsea components.

The data for subsea facilities is rather few. Some failure rate for subsea facilities are adjusted from topside facilities, a correction factor based on expert judgment is used. The reliability data used in this thesis is attached in

Appendix C. Data dossier.

5.4 Model of Reference Case

5.4.1 System Overview

In the model for reference case, the production system consists of two wells with different production profiles. The well fluids are first merged in a manifold and then separated into three phases (gas phase, oil phase and water phase) through the topside separation system. The system model is shown in Figure 5.5. The focus of this model is to reveal the influence of component failure on system performance. Therefore, the process is simplified greatly and only the basic functions are modeled.

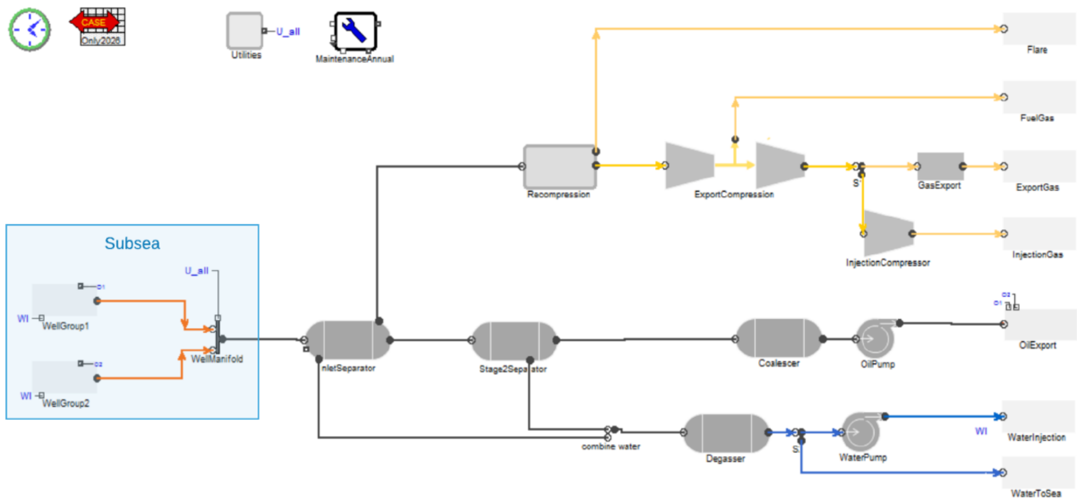


Figure 5.5 System model for reference case

In the manifold, an algorithm is required for the merge of flows from two wells, especially when the flow exceeds the capacity of downstream facilities. In this model, when the total flow is within the capacity of the separation system, all flows from Well1 and Well2 are merged in the manifold and passed to the inlet separator. When the total flow exceeds the capacity of the separation system, the manifold takes only an amount of flow equal to the maximum capacity of the separator, with one-third from Well1 and two-thirds from Well2.

In practice, the separation system usually consists of several stages to fulfill the requirements. The model consists a two-stage separation to demonstrate the modeling process so that the model would not be too complicated. The first-stage separation adopts a three-phase separator and it is assumed that all the gas and part of the water are removed during this process. A mixture of oil and water then flows into the second-stage separation, which adopts a liquid-liquid separator. This process removes the rest water and export only the oil.

The succeeding processing for gas, oil and water is then carried out separately. In the end of each flow, the total production of gas, oil and water are calculated and exported to the connected excel file.

Different maintenance strategies such as preventive maintenance (PM) and group maintenance can be defined in the 'Maintenance Annual' block.

All these blocks shown in the system model are so-called hierarchical blocks, which contain a set of blocks that represent different equipment. The simplified corresponding processes are modeled by these blocks to simulate the whole production process. To transform various information through the model and realize the function of separation, four different variables (which is also called layers), namely (maximum) production rate, gas percentage, oil percentage, and water percentage, are defined. The model of well group and three-phase separator is shown as an example in this section.

5.4.2 Model of Well Group

In practice, production wells extract well streams from the reservoir with different production rate. A number of facilities are used to realize this function. Each of them can experience failures and get repairs, which lead to a certain amount of production loss. Figure 5.6 shows the model of WellGroup2. In this model, the well group is modeled as a finite source of items. The quantity of content changes over years to simulate the change of maximum production per year.

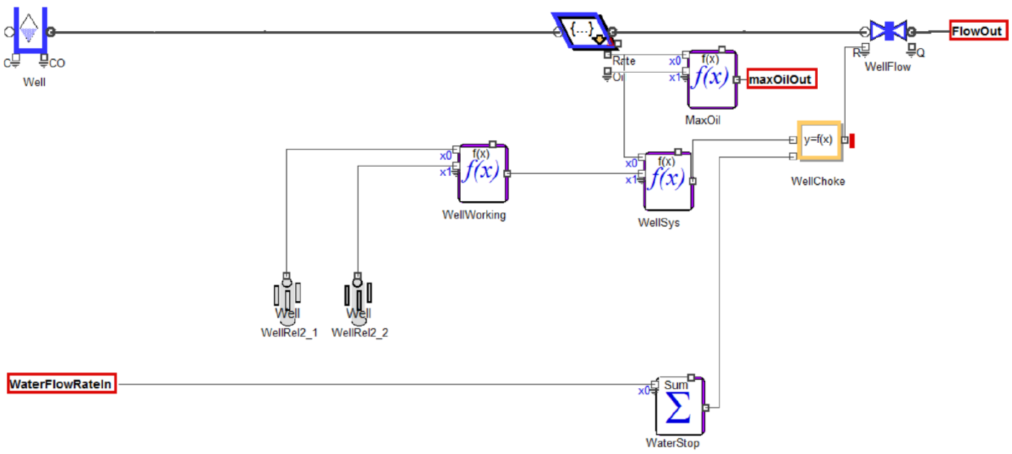


Figure 5.6 Model of well group

The well production is modeled with a Tank block. Figure 5.7 shows the dialog of Well block in WellGroup2. In the study case, it is assumed that WellGroup2 starts to produce since 2018, so there is no production from it for the first two years. Since it is not allowed to set the quantity of content as zero, it is set to be a very small value. There are in total 20 years of production simulated and correspondingly 20 rows in the tank. Each row represents the production profile of a year. Once the quantity becomes empty, the well profile goes to the next row, which represents that the production goes to the next year.

