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Abstract

The oil and gas industry has evolved for centuries. The development of the society and the rapid growth of global economy require energy as a driven force for the engine of global economy. Energy plays a significant role in providing sustainable development for the nations' civilization. Although a diversification pattern of use of energy has established, fossil fuels such as coal, petroleum and natural gas still occupy the dominant position in energy consumption. In China, over 490 million tons of oil was consumed in 2012, and this number will still increase in the future.

However, with oil and gas production approaching its tail end on many onshore oilfields in China, the oil companies are seeking new opportunities towards the deep ocean to open up a new turn of exploration and production. The South China Sea, which is considered as the potential sustaining area for the future growth of the nation's economy, contains probably billions of tons of oil and gas resources. Due to the high risk and high investment in offshore oil exploration and production, safety is considered as the primary principle in any offshore operations by almost all oil companies. Therefore, in order to avoid any fatalities, environmental incidents, and unnecessary stopping in offshore operations, a set of factors ranging from environmental, geographical and cultural aspects should be identified to minimize the potential risk before any operations can be undertaken.

The major objective of this thesis is to identify the possible factors that may influence offshore operations and maintenance processes from environmental, geographical and cultural aspects. And how those parameters affect offshore operations will be discussed also to find out the inner connection between influential factors and offshore operations.

In this thesis, a series of methodologies with respect to risk analysis & risk assessment, decision making engineering and ergonomics will be used to analyze the causes and consequences related to the influence factors on offshore operations and maintenance processes. And a risk-based methodology with regards to offshore operations will be proposed to provide helpful information contributing to show how to identify and deal with circumstance in offshore operations and maintenance processes.

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1. Introduction

This chapter is aimed at describing the background and the motivation of the thesis. The research scope of work, the main goal of the thesis and the research limitations are also involved in this thesis.

1.1. Background and motivation

The oil and gas industry has evolved for centuries. The development of the society and the rapid growth of global economy require energy as a driving force for the engine of the global economy and plays a significant role in providing sustainable development for the nations' civilization. As a developing country, China, on the one hand, has been enjoying its rapid growth in economy over the past 30 years; on the other hand, the prosperous economy has driven the country to a massive energy demand due to high energy consumption.

1.1.1. Energy structure and energy consumption in China

According to National Bureau of Statistics of China (as shown in figure 1), the average rate of China's annual real gross domestic product (GDP) is around 10% from 2000 to 2011 while the consumption of energy increases so rapidly that China ascends to the top countries demanding energy during the past years. In 2010, China became the largest energy consumer in the world and the second-largest oil consumer ranking only second to the United States (as shown in figure 2). According to the U.S. Energy Information Administration (EIA), China will rank as the largest net oil importer by 2014 instead of the U.S. as its oil consumption increases (as shown in figure 2).

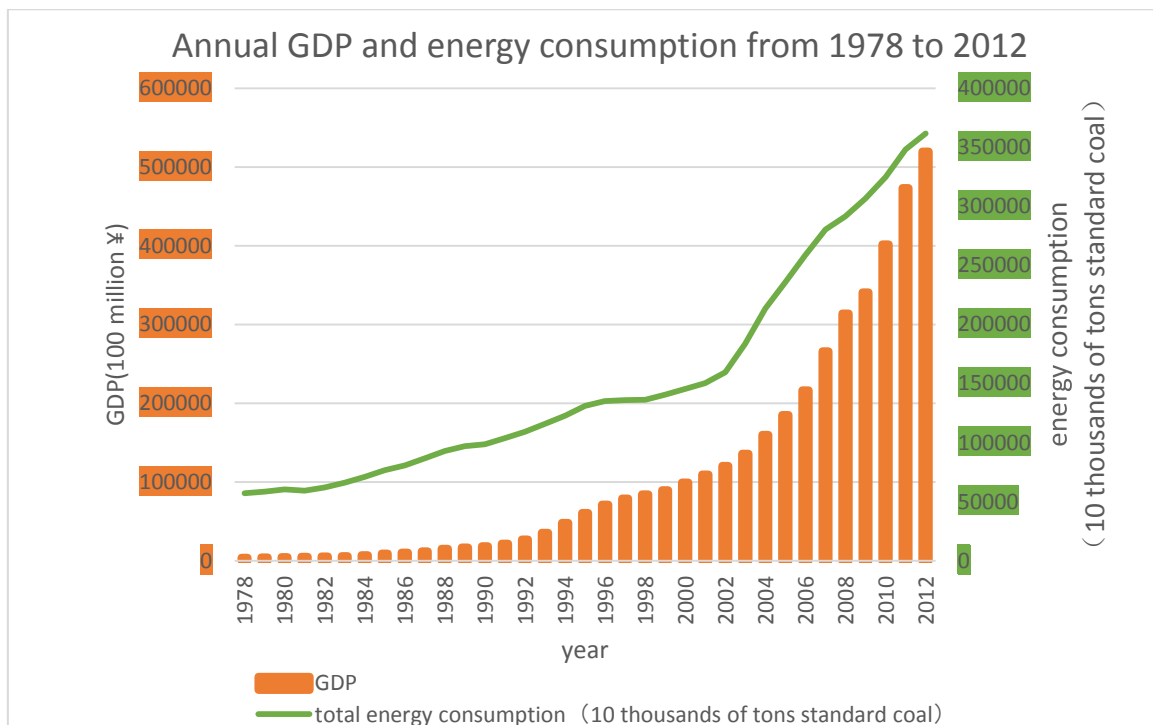


Figure 1 Modified annual GDP and energy consumption from 1978 to 2012 based on National Bureau of Statistics of China (National Bureau of Statistics of China, 2013)

Global primary energy consumption

quadrillion british thermal

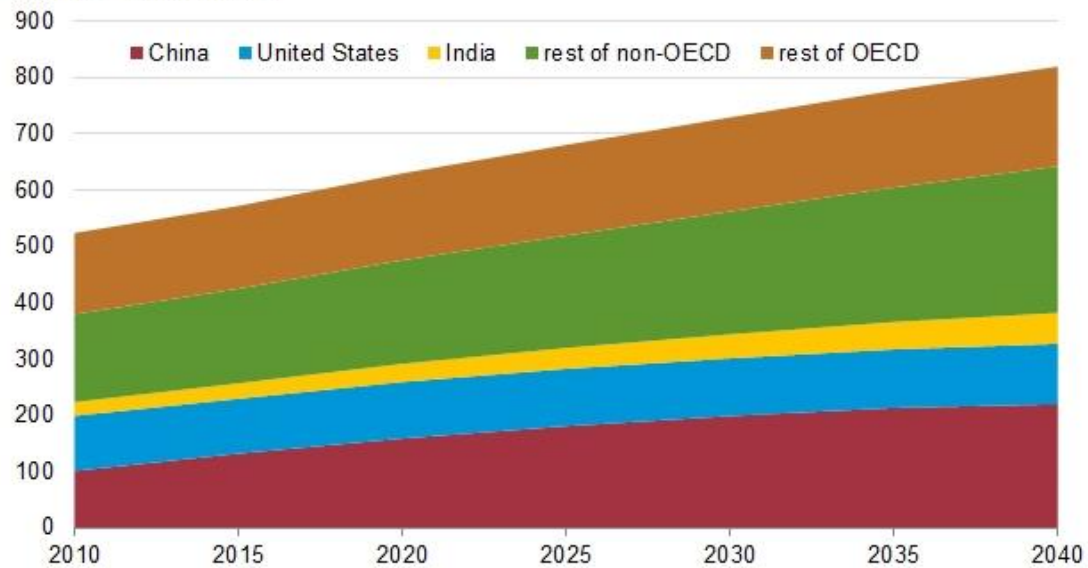


Figure 2 The global primary energy consumption (U.S. EIA International energy outlook, 2013)

In China, although a diversification pattern of energy has established, the use of fossil fuels such as coal, petroleum and natural gas still occupy the dominant position in the total energy consumption. Just as shown in figure 3, fossil fuels contributed the overwhelming majority (92%) of its energy consumption, in which oil and natural gas accounted for 22% in 2011. In China, over 490 million tons of oil was consumed in 2012 and in 2013 China consumed an estimated 10.7 million bbl/d of oil. The EIA's report in 2013 shows that oil consumption in China will continue growing through 2014 to approximately 11.1 million bbl/d, and its net oil imports will reach 6.6 million bbl/d compared to 5.5 million bbl/d for the United States.

Total energy consumption in China by type, 2011

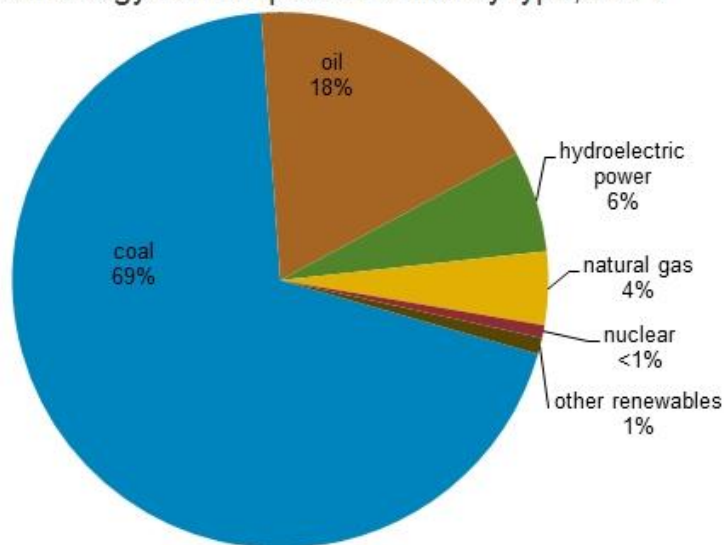


Figure 3 Total energy consumption in China, 2011 (U.S. Energy Information Administration International Energy Statistics, 2011)

1.1.2. The importance of enhancing exploration and production on offshore fields

With oil and gas production approaching its tail end on many onshore oilfields in China, the oil companies are seeking new opportunities towards the deep ocean to open up a new turn of exploration and production. The China National Petroleum Corporation (CNPC) and the China Petroleum and Chemical Corporation (Sinopec), reorganized from China's national oil companies, have most of the state owned oil and gas assets containing both upstream and downstream facilities. According to, to the U.S. Energy Information Administration (EIA) CNPC is the leading upstream player in China and Petro China accounts for an estimated 53% and 75% of China's total oil and natural gas output, respectively. Both the two companies have existed for decades and developed many mature onshore oilfields. Da Qing oilfield, considered as the oldest and largest oilfield in China, has realized a stable production over the past twenty years with a yield of 50 million tons of oil annually. However, over the past 20 years, a vast majority of the largest oilfields in China, which support the backbone of the country's domestic production, now are approaching its tail end with declining production and high rate of produced water.