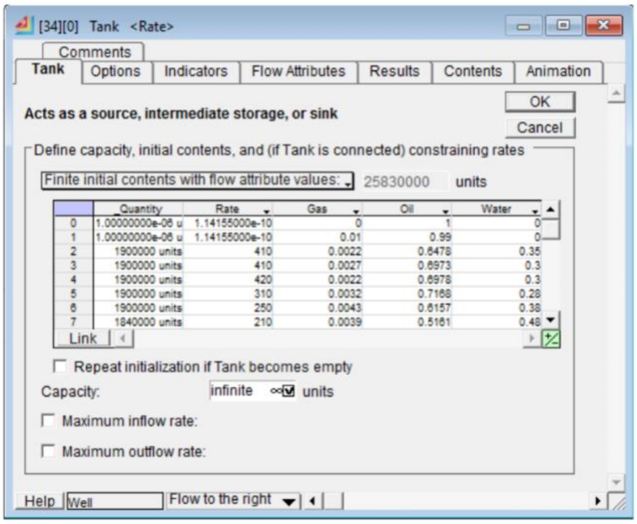


Figure 5.7 Dialog of the Well block

The wells are modeled as a maintainable component. Figure 5.8 shows the dialog of well reliability block. Failures with different distributions or based on external inputs can be generated. In view of the accessible data, lifetime of the item is assumed to follow exponential distribution and the repair is assumed to be carried out immediately after the failure and with constant duration. Different values will be exported based on the condition of the well. The output value is one when it works and zero when it fails.

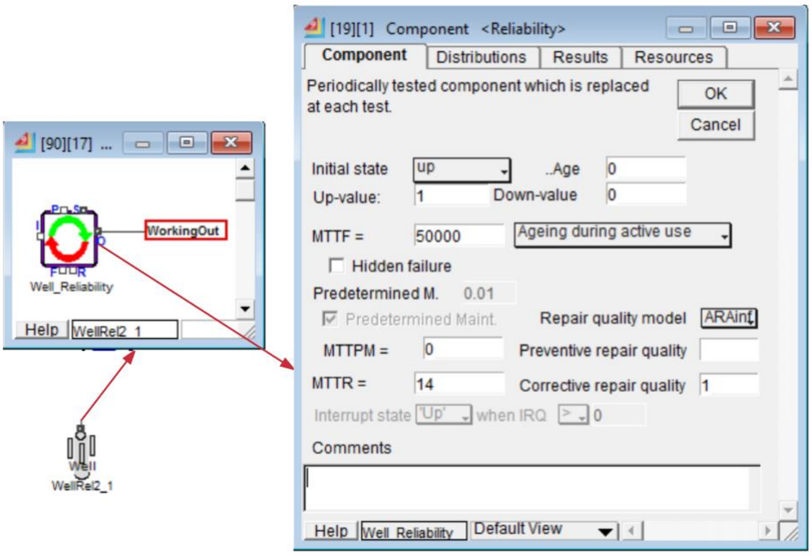


Figure 5.8 Model of well reliability

The Function block named WellWorking quantifies the system condition to evaluate the influence of well failure on production. It exports a value of one when both wells are functioning, 0.5 when only one well is functioning and zero when both of them fail. The Get block reads the values of the production rate layer and oil percentage layer and passes them to the corresponding Function block. The production rate is passed to the WellSys block and multiplied with the system condition. This value is then passed to the Valve block as the maximum value of current production rate.

By doing this, the failure of components is linked to the performance of the well. The well produces with full capacity when there is no failure, while it can only produce with half capacity with one failure and zero capacity with two failures.

5.4.3 Model of Three-Phase Separation

In this model, the separator is assumed a gravity separator, which is basically a big vessel with a set of valves. Figure 5.9 shows the overview of a three-phase separator. The upper part models the separation process while the lower part models the state of system based on component states.

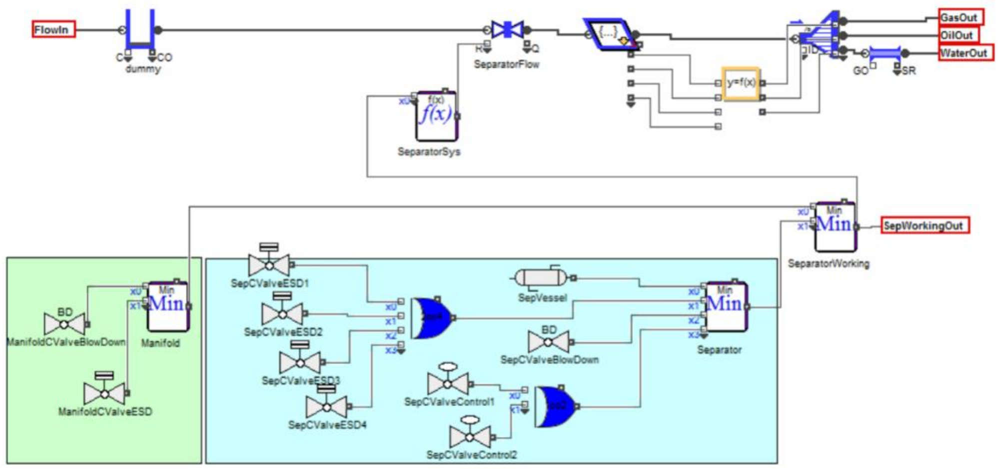


Figure 5.9 Model of three-phase separator

The separation process is mainly realized by the Get block, the Equation block and the Diverge block. The Valve block works as constraint of the maximum flow rate. The Get block reads values from the gas, oil and water percentage layer and passes them to the Equation block. The Equation block then alters the percentages of each phase based on the required function of the separator (how much gas and water need to be removed). The code for the inlet separator is shown as an example in Figure 5.10. Based on this code, all the gas and 70% of the water will be removed in this separator. These values are passed to the Diverge block as proportions for each phase. The Diverge block then realizes the function of separation and separates the well stream into three phases.