To meet the high demands of oil consumption and provide sustainable energy for the nation's economy, CNPC and Sinopec have rapidly stepped up efforts in expanding their purchases of international oil and gas assets and exploring abroad markets. Besides, The China National Offshore Oil Corporation (CNOOC), the third largest state-owned oil company, responsible for offshore oil exploration and production, has occupied the dominated role in oil exploring and production in offshore zones. On the other side, CNOOC has proven to be a powerful competitor to CNPC and Sinopec in offshore technical superiority by increasing its exploration and production (E&P) expenditures in China offshore, but also by cooperating with international oil companies in some technically challenging offshore oil fields in order to share the cost and risk in oil exploration and production.

CNOOC mainly focuses on the offshore areas such as Bohai Bay, East China Sea and the South China Sea (SCS), as well as onshore oil and natural gas fields located in the central and western parts of China such as Xinjiang and Sichuan provinces (as shown in figure 4). The Bohai Bay, located in northeastern China, is the earliest oil producing offshore zone and has been developed for over 20 years. According to PFC Energy, CNOOC's production in the Bohai Bay was 406,000 bbl/d in 2011 before the oil leak in Penglai 19-3 oil field, as being the largest offshore oilfield once peaking at over 120,000 bbl/d crude oil. South China Sea, which is considered as potentially sustaining the future growth of the nation's economy, contains billions of tons of oil and gas resources. In this offshore zone, several significant discoveries were made by CNOOC, such as the Xijiang oil field, the Enping block and the Liuhua oilfield in eastern SCS (South China Sea). In the East China Sea, China has developed the Chunxiao and Pinghu oil and gas fields, although territorial disputes against Japan in the East China Sea have restricted large-scale development of oil and gas fields in this region.

According to the discussion above, the significance of enhancing offshore operation can be summarized in three points:

- 1) To fulfill the rapidly increasing demand of energy and provide sustainable energy for the nation's economy.
- 2) To reduce the dependence on oil and gas imports and ensure the energy security of the country.

- 3) To keep technical superiority on offshore operations and enhance the competence in offshore exploration and production.

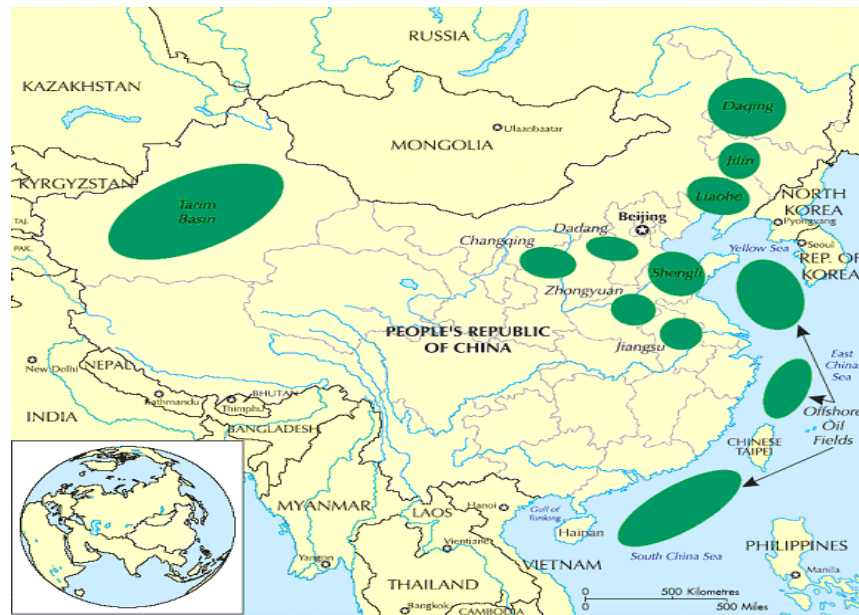


Figure 4 China’s largest oil field (International Energy Information, 2013)

1.2. Problem description

The progress of offshore oil exploration and production is moving forward as the demand of energy is rapidly increasing worldwide. However, many accidents with respect to human injuries or fatalities, environment pollution and big loss of economy have occurred during the progress of offshore oil exploration and production.

Due to an unpredictable direction change of a tropical depression, a typhoon, the ocean current and waves and the underestimate of the wind, “Nanhai Faxian” FPSO was attacked by the powerful typhoon “Kuppo” east in South China Sea in September 14th, 2009, bringing about serious damage of the SPM (Single Point Mooring) and pipelines on the seabed. The whole oilfield had to shut down for over 6 months after the serious accident caused by the typhoon and suffered from a huge loss of oil production.

In November 25th, 1980, Bohai NO.2 jack-up drilling platform sank in a towing operation at Bohai Bay, resulting in 72 fatalities and economic losses of 4000 million Yuan. The explosion of Deepwater Horizon in the Gulf of Mexico, U.S. in 2010 caused 11 fatalities and an uncontrolled blowout which in the end was killed after 5000 thousands of barrels of crude oil were leaking in the Mexico Gulf. This accident in Mexico Gulf is considered as the worst environmental disaster in offshore oil leaking accidents.

A watchful eye is kept on the accidents occurring in offshore operations by the society due to offshore incidents of serious casualties on personnel, massive loss on economy and facilities, and catastrophic pollution on environment. Absolutely, a series of questions have always been asking since each accident occurred: Why did these accidents happen? And how did these accidents occur? Are there any measures that can be taken to prevent these disasters happening? How can the operators identify the potential factors influencing safety to reduce

or avoid the risk in offshore oil exploration and production?

Obviously, incidents as regards to the offshore oil exploration and production are always of severe and unacceptable consequences due to the characteristics of high risk and high investment in offshore oil developments. Compared with onshore oil exploration and production, offshore oil exploration and production usually occur in harsh conditions ranging from technological, environmental, and even cultural aspects. For instance, waves, ocean current and wind have to be concerned when considering shipping, installing the facilities and drilling. And sophistication in deep-water technology is one of the challenges confining humans moving forward to the deep ocean.

Therefore, high risk with regards to personnel casualty, equipment, down hole and the environment pollution make safety the primary principle in any offshore operations by almost all oil companies. Safety first is now becoming a common view accepted by the absolute majority of the oil companies. Thus, in order to reduce or avoid any risk with respect to fatalities, environmental incidents, and unnecessary stop in offshore operations, a set of factors ranging from environmental, geographical and cultural aspects should be identified to minimize the potential risk before any operations can be taken. And an effective and efficient approach for identifying the relevant influencing factors needs to be established to contribute to the safety of offshore oil exploration and development.

1.3. The research scope of work

The research scope of this project shall look into the following:

- Identify the influencing factors with respect to environmental, geographical and cultural aspects by collecting and analyzing incidents in offshore operations.
- Map the existing knowledge of risk analysis.
- Study the factors and find out the effects on offshore drilling and maintenance processes by using risk analysis and risk assessment to support decision making.
- Study the incident cases occurring in offshore oil and gas activities by using risk analysis methods.
- Identify the failure models in maintenance processes by using FMECA to find out the influencing factors in maintenance management.
- Suggest an effective approach for identifying influencing factors in offshore operations based on risk analysis.

1.4. The main goal and sub-goals of the research

The primary goal of this study is to identify the possible factors that may influence offshore drilling, installation and maintenance processes from environmental, geographical and cultural aspects. And the sub-goals of the research are to study the relationships between the influencing factors and offshore operations. And by performing application of risk analysis in offshore drilling, installation and maintenance processes, an approach on how to identify influencing factors in offshore operations will be suggested to provide helpful information contributing to improve the safety of offshore drilling and maintenance processes.

1.5. Research limitations

Offshore operations cover a wide range of activities in respect of offshore such as shipping,

fishing, diving, installation, and oil exploration and production. In order to carry out the thesis precisely, the scope of the work has to be narrowed down to some specific subjects. Therefore, several limitations exist in this study.

- Firstly, in this study, offshore operations are restricted to offshore oil industry operations including exploration and production, embodying drilling, shipping, installation of offshore oil facilities and chopper transportation.
- The second limitation of this study is that offshore drilling and maintenance in this thesis are merely confined to fixed platforms, mobile drilling rigs and FPSOs.
- Thirdly, the identification of influencing factors in this thesis are based on literature, the incidents study and the on-site experience of the author who has worked in COSL (China Oilfield Service Company) for 7 years.
- Finally, data and cases are collected from offshore oil & gas industry. They do not cover all the aspects of all industries.

1.6. Thesis outlines

The thesis consists of seven chapters. The extended background and basic concepts will be introduced in chapter 2 to give the readers a brief comprehension of offshore operations and safety status after the current introduction. And then, identification of environmental, geographical and cultural factors that influence offshore operations will be carried out in chapters 3, 4 and 5, where case study and influencing factors will be analyzed by using risk analysis tools to illustrate the relationship between offshore operations and their impact factors. In chapter 6, some theoretical knowledge with regards to risk analysis and risk assessment will be prepared and some applications of risk analysis in offshore drilling, production and installation will be involved. Finally, the thesis will end with discussion and suggest an approach for identifying influence factors in offshore operations.

2. Offshore operations and maintenance processes

The extended background and basic concepts will be introduced in chapter 2 to give the readers a brief comprehension of offshore operations and safety status. The concept and types of maintenance and offshore operations will be introduced in this part.

2.1. Overview of offshore operations and maintenance processes

2.1.1. Offshore operations

Offshore operations consist of a series of activities with respect to the development of offshore oil and gas oilfield. The main phases and the most important milestones of a field development project are shown in figure 2.1 (Odland, n.d.).

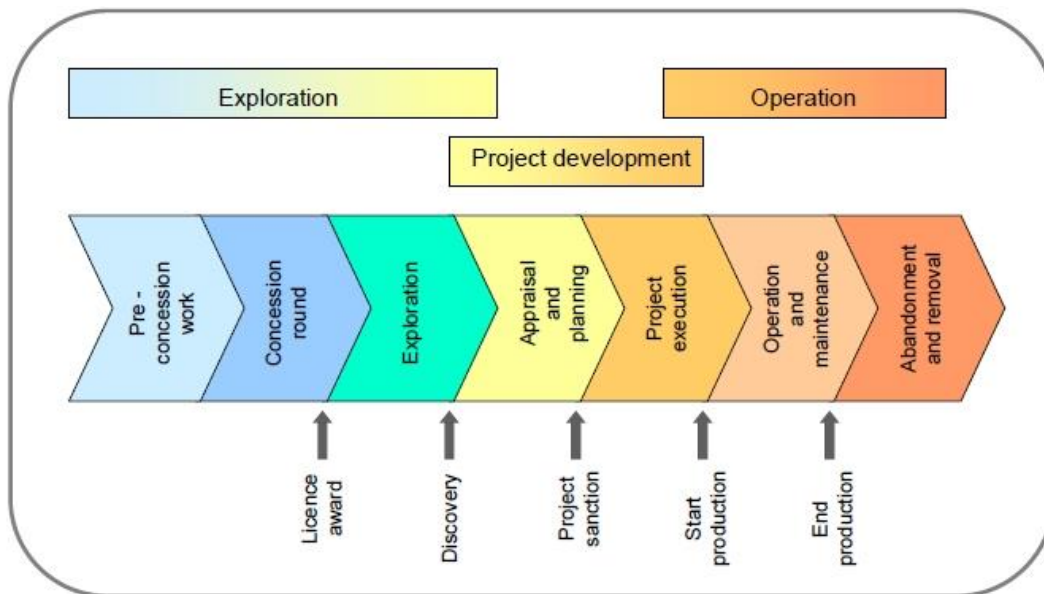


Figure 2.1 Phases and milestones in the process of exploration, development and production of petroleum (Odland, n.d.)