For the modeling of system state, a set of blocks representing valves and separator vessel simulate the working and failure of different equipment. Each of them is modeled as a maintainable component, where the MTTF, repair time and different repair strategies can be defined. The lifetime of each component is assumed to follow exponential distribution while the repair time is assumed with constant value.

A 2oo4 voting strategy is adopted for the ESD valves and a 1oo2 voting strategy is adopted for control valves. This enables the system to continue production with a certain amount of failures. A Function block with a logic of minimum value is used. Therefore, the separator is functioning when all the connectors receive the up-value (one in this case).

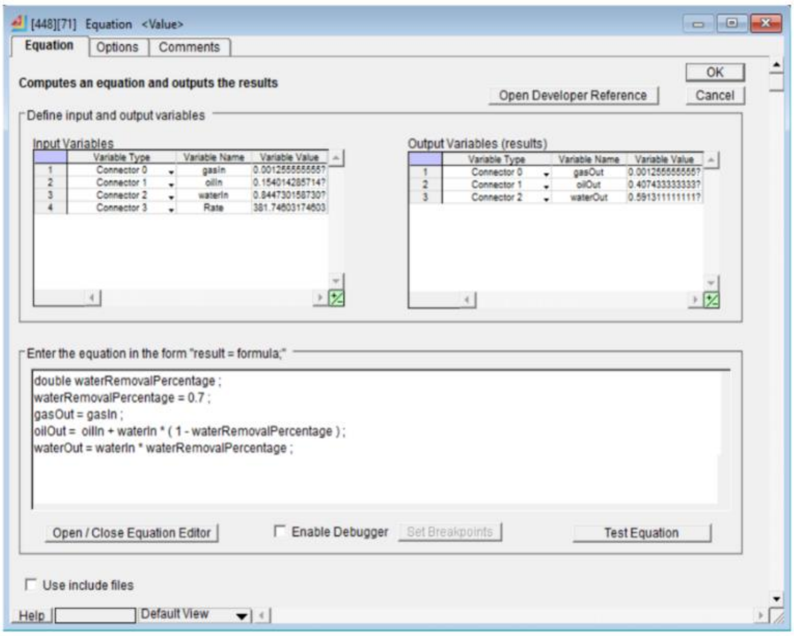


Figure 5.10 Dialog and code for inlet separation

5.5 Model of Subsea Case

5.5.1 System Overview

In the subsea case, the system is assumed with a similar configuration as the reference case. A major difference is that a subsea separator is used to remove the water on the seabed. Only the oil and gas are transported topside in the same pipeline. The water treatment facilities are therefore also moved to the seabed. Compared to the model of reference case, the separation system has a slightly different configuration, with a gas-liquid separator as the second-stage separator. An overview of the subsea model is shown in Figure 5.11.

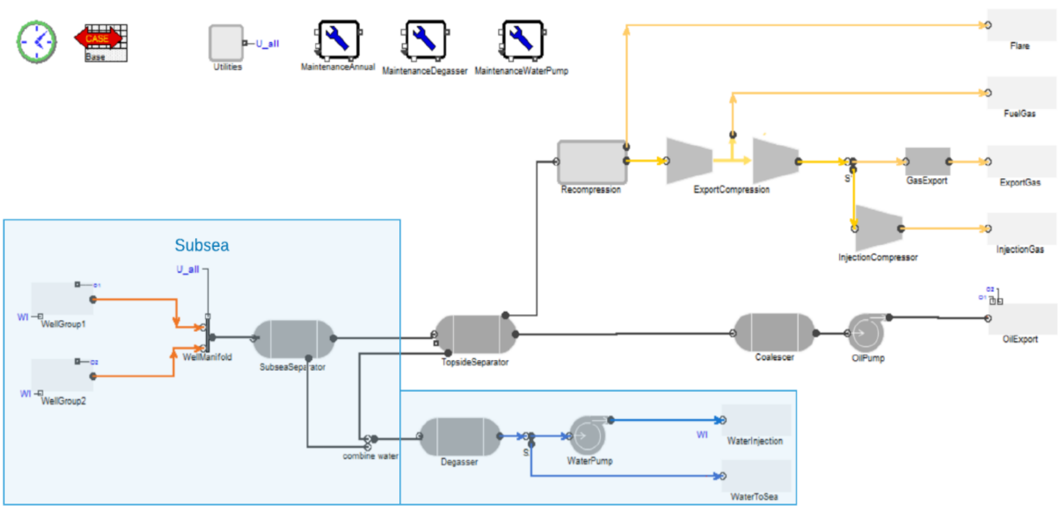


Figure 5.11 System overview of subsea model

In this model, the second-stage separator is still modeled as a three-phase separator while the outlet water percentage is set to zero. This is done to make the model easy to maintain since for many cases, the subsea separator cannot remove all the water and thus on the topside a three-phase separator is required. The code for the topside separator is shown in Figure 5.12.

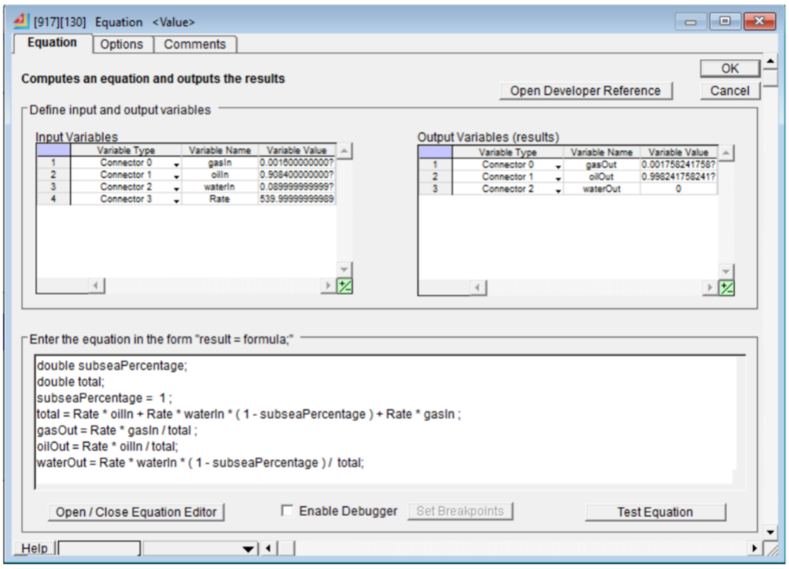


Figure 5.12 Code for topside separator

5.5.2 Failure and Repair of Subsea Equipment

In addition to minor changes in the configuration of the separation system, the main difference between the model for subsea case and the model for the reference case is on the failure rate and the maintenance strategy. The repair time for subsea facilities will be much longer because special vessels could be required for the task, and the replacements are also much slower compared to the topside case. Minor subsea maintenance carried out by remotely operated underwater vehicle (ROV) can take one to three month depending on the weather condition, while the repair of major equipment can normally take half a year.

For the subsea application, there is a trend to have modular design in order to reduce design and manufacturing time, and this allows shorter delivery and installation time (Gundersen et al., 2014). Together with the difficulty of performing maintenance subsea, modularization, which is called group maintenance in this thesis, is becoming a common practice. In view of the efforts required to retrieve the equipment, operators tend to adopt a certain number of redundancies and renew the whole module instead of only failed component in case of maintenance. This might lead to reduced yearly production because the system is sometimes running in a degraded condition, but could be preferable considering the high cost of maintenance.

In the subsea model, the subsea separator, degasser and subsea water pump are considered as three modules. Maintenance within a given module is always performed on the whole module, renewing all components of the group. The subsea separator is showed as an example, where the maintenance is carried out when a system failure takes place or a certain amount of failures occurs to the emergency shutdown (ESD) valves. This can be realized by a function of group maintenance in the Maintenance-Management block. As this case is still at concept phase, there is no system details and real data. The main purpose is to show the modeling process of this issue.

- **Realization of Group Maintenance for Subsea Separator**

The subsea separator is assumed with the same configuration as topside separator, while with longer time to failure and repair time. In the model of separator, the ESD valves are assumed to have a 2oo4 voting mechanism and thus the separator is regarded as failed after three ESD valve failures. For topside model, the maintenance will be performed right after the failure, which is not practical for subsea systems.

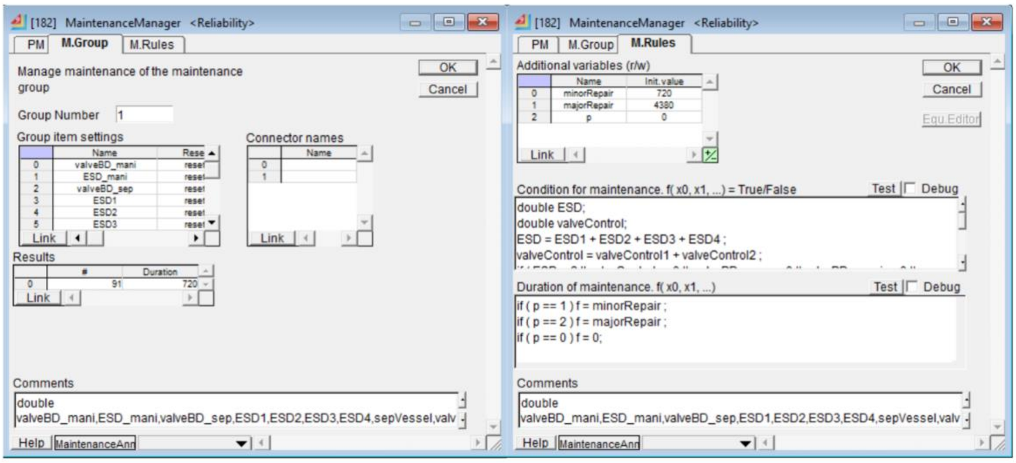


Figure 5.13 Group maintenance

In this model, all equipment belonging to subsea separator is registered to group 1 with distinct names. The conditions where maintenance should be performed and the duration of different maintenance tasks are defined in the Maintenance-Management block. Figure 5.13 shows the dialog of maintenance condition and duration of maintenance group 1.

By defining this, for the equipment in this group, the maintenance will only be performed when the maintenance condition is fulfilled with a predefined maintenance duration. This process will renew all the failed equipment in the group and the whole group will be as good as new. Similar strategies are adopted for the subsea degasser and subsea water injection.

5.6 Model Verification

After modeling for both cases, some verifications are carried out to check their connectivity and examine the model output for different settings. The objective is to make sure the models behave as expected in response to changed input. The following steps are carried out as the model verification.

1. The first step is to verify the simplest case. The predicted performance with stable production and no component failure is first checked. This is done by

assigning long MTTFs to all components ($1 \times 10^{300} hours$ in this model) and therefore their failures can be regarded negligible. Figure 5.14 shows some results from simulation.

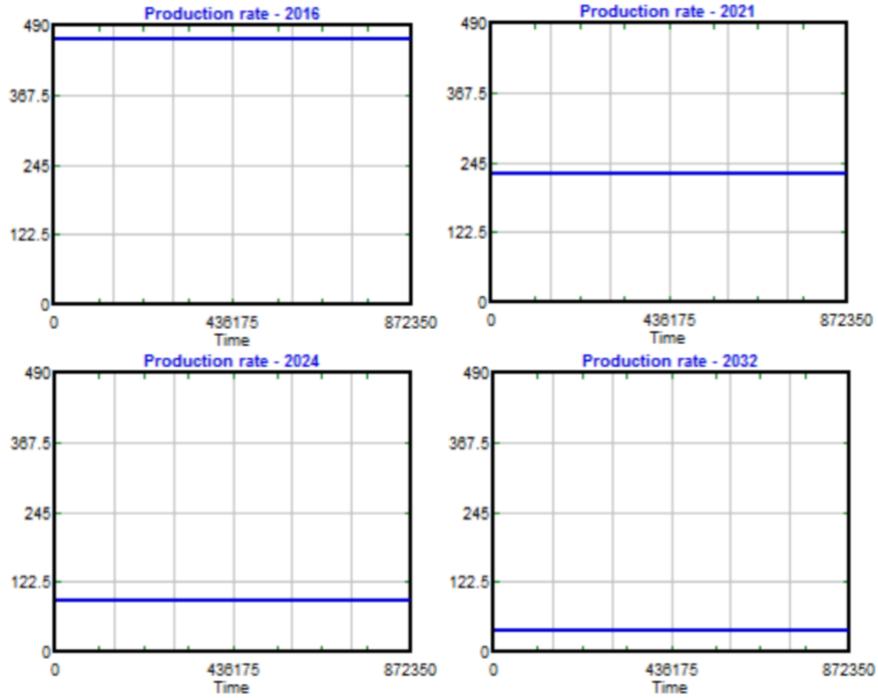


Figure 5.14 System performance with stable production rate and no failure

2. After the stable cases with no failure have been verified, the case with changed production profile and no failure is checked. Based on the production profile for two wells and the parameter settings in the model, a theoretical yearly production could be calculated by hand. From Figure 5.15, the results from the model show consistency with the theoretical results.