To put it simply, five main phases will be included in the life cycle of an offshore oilfield if it is only restricted to specific offshore activities such as exploration, installation, drilling and production. The five phases in the development of offshore oilfield are as following:

- 1) **Exploration phase.** Offshore exploration refers to the process of searching where the hydrocarbons are found and how much oil the reservoir contain by some appraisal techniques and geophysical techniques such as gravimetric and magnetic surveys, seismic surveys, and OBC surveys (Ocean Bottom Cable). Rock cuttings, core samples and geophysical data obtained from well surveys by drilling and geophysical survey are used to gain property and information of the reservoir in order to determine the oil reserves, recoverable volume and where to drill a whole.
- 2) **Construction and installation phase.** In this phase, massive of construction and installation work will take place at the onshore factories and offshore sites. Offshore construction relates to the installation of structures like platforms, sub-sea templates and pipelines in a marine environment for the next drilling and production phase. And construction phase is considered as a rather difficult, risky and costly process in the

offshore environment due to the huge dimensions and complex structure of the offshore facilities, and high vulnerability to the offshore environment such as harsh weather, waves, and winds. For example, in the South China Sea, offshore installations should avoid monsoon season and typhoon season. In other words, the weather window for the continuous installation is relatively narrow and the process of installation might be affected by the harsh weather. What is more, the restriction to lift weight and precise installation on seabed in the deep ocean is also a big challenge in the offshore operations. Modern drilling rigs and production facilities can be designed to several modules in order to reduce the lift weight. And then those modules are constructed onshore and fabricated offshore by large crane vessels and ROV.

- 3) **Drilling and production phase.** After the exploration and installation phases, drilling activities will be involved to drill the well bore to produce the oil and gas. Offshore drilling is a complex and risky systematic engineering which consists of many sub-contractors and sub-systems. Generally, offshore drilling includes well design, down-hole drilling strings, mud design, casing and cementing, well completion, well testing. Many complex facilities and services will be used in the drilling activities, such as the mud pump, top drive system, solid control system, and monitoring and logging system.

The drilling units in offshore drilling can be classified into three types: mobile drilling rigs like jack-up and semisubmersible, fixed platforms with floating drilling tenders, and self-contained fixed platforms. Production will start after completion and fabrication of topside and substructures. In order to transfer the oil at a lower risk by pipeline, it is important and necessary to separate the gas and water from the crude oil produced from the reservoir. The separation of gas and water will take place on process which contains a most basic type of separator known as a conventional separator which comprises a simple closed tank, in which the force of gravity helps separate the heavier liquids like water at the bottom, the light liquid like oil in the middle gases, and the lighter gas like natural gas on the top of oil. Normally, the water separated by the separator will be dehydrated and then discharged to the sea in order to reduce harm to the environment. The gas will be injected to the reservoir or used as fuel for the gas turbine to generate electricity. Finally, the treated oil will be transferred to the onshore terminal by oil tank or by pipeline.

- 4) **Well intervention and enhance recovery phase**

According to the Wikipedia (2014), the definition of well intervention can be described as the following:

“A well intervention or well work is any operation carried out on an oil or gas well during or at the end of its productive life, which alters the state of the well and/or well geometry, provides well diagnostics, or manages the production of the well”.

Well intervention usually consists of wellhead and Xmas tree maintenance, pumping, slick-line, braided line, coiled tubing, snubbing, sub-sea well Intervention, and work over. As the oil field approaches its tail end, a series of problems will come up, including lower productivity, high rate of water, increased sand from the well bore, and high frequent failures on production strings and electric submersible pump. Hence, in order to improve the performance of well production and perform well maintenance, well intervention is involved in the production phase.

5) Abandon and removal phase

2.1.2. Maintenance management

The term of maintenance have various definitions. According to the British standard BS EN 13306 (2008), the definition of this term is defined as the

“Combination of all technical, administrative and managerial actions during the life cycle of an item, intended to retain it in, or restore it to a state in which it can perform the required function. This includes dependability, cost reduction, product quality, environment protection and safety preservation of the facilities”.

Deming (2000) states that maintenance plays a significant role in business success. In the offshore Oil and Gas industry, maintenance refers to a series of activities with respect to engineering, managerial, and administrative aspects. As discussed in the introduction part of this thesis, the offshore Oil and Gas industry of the characteristics of high risk and high investment. The equipment and the systems used in offshore industry is becoming more and more complex. For example, the modern offshore drilling rigs have lots of sophisticate equipment and sub-systems which need to cooperate together in daily offshore activities. The drilling work needs drilling fluid system, top drive system, pump system, traveling block systems and monitoring system etc., which are indispensable and need to be reliable in the whole drilling process. Therefore, we need the machines function well as required to reduce the downtime and maximum its efficiency. And other benefits from good maintenance management can be described as the following:

- Improve the reliability of the systems and reduce breakdown time.
- Reduce the unit cost.
- Lower the maintenance cost and reduces the spare parts or inventory.
- Maximum the use efficiency of sources like labor, material, and energy.
- Reduce the risk with respect to machine failure or system failure.

Bad maintenance in some way means lower productivity, increased cost, decreased life of assets, longer downtime and even poor safety conditions on assets and personnel. To some extent, maintenance contributes to reliability, maintainability, and supportability of equipment and system and ensures the equipment and system continuing to perform its required functions to achieve an optimum delivery for the end-users. The consequences of failure can be avoided or reduced by proper maintenance activities.

Maintenance not only concerns the reliability of equipment and system, but also refers to the safety of installation, personnel, and environment. Many incidents with regards to personnel, facilities and environment are caused by function failure or structure failure which might result from bad maintenance or lack of maintenance. The maintenance related failures may come from improper maintenance and poor planning in the manufacturing and operation phases. The process of maintenance management like any type of management process has the activities including initiation and definition, planning and development, execution and control, and closure (Gardiner, 2005).

A tropical management process can be demonstrated by the Maintenance Management Cycle shown in figure 2.2.

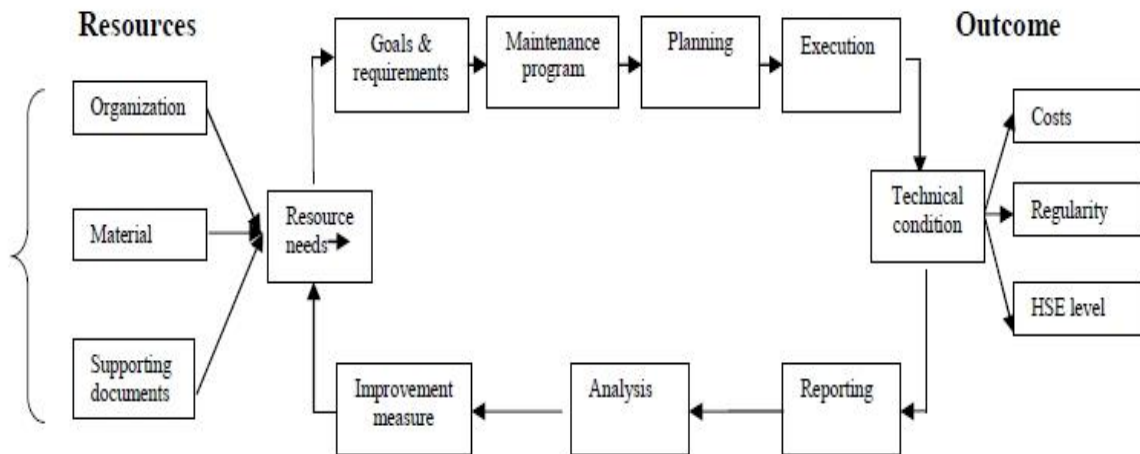


Figure 2.2 Maintenance Management cycle (NPD, 1998)

- **Goals and requirements.** Goals and requirements consist of achieving business and regulatory needs and demands by making proper maintenance goals and requirements. And the goals can be represented by some safety objectives and management indicators.
- **Maintenance program.** Maintenance program includes development, updating, and improvement of preventive maintenance programs, inspection programs, and condition monitoring by using some methods such as RCM, RBI and risk analysis, etc.
- **Planning.** Planning of maintenance activities encompasses long term and short term resource plan, risk management, and work order management.
- **Execution.** Execution includes a series of activities such as preparation, implementation, control, and completion. Job information, work permission, job safety analysis, registration, and verification will be involved in this step.
- **Reporting.** Reporting involves content and formats, trend analysis, qualification of reported data and resources, and improvement processes
- **Analysis.** Analysis relates to analyze the incidents, date, causes, trends and weakness with regards to maintenance work by identifying incidents and events and cause analysis.
- **Improvement measure.** Improvement measures will be taken to find out the deficiency needing continuous improving and to establish a systematic method by performed analysis.

According to EN 13306:2001(2001), the definition of maintenance management can be defined as the following:

“All activities of the management that determine the maintenance objectives, strategies, and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improvement of methods including economic aspects in the organization”. The maintenance objectives relate to the targets assigned and accepted for the maintenance activities by the management. And the maintenance strategy is defined as a management method in order to achieve the maintenance objectives.

Wilson (1999) argued the significant importance to set up a maintenance-management policy for the entire activities so as to visualize and communicate the maintenance strategy. For the

offshore Oil and Gas industry, it is necessary to specify the policies which are used in different sections or phases in the development of the offshore oilfields due to the complexity in systems and long term period in life cycle. For example, in the development of a new oilfield, a series of phases have to be experienced including the early exploration phase, construction and installation phase, drilling phase, production phase, work over phase and the final abandon phases. Therefore, the policies should be specified and adjusted to adapt and fulfil the goal and requirements in different sections or phases in the life cycle of maintenance management.

2.2. Types of offshore maintenance

In general, Maintenance activities can be classified into the following categories:

- a) **Breakdown Maintenance** Breakdown maintenance is also known as run to failure maintenance. The simplest maintenance strategy to be carried out for breakdown maintenance is “run to failure”. In other words, this kind of maintenance strategy is to allow the assets to run until failure occurs, at which moment repair or replace activities will be performed to recovery their functions. Due to no plans or activities preparing before failure occurring, it is important and necessary to keep enough spare parts on hand to replace the failure components and to maintain availability for the organizational requirements. Run to failure maintenance strategy is used for equipment that have no safety risks on personnel and environment, and have no or slight effect on production.