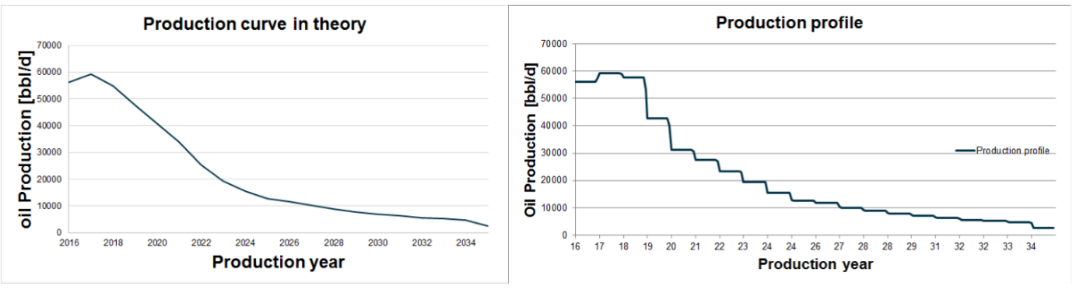


Figure 5.15 Theoretical production profile (left) and production profile by model (right)

3. After the cases with no failure have been verified, the component failures are introduced to the model, which is the main purpose of this modeling. The verification still starts with stable cases where production does not change. Figure 5.16 shows the results of the simulation. Due to the existence of components failure, the production curve is not stable as the case without failure. Random failures occur based on the assigned failure rate and thus the production curves show fluctuations from the average of several runs.

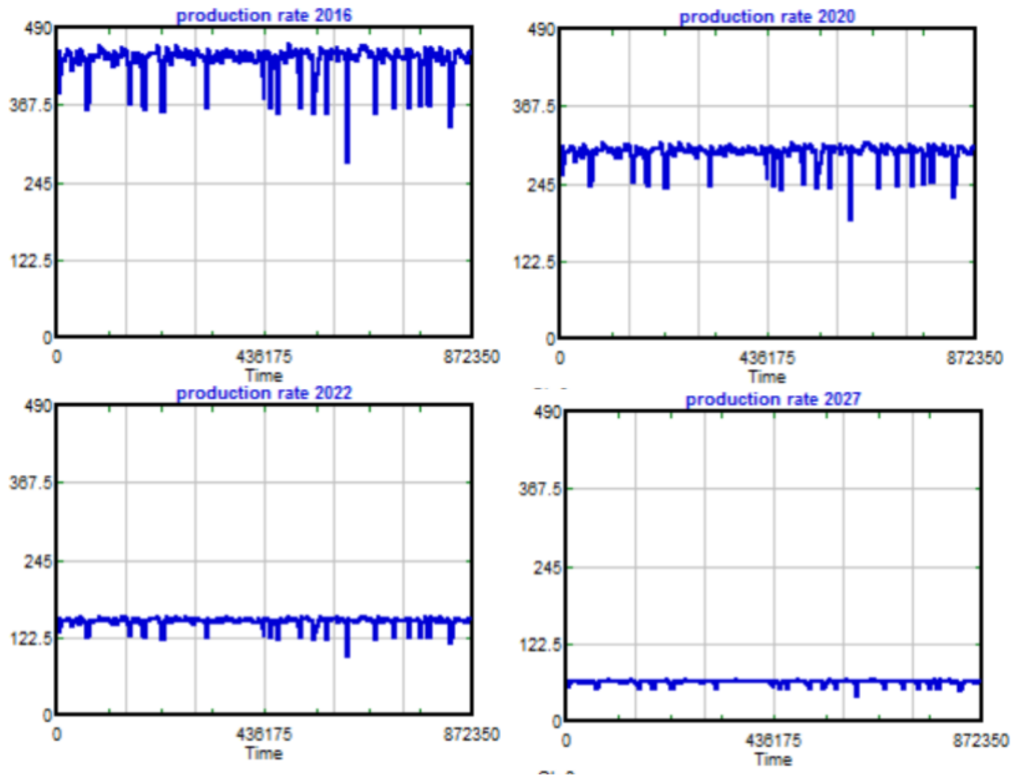


Figure 5.16 System performance with stable production rate and component failure

4. The case with changed production and component failures is verified as the last step. Figure 5.17 shows the results with normal repair time (left) and with a considerable repair time (right). The one with considerable repair time is run to show the influence more clearly. In this example, the repair time of hydraulic power unit (HPU) is set to be three years. As seen in Figure 5.17, a production stop occurs at the 6th year. Three years later, the repair is done and the system starts to produce again.

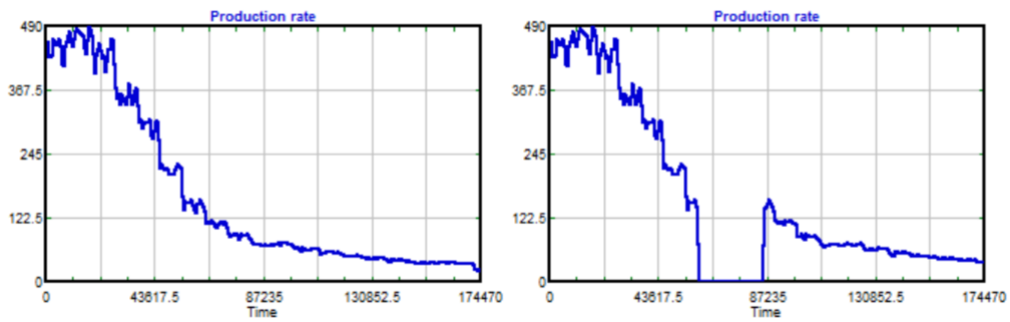


Figure 5.17 Results when changed production and component failures

As all the four steps show reasonable and consistency results, it is considered that the models are verified and the implementation of the model is correct.

Chapter 6.

Results and Discussion

After the model construction and its verification are done, the simulation can be performed to generate the results. The simulation time is set to be 20 years and a total of 100 replications are carried out. The yearly production and loss contributors for both topside and subsea systems are produced.

6.1 Simulation Results

- **System Availability and Predicted Production Profile**

Based on the well profile and the reliability data mentioned in section 5.3, the production profile for two systems are predicted, which is shown in Figure 6.1.

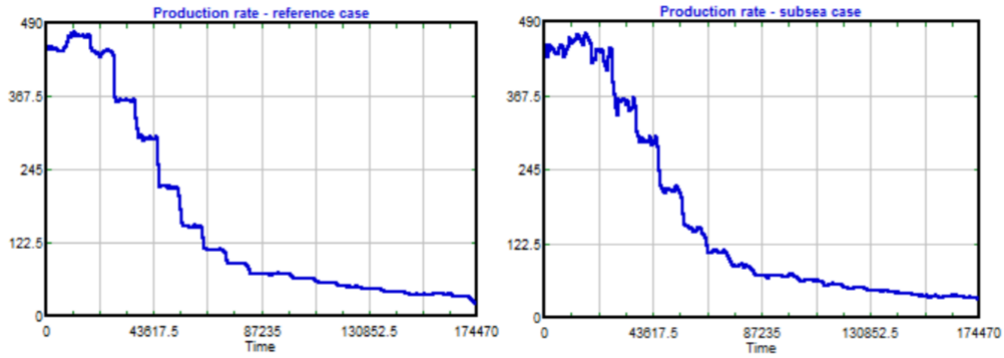


Figure 6.1 Predicted production profile for reference case (left) and subsea case (right)

It is obvious that due to the longer maintenance time, the failures of components have larger influence for the subsea system, which shows in the production profile as a more unstable curve. For the topside system, the repair time is rather short and thus the influence of component failure is smaller.

According to the predicted production and the production without system failure, system production availability can be calculated. The simulation shows that the production availability for reference case is 97.3% while that for the subsea case is 96.8%.

- **Loss Contributors**

The contributors to production loss by equipment type are shown in Figure 6.2. The percentage is derived as a ratio of production loss due to a certain equipment to the total production loss.

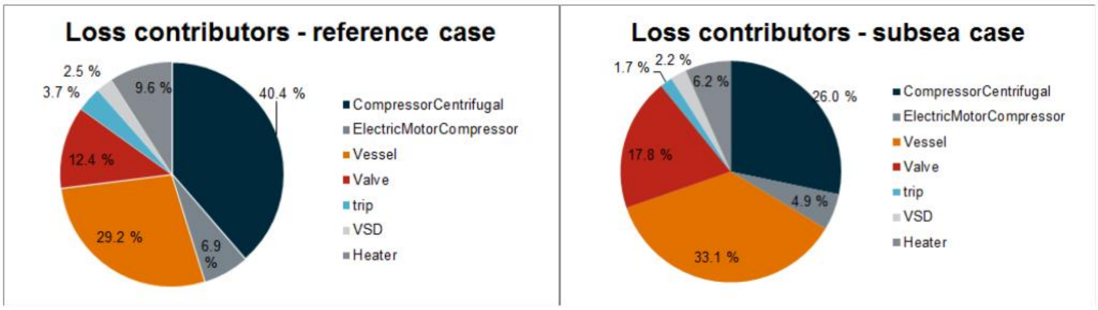


Figure 6.2 Loss contributors for reference case (left) and subsea case (right)

For the reference case, the centrifugal compressors lead to a total of 40% production losses, making them the largest contributors to system unavailability. This is reasonable considering that the centrifugal compressors have both relatively high failure rate and long repair time. Besides, vessels and valves also take up a big proportion of the production loss due to their relatively large quantity, especially for valves.

For the subsea case, the centrifugal compressors remain a large contributor to system unavailability but with a lower percentage. This is because of increased total production loss compared to the reference case. The vessels and valves have larger contributions since a subsea separator is adopted and the related produced water processing facilities are also moved subsea. A number of vessels and valves are thus implemented subsea and longer repair time is required once they cause a system failure. Figure 6.3 shows the contribution from subsea equipment and topside equipment. In this case, over one-third of the production loss comes from the subsea equipment.

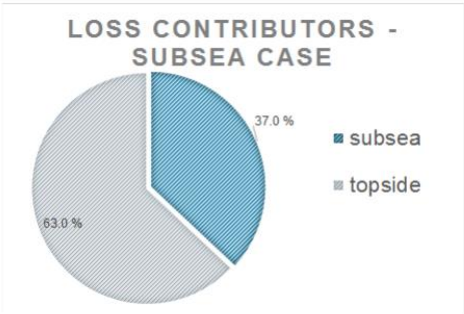


Figure 6.3 Loss contributor from subsea and from topside

A more detailed list of loss contributors showing the contribution of each component can also be derived. Table 6.1 and Table 6.2 show the top five contributors for the reference case and the subsea case. This gives the operators information about the critical equipment and thus a targeted and more cost-effective system optimization can be carried out.

Table 6.1 Main loss contributors for reference case

Contributor	%
Recompression.RecompCentrifugal1.CompressorCentrifugal	17.20
Recompression.RecompCentrifugal2.CompressorCentrifugal	13.30
ExportCompression.ExportCompressorLarge.Centrifugal2.CompressorCentrifugal	8.40
ExportCompression.ExportCompressorLarge.Centrifugal1.CompressorCentrifugal	5.80
Recompression.RecompCompressor1Motor.ElectricMotorCompressor	2.80

Table 6.2 Main loss contributors for subsea case

Contributor	%
Recompression.RecompCentrifugal1.CompressorCentrifugal	10.2
SubseaSeparator.SubseaSepVessel.VesselSeparator_subsea	10.0
Recompression.RecompCentrifugal2.CompressorCentrifugal	9.7
Degasser.DegasserVessel.VesselKOdrum_subsea	5.7
ExportCompression.ExportCompressorLarge.Centrifugal1.CompressorCentrifugal	5.6

6.2 Discussion

The model can produce the desired outputs for production availability analysis. By running simulations, the system performances for different cases can be predicted and the critical components can be identified for system optimization.