Although “run to failure maintenance” strategy is quite simple with minimum planning and easy to be understood. It has some disadvantages like unpredictable of failure, inconsistency of resource and staff, and costs with respect to breakdown time and spare parts inventory. Because the possible failures are unpredictable in run to failure maintenance, it is quite hard to anticipate when any maintenance action and manpower are needed to repair. The application of “run to failure” maintenance makes sense when the failures of assets have no safety risks on personnel and environment, and have no or slight effect on production and the total cost of maintenance after failure is less than the cost of performing other types of maintenance strategy. The process of failure and the consequence of failure need to be understood before the run to failure maintenance is used.

- b) **Preventive Maintenance.** There are many definitions of preventive maintenance. However, all preventive maintenance management programs are based on elapsed time of hours of operation. Figure 2.3 as a bathtub curve illustrates an example of the statistical life of a machine. The bathtub curve indicates that failure rate is different at different periods of the life cycle of a machine. At the early “infant period”, a new machine has a high failure rate may due to some installation problems. And then the probability of failure goes down to a lower and constant failure period. Following this period, the wear out period has an increasing failure rate as time goes by at the tail of life cycle. In this kind of maintenance, repair work and maintenance schedule are based on the MTTF (mean-time-to-failure). Compared to run to failure maintenance, preventive maintenance is regularly performed on assets or systems based on scheduled or planned maintenance actions by MTTF statistics aimed at reducing the likelihood of failure and the unexpected breakdown. Preventive maintenance activities consist of lubrication, oil changes, repairs, adjustments and so on.

The applications of PM method suit for those that have degrade with the time elapse and the probability of failures increasing with time, following the bathtub curve. And the machines that have a crucial function and have the failure models which can be prevented by appropriate maintenance are also suited to the PM method. Because the maintenance plan is scheduled and the maintenance activities are performed regularly in advance, the loss of production due to breakdown and costs including labor cost, shipping, time response and spare parts can be reduced. Safety is also improved because the reliability of equipment is ameliorative with breakdown less often than for less complex strategies. However, the PM method requires maintenance planning in advance, which need massive statistics and investments in time and resources available.

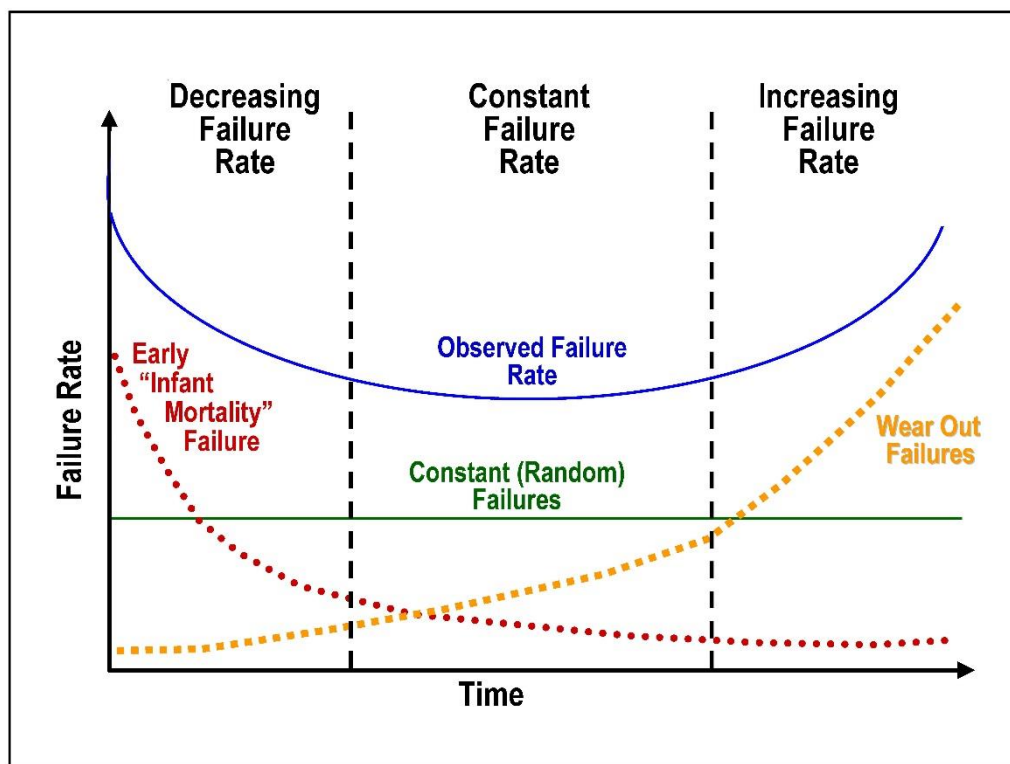


Figure 2.3 Bathtub curve (U.S. Army document, 2005)

c) Predictive Maintenance

Predictive Maintenance is also known as Condition Based Maintenance (CBM). It is a regular condition-driven preventive maintenance program, which is used to detect developing failures and predict the failures in advance to schedule maintenance activities by condition monitoring including mechanical condition, system efficiency, and other indicators. Obviously, the aim of predictive maintenance is to predict before the failures occur and to prevent the occurrence of catastrophic failures by analyzing information and data provided by condition monitoring.

Predicting failure can be done with many techniques. There are two main requirements that should be fulfilled when we select the appropriate technique. The first one is that the selected technique should be feasible and effective at predicting failure. For instance,

restricted by space, time, and equipment in offshore maintenance processes, condition monitoring techniques should be practical and time efficient because there is not enough space for some huge and complex testing tools. And long breakdown time is might also unacceptable by the operators. The other one is that the technique should be precise and reliable enough to provide sufficient warning time for maintenance to be executed. Condition monitoring consists of many techniques including Vibration Measurement and Analysis, Process parameter monitoring, Infrared Thermography, Oil Analysis and Tribology, NDT (non-destructive testing), Ultrasonic, Sound intensity measurement, Motor Current Analysis, Hydraulic and pneumatic testing and etc. By diagnosing data collected from condition monitoring, corrective maintenance activities will be scheduled and performed at an optimal time to reduce the total cost of maintenance and the breakdown time.

Due to predictive maintenance based on condition monitoring, there are many advantages when we used CBM.

- Reducing cost of maintenance
- Improving system or equipment reliability
- Minimizing breakdown time due to catastrophic failure and increasing productivity
- Prolonging machine life
- Reducing spare parts and inventories
- Improving worker safety and operating safety.

Although predictive maintenance has many benefits, the cost of condition monitoring used in predictive maintenance is often high, compared with run to failure maintenance or preventative maintenance. What's more, people need high skill level and experience to operate testing tools and to accurately interpret condition monitoring data. Thus, not all equipment can be maintained cost-effectively by using predictive maintenance, preventative maintenance or a run-to-failure maintenance strategy. Whether or not deciding on predictive maintenance for a particular system or equipment should be based on techniques such as Reliability Centered Maintenance and Risk Based Maintenance, which provide a systematic method for determining if predictive maintenance is the best option as a maintenance strategy.

2.3. Safety issues in offshore operations

As discussed above in the introduction part, the offshore O&G industry is of high risk with respect to personnel safety, environment issues, and financial problems. During the development process of offshore oil and gas industry, accidents related to personnel fatalities, environmental pollution, and facility and operation failure inevitably accompany offshore operations at all the phases of offshore development. The causes, scale and severity of the undesirable events are variable in different operations and facilities. Some consequences of the undesirable events are slight, but some are severe and unacceptable.

For instance, the latest catastrophic accident of Deepwater Horizon occurred in the Gulf of Mexico, in 20th April 2010 is still remembered and vigilant by the ambitious oil seekers, in which the explosion caused the fatality of 11 workers and severe ocean pollution with the oil spill of over 5 million barrels of crude oil. The accidents happened in offshore oil and gas

production are triggered by a series of influencing factors related to environmental, technological, organizational and cultural aspects.

Therefore, necessary terminologies are needed to describe the events occurred in offshore operations when we analyze the causes and consequences of the accidents, scale, possibility of events, and severity of the consequences. The terminologies related to safety issues are listed in figure 2.4.

Terminology	Description
Hazard	Physical activities or situation with the potential threat to cause personnel harm, damage to environment, and loss of facilities and financial interests.
Accidental event	An undesired event that may cause personnel fatality, personal injury, environment damage, and loss of facilities and financial interests.
Accident	An occurred event that caused personnel fatality, personal injury, environment damage, and loss of facilities and financial interests.
Near miss (incident)	An undesired event that could have caused personnel fatality, personal injury, environment damage, and loss of facilities and financial interests, under slightly different conditions or circumstances.

Figure 2.4 Terminologies used to describe undesired events

According to the statistics of accidents occurred in recent years, the most typical accidents happened in offshore oil and gas production cover rigs or platforms loss, casualties on workers, damage to facilities, operation failure, and environmental issues like pollution, oil spill, and emission of NOx or harmful chemicals. Here overviews of some typical accidents with regards to offshore oil and gas production will be listed as following:

Piper Alpha Explosion

On 06th July, 1988, the Piper Alpha platform was destroyed on account of explosions and fire on board in North Sea, leading to 167 fatalities, which was considered as the deadliest accident in the history of the offshore oil and gas industry. Investigations after the disaster reveals that some influencing factors related to procedure, organization and management, culture contributed to the severity of the accident.

- Lack of any communication to the crew on platform
- Poor design and upgrade on barriers like fire walls and blast walls
- Problem on authority: due to lack of authority, the Tartan and Claymore platforms was not shut down and continued pumping oil and gas, even though personnel could see the fire on Piper.

Macondo Blowout

As mentioned above about Deepwater Horizon accident in the Gulf of Mexico, 11 workers lost their lives and a modern drilling rig was destroyed in this accident. What is worse, over 4 over 4 million barrels of crude oil spilled into the Gulf of Mexico, leading to severe ecological disaster and damage to fisheries and critical habitats. Investigations of the accident reveal that several causes from technique aspect, organizational and cultural aspect, and safety management aspect contributed to the accident.

- Poor design and test of cementing slurry
- Inadequate design of blowout preventer
- Signals and sensors of hydrocarbons were missed
- Lack of adequate hazard identification under frontier circumstance and changes to well design and conditions
- Lack of detailed procedures in operations
- Lack of react to early warning signals and failures on test
- Lack of communication
- Lack of appropriate training of personnel, especially in reacting to emergency situations.
- Lack of a clear responsibility

Java Sea Drillship

The U.S. drillship Glomar Java Sea capsized and sank in the South China Sea, in 1983 during the Typhoon Lex, leading to 81 fatalities. Typhoon weather, inadequate procedures, and key components failure contributed to the disaster.

The hazards of accidents occurred in offshore oil and gas production including fire, explosion, and oil spill, have a significant impact on personnel safety, environment security, and assets interests. Accidents do not just happen; they are triggered by a chain of crucial events. The major causes of the accidents range from component or system failure, fire or explosion, outer factors like extreme weather and typhoon, human error, poor design and procedure, inadequate regulations, and poor organizational and cultural management. Clearly, each accident can be considered as a combination of relevant influencing factors.