Although the simulation approach is flexible and able to provide detailed results, the modeling process is very time-consuming and challenging. The construction of the model requires plenty of inputs, including system configuration, reliability data, maintenance policy, production profile and so on. This requires efficient communication with customers. Besides, the analyst needs to be familiar with the simulation tool and the verification is usually very challenging.

Besides, for the modularization of subsea components, the case study in this thesis shows a way to address this issue with the use of group maintenance. However, due to the use of exponential distributions, the benefits of modularization are not fully demonstrated. The characteristics of delayed maintenance and running with component failure are realized. The maintenance is performed to every component in a group when the defined condition is fulfilled, but this model cannot reflect the renewal process for the working components since it is assumed that the lifetime of all components follows exponential distribution, which disregards the aging of components and assumes they are always “as good as new” as long as functioning.

In order to treat the above-mentioned issues, the assumption of exponential distribution needs to be amended. A more advanced statistic model considering the aging of components is required, for example, Weibull and non-parametrical distribution based on collected data. ExtendSim includes such models and functions and thus the problem is mainly the lack of input data.

Per Kuhnle et al. (2015), subsea separation could facilitate increased or prolonged production for brownfields. This potential advantage for subsea systems is not covered in the model. Since both cases use the same well profile, same productions are expected if there is no degradation and failure. Due to long repair time for subsea components, the subsea case experiences more production loss and is thus with a lower production availability, which results in less total production.

From the given results, the subsea case is not preferable with lower production availability. However, this is one single aspect to consider for the selection of production concept. Many other factors show promising arguments for the subsea case. The decision-making needs to consider all these factors.

According to ISO20815 (2008), the purpose of such an analysis is to achieve and maintain a performance that is at its optimum in terms of the overall economy. While showing lower production availability, the subsea case facilitates lower riser cost, lower OPEX, improved HSE conditions and act as debottleneck for topside water processing. These will greatly reduce the cost and enable a prolonged and accelerated production. Besides, subsea separation also decreases the requirement of injection chemicals for flow assurance, which will also lead to reduced cost. Together with other potential benefit brought by subsea separation, the subsea case could become the overall optimal solution with regard to overall economic return.

Chapter 7.

Summary and Recommendations for Future work

7.1 Summary and Conclusion

The objective of this thesis was to investigate the influence on system performance by implementing subsea separator. Production availability analysis serves as the methods to produce desired indicators. To achieve this goal, this thesis first reviewed background knowledge required for the studied system and the analysis approach.

A literature review was carried out to get familiar with the subsea system and its features. The main elements in subsea systems were introduced. Since the study case was about implementing subsea separator, a more detailed introduction on subsea separator was provided. The drivers for subsea and the challenges were also discussed in this part together with considerations for reliability modeling.

Production availability analysis was selected as the approach for analysis. By conducting production availability analysis, the system performance could be predicted and the critical components could be identified for system optimization.

Two different types of approaches, the analytical approach and the simulation approach, have been discussed in this thesis. The analytical approaches have restricted use and provide less precise results but require less effort. The simulation approaches are more flexible and can provide more detailed predictions, while is rather time and cost consuming, and a solid mathematical and programming basis is often needed. Each approach has its own strength and weakness, and therefore it is important to select the one best suited for the purpose. Analytical approaches are preferred during the early project phase due to its ability to evaluate a variety of alternatives in a short time, while simulation approaches could be used in a later project phase where detailed designs are available.

A set of software tools based on Discrete Event Simulation were developed to help analyzers focus on the reliability analysis instead of the programming. Maros and Taro, MIRIAM Regina and ExtendSim were introduced in this thesis. In collaboration with DNV GL, ExtendSim was suggested for the case study. The basic principles of Discrete Event Simulation especially of ExtendSim was introduced for a better understanding of how simulation is performed in these tools.

After all preparations are ready, a case study was carried out to demonstrate the analysis process. The study case is to evaluate the influence on system performance by implementing subsea separator, which is based on a position paper from DNV GL. A reference case with all separation equipment on FPSO and a subsea case with the use of subsea separator are modeled in ExtendSim. The modeling process for two cases is demonstrated in detail. An ExtendSim library including a set of function for reliability modeling is provided by DNV GL and used in the model.

To address the maintenance issue subsea, a function named “group maintenance” was used to simulate the modularization in subsea systems. The characteristics of delayed maintenance and running with component failure are realized. The maintenance is performed to every component in a group when the defined condition is fulfilled, but this model cannot reflect the renewal process for the working components since it is assumed that the lifetime of all components follows exponential distribution, which disregards the aging of components and assumes they are always “as good as new” as long as functioning. Therefore, it is suggested to adopt more advanced statistic models considering aging of components such as Weibull model.

Based on the results of the simulation, the subsea case is not preferable regarding lower production availability. However, it facilitates lower riser cost, lower OPEX, improved HSE conditions and act as debottleneck for topside water processing, which will greatly reduce the cost and enable a prolonged and accelerated production. Together with other potential benefits brought by subsea separation, the subsea case could become the overall optimal solution with regards to an overall economic return.

7.2 Discussion

According to ISO20815 (2008), the purpose of performing production availability analysis is to achieve and maintain a performance that is at its optimum in terms of the overall economy. Based on the results of the case study, subsea case shows lower production availability due to long repair time for subsea components. However, it can still be the optimum solution with regards to the overall economic return, since the lower availability could be compensated by the potential benefits from subsea systems.

Availability is therefore not a suitable parameter for optimization with respect to such problems. A better parameter would be the economy. Suitable economic values such as CAPEX and OPEX including Net Present Value (NPV) are therefore required. The predicted production from the production availability analysis can be used as input to calculate the overall economic return, while the loss contributors can then provide input for a more cost-effective system optimization with the identified critical components.