2.4. Characteristics of offshore operations and maintenance processes

Compared with onshore oil and gas production, offshore oil and gas industry is quite different and much complex on facilities and operations. The difference between the two is determined by the offshore operational environment, technology, installations, cost and benefits, risk, and requirements on personnel. Offshore oil and gas production is restricted to space, depth of water, period of production, and environment. And it is more vulnerable to the marine environment such as wind, waves, typhoon, solitons, salinity, and other extreme climate. Thus, high risk, high input, and severity of consequences in offshore oil and gas production make “safety first” as the priority in any activities. And more strict standards and regulations related to offshore oil and gas production are made to ensure operation safe. The major features of offshore operations and maintenance are described as the following:

- **High investment and high technology.** As discussed in 2.1.1, there are five phases in offshore oil and gas production. Massive work including construction, shipping, installation, exploration, and drilling need to be done before the oil is pumped to the ground. New inventions and latest technology are consistently applied in the offshore oilfields to maximize profits and minimize risks and uncertainty in offshore operations.
- **High risk.** Offshore operations consist of lots of complex activities, which are discussed above, and those activities are quite vulnerable to the outer factors and usually affected by personnel, environment, organization, and management. Hazards related to offshore operations involve fire, explosive, and oil release on sea surface or subsea, which may

cause severe consequence on personnel safety, environment problem, and economy loss.

- **High CAPEX/OPEX (capital expense / operation expense).** Many factors influence the total costs of offshore operations. These factors include capital costs, operation and maintenance costs, risks, and performance.
- **Complex dynamic environment.** Offshore operations are exposed to complex marine conditions and influenced by the ocean environment. These influencing factors include water depth, sea wind, waves, fog, typhoon, temperature, and human reaction on extreme climate. And they are varied from different time and regions. The influences are reflected in safety of personnel and environment, costs of operation, and period of project. Many operations like shipping, helicopter transportation, and installations have very narrow operation window and are restricted to some specific conditions.
- **High demands on profession and personnel.** There are many types of work and disciplines applied in offshore operations, covering mechanical engineering, electrical engineering, instrument engineering, mud engineering, logging services, well survey, and remote control, etc. Therefore, coordination, responsibility, cooperation, the division of labor, and the management of contractors in the offshore activities have to be concerned.
- **International cooperation.** Multi-participation and international cooperation is a key feature of offshore oil and gas industry due to the complexity and risky of offshore activities. In china, the joint venture mode is adapted by the oil companies at the initial stage of offshore development. Due to the complexity on offshore technology and tough condition of marine environment, multi-participation and international cooperation is an effective manner for the oil companies to share risk on safety, technology, and investment.
- **Challenges on managing contractors and sub-contractors.** There are many contractors servicing the offshore oil and gas production. Even in a single activity, many suppliers and contractors are involved to provide relevant necessary services. Due to the difference on scale, management manner, culture, and even regulations, to well manage a group of different companies and to cooperate together without chaos is quite a big challenge for the management board.
- **High requirements on maintenance management.** Reliability, availability and maintainability of offshore assets play a crucial role on maintenance management in offshore maintenance processes. Good maintenance management means lower maintenance costs, fewer assets failures, less repair downtime, longer machine life, and good quality of production. What' more, good maintenance management can improve safety performance by reducing the potential of destructive failures, which may cause severe consequences on personnel, equipment and environment.

3. Environmental factors influencing offshore operations

In this chapter, the environmental factors and their influence on offshore operations will be discussed. Environmental factors influencing offshore operations consist of climate, weather, and sea conditions. To be more specific, these factors are related to temperature, wind, waves, storm, and typhoon etc. Many activities as regards to offshore oil and gas production are might affected by these factors. Thus, effective identification of the environmental factors and necessary analysis of these influencing factors with respect to offshore operations must be concerned to reduce risk on personnel and environment when we make decisions. The

South China Sea (SCS) as a representative marine environment is selected as the researching object due to its important role in China's offshore O&G industry.

3.1. Overview of the South China Sea

Nan hai, known as the South China Sea in the south of Chinese mainland (as shown in figure 3.1), as part of the western Pacific, is surrounded by the Chinese mainland, Chinese Taiwan Island, Philippine Islands, the large Sunda Islands and the Indochina islands. The South China Sea has an area of about 3.56 million square kilometers, in which there are more than 200 uninhabited islands, rocks, and reefs, called the South China Sea islands. The South China Sea is the world's third continental margin, with an average depth of about 1,200 meters and the deepest of the central abyssal plain, deeper than over 5,500 meters. In addition to the main maritime transport routes, the South China Sea is believed to be also rich in oil and natural gas. The South China Sea plays a critical role in world trade transportation route and energy supply for Asian countries.



Figure 3.1 The South China Sea (U.S. Energy Information Administration, International Hydrographic Organization, 2013)

Reserves and resources

U. S. EIA (2013) estimates about 11 billion barrels (bbl) of oil reserves and 190 trillion cubic feet of natural gas reserves in the South China Sea. These numbers include both proved and probable reserves. In 2012, the Chinese National Offshore Oil Company (CNOOC) estimated the area holds around 125 billion barrels of oil and 500 trillion cubic feet of natural gas in underexplored areas, although independent studies have not confirmed this figure due to the geopolitical disputes, the contested areas territory, geological and technological challenges. Although the South China Sea is exposed to extensive geological, technological, and political challenges, the process of offshore exploration and production has never suspended. Many national oil companies (NOCs) have been successful in extracting oil and gas near the

shorelines or in the shallow water of the South China Sea. Figure 3.2 lists the estimated oil & gas production, the countries, and oil companies in the South China Sea.

South China Sea Estimated Oil and Gas Production					
	Estimated production in South China Sea (2011)			SCS contract holders and operators	
Country	Oil ¹ 1000 barrels/day	Natural gas billion cubic feet	Major exploration and production areas	National oil companies	Foreign firms
Brunei	120	400	Baram Delta	PetroleumBRUNEI	BHP Billiton, ConocoPhillips, Hess Corporation, Kulezyk Oil Ventures, Mitsubishi Corporation, Murphy Oil, PETRONAS, Polyard Petroleum, QAF Brunei, Shell, Total
China	250	600	Pearl River Mouth Basin Qiongdongnan Basin	CNOOC Sinopec CNPC	BG Group, BP, Chevron, ConocoPhillips, Eni, ExxonMobil, Husky, Newfield, Shell, Total
Indonesia	60	200	Natuna Basin	PT Pertamina (Persero)	PetroChina, Chevron, CNPC, ConocoPhillips, Eni, ExxonMobil, Husky, KUFPEC, PETRONAS, Santos, Statoil, Total
Malaysia	500	1,800	Sabah Sarawak Malay Basin (w/ Thailand)	PETRONAS	Lundin, BHP Billiton, ConocoPhillips, ExxonMobil, Hess, KUFPEC, MDC O&G, Murphy Oil, Newfield, Nippon, Petrofac, Roc Oil, Shell, Talisman Energy
Philippines	25	100	Palawan Basin	PNOC	ExxonMobil, Shell

South China Sea Estimated Oil and Gas Production					
	Estimated production in South China Sea (2011)			SCS contract holders and operators	
Country	Oil ¹ 1000 barrels/day	Natural gas billion cubic feet	Major exploration and production areas	National oil companies	Foreign firms
Thailand	-	-	Gulf of Thailand Malay Basin (w/ Malaysia)	PTTEP	BG Group, Chevron, Shell
Vietnam	300	300	Cuu Long Basin Nam Con Son Basin	PetroVietnam	KNOC, ConocoPhillips, Geopetrol, Premier Oil, PTTEP, Santos, SK Corp, Total, Zarubezhneft

Figure 3.2 South China Sea Estimated Oil and Gas Production (U.S. Energy Information Administration, 2013).

Climatic characteristics

All of the South China Sea and South China Sea islands between the south of the Tropic of Cancer and the equator is equatorial and tropical monsoon climate. Due to the proximity to the equator, the whole region is partial to warm climate with an annual average temperature at 25-28 °C, the coldest month average temperature at above 20 °C, and the hottest extreme temperature at around 33 °C. In addition, South China Sea tropical monsoon climate is very obvious, due to the Siberia and the Mongolian Plateau winter flow constantly blowing toward southern China Sea in October, the northeast monsoon prevails in the South China starts every year in November till next March. And each year in April, the South China Sea and the South China Sea islands in turn are influenced by southwest monsoon which prevails from May to September on account of tropical and equatorial air masses in the ocean. April and October is the monsoon transition period, under which the currents of the South China Sea Monsoon also have obvious characteristics, flowing northeast in summer and southwest in winter.

One of the most important climatic features in SCS is typhoon, which has a significant influence on offshore activities in this area. South China Sea islands in summer and autumn are also often affected by typhoons. Around 70 percent of the occurrences of typhoon are from the western Pacific Ocean surface and near the Caroline Islands east of the Philippines and the other thirty percent are from the Paracel Islands and the Zhongsha Islands in the South China Sea. Typhoon entranced in the South China Sea usually accompanied by strong wind wild, rainstorm, and surges, on the one hand, have a great influence on maritime shipping, construction of the island, and offshore installation & production. However, on the other hand, the typhoon takes abundant precipitation to the South China Sea islands, as well as most parts of southeast China Hainan province.

3.2. Identification of environmental aspects on offshore operations in South China Sea

3.2.1. Typhoon and its influence on offshore operations

A typhoon is defined as one kind of tropical cyclone that can occur in the Western Pacific Ocean. According to GBT 19201-2006, the tropical cyclones can be classified into six categories in terms of the maximum wind speed. (As shown in figure 3.3) The typhoon season is the time when tropical disturbance are forming in the Southwest Pacific Ocean and are likely to hit the Southeast Asian coast. Normally typhoon season begins in June and runs through October even November.

Classification	Wind Speed		Beaufort Scale (Force)
	(Knots)	(m/s)	
Tropical Depression (TD)	21.0-33.2	10.8-17.1	6-7
Tropical Storm (TS)	33.4-47.4	17.2-24.4	8-9
Severe Tropical Storm (STS)	47.6-63.4	24.5-32.6	10-11
Typhoon (TY)	63.6-80.5	32.7-41.4	12-13
Severe Typhoon (STY)	80.7-98.9	41.5-50.9	14-15
Super Typhoon (Super TY)	99.1	≥51.0	≥16

Figure 3.3 Grades of Tropical Cyclones (GBT 19201-2006)

As the global climate is becoming warm, the intensity and frequency of typhoon in recent years is increasing. In the SCS, the occurrence of tropic cyclone starts from February until December every year, but high frequency of typhoon occurrence mainly focus on from May to October. Figure 3.4 shows the frequency of typhoon occurrence from January to December in the South China Sea during the period from 1958 to 2010. There are two types of typhoon occurred in the SCS. The first type is the West Pacific typhoon, which comes from the western Pacific Ocean surface and near the Caroline Islands east of the Philippines and accounts for 70 percent of the total numbers of typhoon in the SCS. The other one is the South China Sea typhoon, also known as “local typhoon”, which is generated and enhanced in the SCS. Compared with the West Pacific typhoon, the local typhoon has more variability on its direction and wind speed, thus, it is very difficult to predict the track precisely. (Wu et al., 2005)

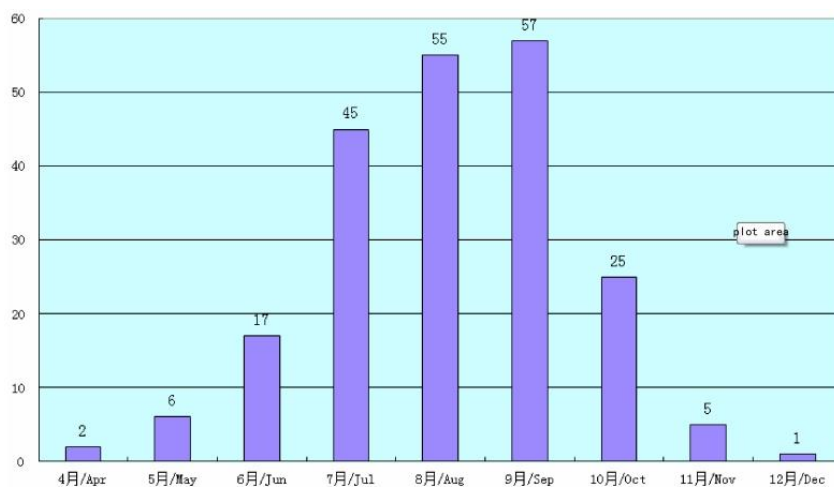


Figure 3.4 Typhoon occurrence in each month from 1958 to 2010 (Xu, L. B., 2013)

Typhoon becomes the most crucial factor contributing on offshore operation safety. Almost all offshore oilfields in the South China Sea are exposed to typhoon weather. In China, the offshore oilfields such as Huizhou oil fields, Xijiang oilfields, Panyu oilfields and Lihua oil fields located at the path of typhoon are affected by typhoon attack every year. The potential threat from typhoon may result in severe losses of lives and economy. Typhoon can damage offshore facilities, delay offshore installation, lead to unnecessary shut down, and influence transportation of cargoes and crew shift. For example, on September 14th, 2009, typhoon “Kuppo” east in South China Sea caused the Mooring System Failure of Nanhai Faxian” FPSO, bringing about serious damage of the SPM (Single Point Mooring) and pipelines on the seabed. The whole oilfield had to shut down for over 6 months after the serious accident caused by the typhoon and suffered from a huge loss of oil production. Many factors including weather conditions, equipment failure, and human errors, etc. influence the offshore operations like offshore drilling, shipping, loading & unloading, production, and installation. The deep water semi-submersible drilling unit HYSY981, as the first sixth generation semi-submersible drilling unit with an operation depth of over 3000m, has experienced 4times of typhoon since its first drilling operation in March, 2012 until August, 2012 in the South China Sea. During the process of offshore operations, the advanced deep water drilling unit HYSY981 was attacked by typhoon “koppu”, resulting in damage on riser joint and tensioner, which are considered as the crucial components in drilling and work-over activities.

Due to the high frequency of typhoon occurrence and significant impact on offshore operations in this area, typhoon emergency response procedure was made by different organizations to provide for the safe and timely evacuation from the area of all personnel working in the South China Sea, ensure all the wells and facilities are secured in such a manner to minimize the potential damage to the environment, and secure all Production, Storage and Drilling facilities in a manner to minimize damage or loss of company property.

Generally, the main steps of a typhoon evacuation plan consist of alert phase, warning phase, and evacuation phase. For instance, the former CACT oilfield in the South China Sea declared the three phase by the following conditions (CACT internal report).

Phase I (Alert) should fulfill one or more of the following conditions.

- A. The leading edge of a typhoon or severe tropical storm is within 800 nautical miles of the operations, this distance represents the approximate distance covered in 54 hours by a typhoon moving at 15 knots.
- B. A typhoon or severe tropical storm develops within the South China Sea that is forecasted to directly affect the operations.
- C. Timing of evacuation needs to consider the speed and direction of the storm and impact of daylight on flying.

Phase II (Warning) is declared by the Operations Manager using one or more of the following conditions as guidelines:

- A. The leading edge of a typhoon or severe tropical storm is within 48-36 hours of any offshore operations.

B. A typhoon or severe tropical storm develops within the South China Sea that is forecasted to directly affect the operations.

C. Timing of evacuation needs to consider the speed and direction of the storm and impact of daylight on flying.

Phase III (Evacuation) is declared by the Operations Manager using one or more of the following conditions as guidelines:

A. The leading edge of a typhoon or severe tropical storm is within 24 hours of any operations.

B. A severe tropical storm or typhoon that develops within the South China Sea and is forecasted to intensify and/or represents an imminent danger to personnel and operations.

The typhoon information received by the offshore operators mainly rely on weather forecast organizations. There are lots of typhoon prediction agencies from different countries predicting typhoon path, but different agencies may have different results on typhoon path prediction (As shown in figure 3.5). Figure 3.6 shows the average forecast track errors for tropical cyclone in 24 hours. And figure 3.7 shows the average forecast track errors for tropical cyclone in 48 hours. As we can see from the charts above, the accuracy of typhoon prediction is dramatically increasing year by year. However, the errors in predicting typhoons still exist. In other words, decision making under wrong or uncertain information may cause risk on safety issues and economy issues. Decision making with uncertainty should be involved as a specific circumstance when handling typhoon evacuation plan in offshore operations. Relatively, by statistics in recent years, Guangzhou (Guangzhou Central Meteorological Observatory) provides the more accurate path on typhoon prediction than Japan and US. That is why offshore oilfields in South China Sea select Guangzhou as their supplier for weather forecasting.

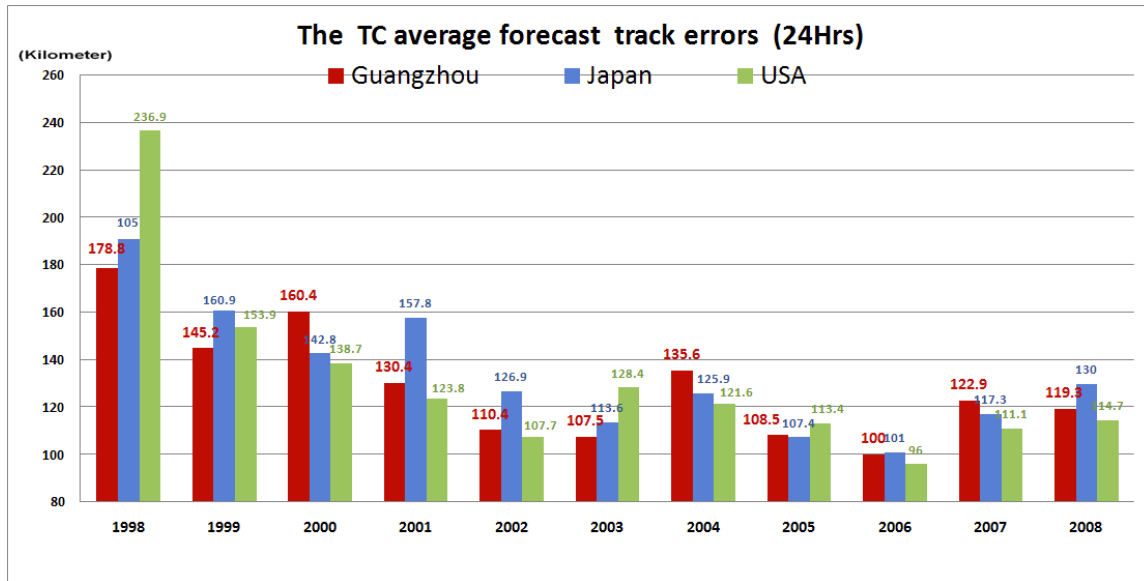


Figure 3.6 The TC average forecast track errors (CACT internal report, 2009)

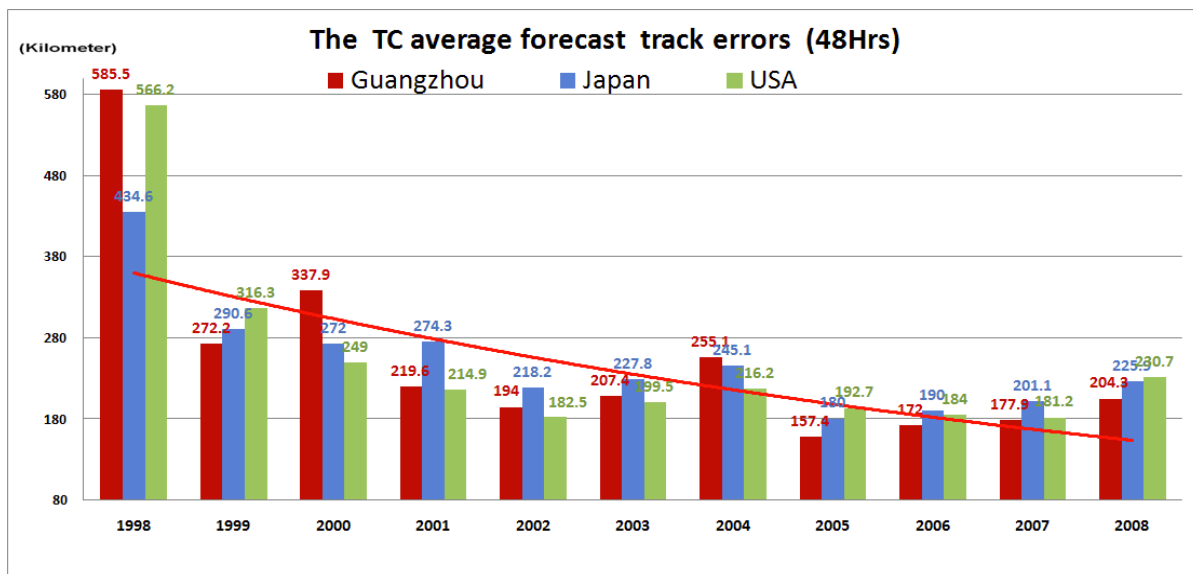


Figure 3.7 The TC average forecast track errors (CACT internal report, 2009)

According to the figures above, the accuracy of typhoon prediction is increasing as the development of technology. However, uncertainty with typhoon path prediction still exists and no one can predict the path exactly, even the similar path is predicted by different meteorological organizations. In 2009, the moving path of typhoon “Koppu” is predicted by China, Hong Kong, Japan, and US, but the real route and intensity of “Koppu” did not track any of the paths predicted by the four meteorological centers. As the weather was a primary contributing factor in the event and no control measures can be placed on it other than weather forecasting & predictions, even if the prediction is with some uncertainty. From another perspective, the decision makers, on the one hand, should require a more accurate weather forecast services. On the other hand, uncertainty on typhoon forecasting, and typhoon evacuation should be considered when making decision.