In addition, for a better representation of the component status in subsea systems, instead of the exponential distribution, other statistic models able to model aging should be adopted for the lifetime of subsea components. The degraded performance of subsea systems and more advantages of modularization could then be reflected. Detailed reliability data is required for the estimation of such models.

7.3 Future Work

This thesis is carried out with limited time and resources, while production availability analysis is rather time-consuming and some required data are difficult to acquire. Some important issues are recognized but without enough time and/or resource to investigate and implement. These are recommended as the future work.

- For the maintenance of subsea equipment, intervention vessel and ROVs (remotely operated underwater vehicles) are usually required. This can be influenced significantly by the weather condition and it is impossible to carry out maintenance during extreme weather such as typhoon, heavy wind and huge waves. Therefore, the meteorological record could be included in the model and then weather condition could be taken into account when planning the maintenance work.
- In parallel with this project, one of my colleagues is working on the dynamic reliability of a valve in separator using Matlab and Simulink. The degradation propagation is modeled in detail, and therefore a more realistic reliability based on environment, operation condition and so on is produced as the result. This can be used as the input for this model.
- The two study cases have very different system configuration. One of the biggest advantages for subsea systems is to have reduced OPEX and reduced CAPEX for deep water. This is not reflected in the production availability analysis. A life cycle cost (LCC) analysis based on CAPEX and OPEX including Net Present Value (NPV) can be used to compare the total LCC for different alternatives. This can provide a supplement to the production availability analysis since the operators want to achieve the most cost-effective solution, instead of the highest availability.

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Appendix A. Abbreviations

FPSO Floating production storage and offloading

RAM Reliability, availability and maintainability

DES Discrete Event Simulation

CAPEX Capital expenditure

OPEX Operational expenditure

HSE Health, safety and environment

MTTF Mean time to failure

MTTR Mean time to repair

EMP Entity Movement Phase

CUP Clock Update Phase

OREDA Offshore reliability data

PM Preventive maintenance

ESD Emergency shutdown

NPV Net Present Value

ROV Remotely operated underwater vehicle

Appendix B. Well profile

The full profile of WellGroup1 and WellGroup2 is shown in Table A.1 and Table A.2 respectively.

Table A.1 Profile of WellGroup1

Year	Flow rate (t/year)	(Max) Rate (t/h)	% gas	% oil	% water
2016	4120000	470	0.16	98.84	1
2017	4740000	540	0.16	90.84	9
2018	3800000	600	0.14	77.86	22
2019	3800000	630	0.1	46.9	53
2020	3800000	600	0.08	24.92	75
2021	3800000	590	0.06	16.94	83
2022	3800000	580	0.06	13.94	86
2023	3860000	580	0.06	11.94	88
2024	4030000	580	0.05	9.95	90
2025	4120000	570	0.04	7.96	92
2026	4030000	460	0.05	8.65	91.3
2027	3680000	420	0.05	8.95	91
2028	3680000	420	0.05	7.95	92
2029	3680000	420	0.05	7.45	92.5
2030	3680000	420	0.05	6.95	93
2031	3680000	420	0.05	6.45	93.5
2032	3680000	420	0.04	5.96	94
2033	3070000	350	0.04	6.96	93
2034	2980000	340	0.04	6.46	93.5
2035	2370000	270	0.05	7.95	92

Table A.2 Profile of WellGroup2

Year	Flow rate (t/year)	(Max) Rate (t/h)	% gas	% oil	% water
2016	1.00E-06	1.14155E-10	0	100	0
2017	1.00E-06	1.14155E-10	1	99	0
2018	1900000	410	0.22	64.78	35
2019	1900000	410	0.27	69.73	30

2020	1900000	420	0.22	69.78	30
2021	1900000	310	0.32	71.68	28
2022	1900000	250	0.43	61.57	38
2023	1840000	210	0.39	51.61	48
2024	1670000	190	0.34	43.66	56
2025	1580000	180	0.34	37.66	62
2026	1490000	170	0.33	33.67	66
2027	1320000	150	0.34	30.66	69
2028	1320000	150	0.35	26.65	73
2029	1230000	140	0.35	23.65	76
2030	1230000	140	0.36	20.64	79
2031	1230000	140	0.36	17.64	82
2032	1140000	130	0.37	15.63	84
2033	1140000	130	0.37	14.63	85
2034	1140000	130	0.37	13.63	86
2035	1.00E-06	1.14155E-10	0.37	11.63	88

Appendix C. Data dossier

All the MTTFs and repair times used in the model are given in Table B.1.

Table B.1 Input data for topside system

Component	MTTF critical (years)	Equipment downtime (hours)
Compressor centrifugal	0.8	67
Electric generator gas turbine driven	2.0	47
Electric motor - compressor	1.7	30
Electric motor - pump	10.8	32
Gas turbine aero derivative	0.3	40
Electric heater	6.2	27
Heat exchanger S&T	8.3	12.5
Heat exchanger plate	4.8	15.2
Hydraulic power pack	126.8	33
Pump centrifugal	1.5	36
Blowdown valve	29.3	14
Pressure reduction valve	27.1	14.5
Process control valve	16.5	14.4
ESD/PSD valve	21.5	14.8
Variable speed drive	2.0	43.8
Electrostatic coalesce	3.3	39
Hydrocyclone	18.3	12.7
Knock-out drum	3.2	16.1
Degassing drum	3.2	16.1
Scrubber	4.8	16.8
Separator	3.2	16.1
TEG contactor	1.2	24
Heaters and boiler, (energy source ->exhaust)	1.4	26
X-mas tree valve	57.1	14.8
DHSV	20.4	200

ESD trip	1.0	8
PSD trip	0.5	4
Well Reliability	5.7	14
Subsea blowdown valve	62	Group maintenance
Subsea process control valve	48	Group maintenance
Subsea ESD valve	49	Group maintenance
Subsea knock-out drum	21	Group maintenance
Subsea variable speed drive	22	Group maintenance
Subsea centrifugal pump	12	Group maintenance
Subsea electric motor pump	38	Group maintenance
Subsea separator	16	Group maintenance