3.2.2. Tropical climate in South China Sea

Tchernia (1980) declared that the climate of the South China Sea (SCS) and the ambient land masses is dominated by the East Asian monsoon. The northeast monsoon wind in the South China starts every year in November till next March. And each year in April, the South China Sea and the South China Sea islands in turn are influenced by the southwest monsoon which prevails from May to September on account of tropical and equatorial air masses in the ocean. In monsoon season, the wind speed can vary from 20 knots to over 40 knots, and windy weather usually lasts for a long period, which has an important impact on offshore activities.

Monsoon wind affects loading & unloading for supply vessels. Supply vessels as the main transportation mean for the offshore platforms are used to load necessary cargoes required in offshore operations. Due to the restriction on weight and size of equipment for the choppers, supply vessels are an ideal transportation mean to carry drill pipes, casing, huge tanks, and blowout preventers. Another important role for supply vessel is to provide for the platforms with necessary fuel, fresh water, and cement. Loading and unloading work mostly are performed by crane on platform. Windy weather and bad sea circumstance increase the risk of crane job. On the one hand, the supply vessels have to undertake high risk to approach the platform to be available for the crane on the platform. On the other hand, crane operator have to operate the crane at some bad circumstance such rainy, windy weather to provide continuous support for other activities like running casing, well completion.

High salinity and humidity.

The influence on offshore operation caused by salinity and humidity in the South China Sea mainly focus on maintenance activities. In the South China Sea, high temperature combined with salinity and humidity greatly increases the corrosion of the structure and equipment on the platform. Corrosion on the platform brings lots of harm to the equipment and result in some potential risk on offshore operations. Corrosion can weaken the structure and lower the safety loading of structure. And in some crucial component such as high pipe line and motor, the rust caused by corrosion may have a great damage on the equipment. The rust inside the motor may cause short circuit and make the motor lose function, which may bring high potential risk to the operation. Many drilling equipment used in offshore operation are designed with anti-salinity to decrease the corrosion. Hence, anti-corrosion as an important activity in maintenance management is performed as daily schedule in most of the platforms.

3.3. Case study

On 14th September, 2009, at 17:32(local time) the FPSO Fai Xian connected to the Buoyant Turret Mooring (BTM) parted 4 of her 8 mooring wires in Typhoon strength wind & seas a drifted off station approximately 700m to the north. There were no reported injuries to personnel in the incident; however, the oilfield had to shut down over half a year due to the failure of FPSO. (CACT Internal report of FPSO Mooring System Failure, 2009)

Sequences of events

12 Sept, 17:30 –Storm “Koppu” was Tropical Depression (TD) and forecasted to go no higher than Severe TS (6m max wave, 50 knot winds). Decision made to keep personnel on board and continue producing.

13 Sept, 08:30 – Storm entered South China Sea as Tropical Storm (TS) status and forecasted to go no higher than Severe TS (6m wave, 50 knot winds). Held TECT meeting. Decision made – no change producing/ personnel

14 Sept, 09:00 – Held regular operational morning meeting. It was reported that edge of storm (TS strength) was entering field area. 48 knot winds being reported at south fields

14 Sept, 14:00 – Storm forecast had changed to become typhoon strength after passing the southern part of the field. Phase II declaration made.

14 Sept, 17:00 – Storm forecast had changed significantly to become typhoon strength while passing the southern part of the field. Maximum sustained winds of 65 knots and 12m wave.

17:10 to 17:32 – FPSO position holding at +/- 25m North off normal station (wind from the south)

18:00 – FPSO 700m off station due North. No significant further drift beyond this point indicating remaining mooring lines holding FPSO in place. Max drift occurred at 20:49 at 723m. BTM position now at 600m North of original position.

Investigation report was made after this incident, and contributing factors and root causes was given as the following:

1. Weather

As the weather was a primary contributing factor in the event and no control measures can be placed on it other than weather forecasting & predictions, it is noted that Typhoon Koppu did not follow the predicted intensity as forecast by 4 independent weather bureaus.

2. Surface Current Speed & A Soliton Event (not terminated as proper condition)

The marine SME's on the investigation team given the available data feel there may have been a strong influence of sea currents on the event; however as no surface current measurement equipment is deployed in the field.

3. FPSO Topside Structure Modifications

Some FPSO topside structures have been modified during dry docking for what concerns crane structure, flare structure, treatment facilities and relevant deckhouse. This may have increased wind load.

3.4. Findings on case study

Firstly, the decision-making board should be human-oriented and consider safety as the first principle when making decision under too much uncertainty. And the integrated procedure and emergency response plan must be executed strictly, and less interference by personal subjectivity should be involved. Further, it is necessary to establish effective typhoon warning system, increase the accuracy of typhoon predictions, and develop effective prevention design criteria for offshore operations and offshore structures under typhoon conditions in order to enhance the capability of typhoon resistance for the facilities at design

phase. In addition, reviewing the criteria of the existed typhoon evacuation plan and making some necessary improvement according to the change of practical situation are important and crucial. Last but not least, decision making should base on optimizing critical offshore activities in terms of comprehensive information like further weather condition, transportation means, logistics support and uncertainties in offshore operations like drilling, POOH, running casing, and cementing job, and avoid performing offshore activities as possible in severe weather condition.

4. Geographical factors influencing offshore operations

4.1. Definition of geographic factors

Geographic factors relate to a specific area and a social or natural environment which influence many aspects including the way people live, the distribution of climate, resources, culture and customs. There are main two types of geographic factors: natural geographic factor and artificial geographic factor. The natural geographic factor refers to climate, location, and landforms, while the artificial geographic factor are regarding to social aspects like language, culture, and customs.

One of the most important factors in natural geographic factors is climate. Climate varies from different regions distinguished by longitude and latitude. For example, climate in north of China is bias to cold and has a lower temperature during the winter, compared to the South of China. And in the South of China, temperature in summer is much higher than the north and the hot weather usually starts from May and ends after November. As for the offshore oil and gas industry, operations in the Bohai Bay are quite different from the South China Sea. These differences which are caused by climate include operational procedure, design of facilities, selection of drilling rigs, transportation and logistics.

Location is another factor influencing the development of offshore oil and gas industry. For instance, the Bohai Bay has an average water depth of about 40m, while the average water depth of the South China Sea is around 1500m. Jack-up rig is the most common drilling equipment used in the Bohai Bay, while the semisubmersible is widely used in the South China Sea due to the deep water in this area. The selection of basement or inventory store is also affected by the location factor. It is very common to see that most inventory stores or basements in offshore oil and gas is located near the offshore in order to conveniently transport to offshore platforms on account of the size or weight of the equipment which will be transported to the platform.

Artificial geographic factors relate to social aspects like language, culture and customs. Food culture as one aspect of culture in the North of China is different from the South. And language in the South of China is quite different from the North, where the local speak mandarin. People from the North usually feel difficult to understand the language like Cantonese and Min Nan language, which is widely spoken by Fujian and Guang dong province in the South of China, when they communicate with each other. Hence, the differences of language, culture and customs, caused by geographic factors have to be considered in logistic support, team building, operation and organization in offshore operations.

4.2. Influence of geographic factors on offshore operations

4.2.1. Preference of drilling rigs

- Water depth

There are mainly four types of drilling rigs, including jack-ups, semi-submersibles, drill-ships and fixed platforms with drilling module. Jack-ups and fixed platforms with drilling module are the preferred drilling rig, suitable for the depths of up to 400 feet, particularly suitable for Bohai Bay. For depths over 400 feet, the preferred rigs are semi-submersibles and drill-ships, which can be used in harsh environment but more expensive than jack-ups.

- climate

Climate has a significant influence on drilling equipment and offshore operations, which require high stability, reliability, maintainability and safety. The same equipment would have different performance at different environment like cold climate and warm climate. The drilling rigs operating in harsh-environment such as strong wind, low temperature, snow storm, and icing environment must be of high reliability, efficiency and safety. For example, in the North Sea, winterized semi-submersibles are the preferred option, which can work in the harsh weather and North Sea's deeper waters, due to their stability and reliability. In warm climates like the South China Sea and West Africa, standard semi-submersibles and jack-ups are optional due to the stable marine environment and unnecessary for winterized facilities.

4.2.2. Influence on design phase.

Climate factor as an important influencing factor must be considered at the design phase when the structure and function of a facility are designed. In cold climate like Bohai bay, winterization of a facility must be concerned. Temperature, wind Chill, snow cover, personnel, and machinery protection are the main concerns in cold climate. How personnel can work in the cold and how safely equipment such as firefighting, evacuation means, alarms, and wind wall can function should be considered at the beginning. There are lots of protective means used in cold climate to maintain the normal function of offshore operations. For the pipe lines in the cold climate, measures by insulation, internal or external heating, circulating, and chemical injection can be taken to avoid freezing. These protection measures need to be involved when designing offshore facilities.

5. Identification of cultural aspects in offshore operations

5.1. Definition and types of culture

The term "culture" is a very broad concept, and trying to propose a rigorous and precise definition is a very difficult thing. Many philosophers, sociologists, anthropologists, historians and linguists have been trying to define the concept of culture from the perspective of their respective disciplines. American Heritage defines culture as the following: "The sum of attitudes, customs, and beliefs that distinguishes one group of people from another. Culture is transmitted, through language, material objects, ritual, institutions, and art, from one generation to the next."

In 1871, Tylor in his book, "Primitive Culture", mentioned culture as "that complex whole which includes knowledge, belief, art, law, morals, custom, and any other capabilities and habits acquired by man as a member of society". It is culture that distinguishes human beings from the Animalia. Generally speaking, culture as a product of the long-form creation is a social phenomenon. And it is also a historical phenomenon with regard to the accumulation of social and historical product. Rather, culture refers to a country or a nation's history, geography, customs, traditions and customs, lifestyle, literature and art, behavioral norms, ways of thinking, world outlook and universal values.

For a company, culture is a set of perceptions or beliefs accepted by an individual, a group of people or organizations. And culture as soft power affects the values, beliefs, and behaviors of an individual or organization from spirit level, and influences the management of an organization or a company. Good corporate culture attracts people from different distinct culture working together and guides their behaviors toward the same goal under the regulation of an organization. In this part, national culture and corporate culture or organizational culture will be discussed.

➤ **National culture**

National culture is the value system, norms, general attitudes, customs, languages, behaviors, and beliefs that exist in the population of a nation. National cultures differ from different countries and regions, and affect the way people think and do business. For example, food culture in China is different from European countries. Chinese choose rice as their main food while the Europeans choose wheat or potato. Hall and Hall (1990) revealed that cultures from the Japanese, Arabs, Mediterranean, and Latin are of high context, which tend to place great emphasis on friends and networks, rather than formalistic in negotiations, comprehension and preferring instead to rely on trust, while low context culture countries like Germans, Scandinavians and Anglo-Saxon countries tend to be more precise, specific, and require more explicit information in order to communicate effectively. Different national cultures have direct impact on regulation making, business policy, and communication manners. National culture is becoming more and more important and valued in the management of organization, because international cooperation and business is prevailing gradually as the development of globalization. People from different countries with different background join in the same team and work together for the same business. Hence, it is necessary for the managers to have a better comprehension of national culture, and the importance of inter-culture and cross-culture communication should be focused in the management of enterprises or organizations.

➤ **Organizational culture**

Ravasi and Schultz (2006) mention organizational culture as a set of shared mental assumptions guiding interpretation and action in organizations by regulating appropriate behavior for various situations.

Organizational culture (or corporate culture) is kind of spiritual and material wealth created by organization under certain conditions, operation and management activities. It includes cultural attitudes, values systems, ethics, codes of conduct, entrepreneurship, history and tradition, and enterprise system. Corporate culture, with the organizational characteristics of spirit, values, philosophy, management systems, employee behavior and corporate responsibility, gradually formed in the development of enterprises, is recognized and

accepted by all the employees in the organization. Further, an excellent corporate culture can be considered as an inexhaustible motive force to promote enterprise development and can provide a good environment for nourishing other cultures like management culture and safety culture, which have significant sense for the development of an organization.

5.2. Safety culture

The concept of safety culture was first introduced in 1988 by the International Nuclear Safety Advisory Group (INSAG), for the safety of nuclear power plants proposed after the Chernobyl nuclear plant disaster in 1986. The attention to the importance of safety culture and the impact of managerial and human factors on the outcome of safety performance has been aroused since this disaster (IAEA, 1991). INSAG in its report 'Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident' (1988) described safety culture as:

"That combination of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance."

Health And Safety Commission (HSC) in 1993 defined safety culture as a product with respect to individual and group values, attitudes, perceptions, competencies, and patterns of behavior that determine an organization's health and safety management.

Berends (1996) argued that safety culture shapes the employees' safety behavior. Safety culture affects the way people think and the behavior they do things. The direct manifestation of safety culture is safety attitude, safety awareness, and safety perceptions, which determine the thinking manner and behavior when they face the tasks with high risk. The initiative safety awareness and attitude can conduct the employees to identify potential hazards positively and regulate their behaviors in the safety management. For example, in offshore oil and gas industry, PPE (personal protection equipment) is the first and basic protection for personnel safety in a work site. Employees with good safety attitude and awareness would wear the PPE all the time even if in the hot weather, but very few employees like uncapping or taking off their gloves in the work site, because they may think occasional uncapping does not matter and have nothing to safety. Again for instance, handling the handrail when up and down stairs is a stipulation applied in all the platforms in South China Sea oilfields. However, someone always breaks the rules, because he or she, who did not experience the falling down accident, may think it is a habitual behavior and unnecessary to do with the rules. A very detailed behavior sometimes can display a person's attitude towards safety. Form the other aspect, it is necessary and important to focus on very detailed issues when creating safety culture and making safety regulations.

As discussed in chapter one and chapter two, high risk is an obvious characteristic in the offshore oil and gas industry. Hence, safety first is the priority principle in any offshore operations. The cultivation of safety culture and the impact of safety culture on an organization and safety performance should be an independent research direction in the management of an organization.

5.3. The importance of culture factors on offshore safety

In 5.2, the concept of the term "safety culture" was discussed; this part mainly focuses on the

elements of culture (Figure 5.1) and importance of culture on offshore safety. Reason (1997) explored the components of a safety culture consisting of just culture, reporting culture, learning culture, and informed and flexible cultures (Figure 5.2). Reason (1997) describes a Just Culture as an atmosphere of trust. People are proactive to provide essential safety-related information under Just culture, but they are also clear about distinguishing between acceptable and unacceptable behavior. Reporting culture or reporting system related to reporting errors, near-misses, and accidents, is carried out by all the level of an organization. Employees in the organization tend to be active to face their errors rather than hide their mistakes.



Figure 5.1 GL Noble Denton’s Safety Culture PROFILER Model (GL Noble Denton, source: <http://www.gl-nobledenton.com/en/consulting/1492.php>)

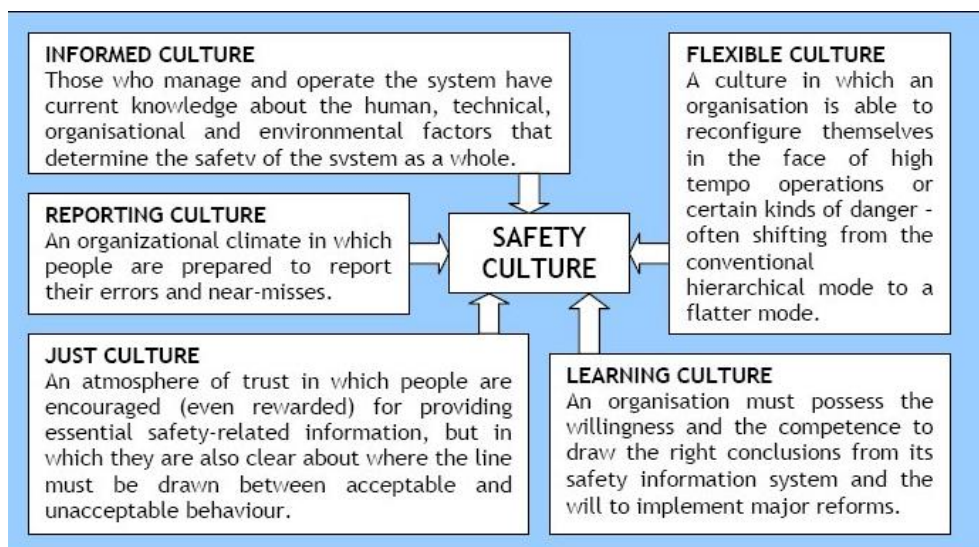


Figure 5.2 The Components of Safety Culture (Reason, 1997), prepared by Global Aviation Information Network (2004)

It’s important to conclude a common sense of safety culture among all the employees at all levels of an organization. The content of a safety culture should consist of a set of core values

and behaviors stressing safety as a priority above cost and production. In other words, the mindset of a safety culture should be human oriented and safety oriented, which is the starting point of any safety culture creating and regulation-making.

However, by reviewing the disasters over the latest 30 years, like Piper Alpha explosion, Bohai No.2 jack-up sinking, Java Sea capsizing, and the recent Deepwater Horizon blowout, causing huge loss of human life, environment pollution and economy loss in offshore oil and gas industry, weaknesses contributing to poor safety culture and safety management are found to be still existed in the management of the organizations, after reports. In terms of reviews of accident reporting, these related contributing factors in poor safety culture and safety management can be summarized as the following.

- 1) Inconsistent creation of safety concept or safety behaviors in leadership.
- 2) Ill-defined understanding of safety culture and its importance of safety culture in the development of an organization.
- 3) The volition of management board bias to production and cost-cutting instead of safety first and human oriented.
- 4) The consequences of hazards and the cost of incidents are not analyzed by the decision level.
- 5) Lack of executive force in performing safety regulations, HSE, and safety behaviors in the management.
- 6) Lower standards and poor commitment to safety goals in the organizations.
- 7) Bad communication culture at all the levels of an organization.
- 8) Poor handover procedure in work shift or crew shift.
- 9) Inadequate allocation of labors and resources, and excessive work load without considering the capability of staffs.
- 10) Passive reporting culture in revealing near miss, potential hazards, and accidents.
- 11) Faulty inspection systems and pre-job safety meeting systems.
- 12) Training shortage on safety behaviors and safety techniques for identifying risk or potential hazards in daily work.
- 13) Absence of training for emergencies and regular safety drill.
- 14) Less reviewing and learning from past incidents, and root causes of incidents are not corrected.

As discussed above, these contributing factors of improving safety culture refined from review of accident reports can be categorized into the following aspects:

Personnel values and mindset on safety culture. As a core value and stating point of safety culture creating, personnel values and mindset on safety culture includes well-defined understanding of safety cultural impact on management by the leadership and employees at all levels, management commitment to safety, risk perception, and volition of management board on safety culture. The mindset of leadership on safety culture plays an important role in creating a safety culture. However, there is a universal phenomenon that the leadership naturally or unconsciously bias to production, short-term for a project, and cost cutting over health and safety.

Safety meeting and safety drill aspects. In offshore operations, meetings in offshore operations including pre-job safety meeting, kick-off meeting, pre-shift meeting and after work meeting, and weekly safety meeting, convey effective information about the procedure of tasks to be executed and analyze the potential risks in the operations. Staffs involved in the

meeting have a clear understanding about the risks in the tasks and tend to take effective risk reducing measures to minimize or avoid risk. Regular safety drills in offshore oil and gas industry play a significant role in training staffs' response to emergencies under kinds of work circumstances. And performing safety drills is also a practical way to cultivate staffs' crisis awareness and risk perception, which can conduct the staffs to nourish safety behaviors.

Procedure and responsibility aspect. Clear and define responsibilities for safety and health at all levels of the organization. To be safe and health must be considered as everyone's responsibility in the organization. Staffs in the organization should have a common sense that reminding and warning on unsafe behaviors is fulfilling the responsibility for personnel safety, family happiness, and environmental safety.

Barrier-free communication at all the levels. Communication between employees should be carried out through all the levels of an organization.

Learning and reviewing systems. Training system in an organization has a positive influence on team building and safety performance. Training is conducive to assistant staffs to identify potential risk positively in the work site and conduct the staffs' safety behaviors to reduce or avoid risk by taking necessary measures. The contents of creating training plan covering all the employees need consists of professional training, skill training, and safety technique training.

Feedback and improvement process. The creation of safety culture is a continuous improving process with an opening system participated by all the employees at all levels of an organization. Further, safety recommendations should be welcomed and the staffs contributing to safety creation should be awarded. What's more, safety performance and communicate results should be publicized to keep efforts and motivation. Employees involved in the organization need to be updated during the process. And they are encouraged to have their voice on safety recommendation and improvement for the safety management system.

5.4. Summary on cultural aspects influencing offshore operations

The importance of cultural factors should be valued and emphasized by the leadership of an organization, and the concept and spirit of organizational culture and safety should be carried out through all the levels of an organization. Safety centered and human oriented should be the core value of safety culture creating.

Nourishing training culture, reporting culture, learning and reviewing culture, communicating culture, and self-checking and supervising culture in a safety culture setting creating and emphasizing the importance of these managerial cultures on the safety culture are important.

Learning and reviewing of accident reports is an effective method to inspect the weaknesses of safety management and identify the contributing factors with respect to managerial aspect and cultural aspect in offshore operations. By leaning from and reviewing the past accidents, self-checking and improvement will be carried out according to the analysis of root causes of accidents, by which the safety performance in offshore operations will obtain great improvement.

6. Application of risk analysis & risk assessment in offshore operations and maintenance

In this chapter, some theoretical knowledge with regards to risk analysis and risk assessment will be prepared and some applications of risk analysis to offshore production installation and maintenance will be discussed. An example coming from Havis and Skrugard oil fields/reservoirs (commonly known as the Johan Castberg field) in the Barents Sea will be introduced to apply the theoretical knowledge of risk analysis and risk assessment to suggest an approach for identifying risk factors.

6.1. Brief introduction of Havis and Skrugard oil fields in the Barents Sea

According to the homepage of Statoil, the Havis and Skrugard oil fields are located 100 km north of Snøhvit and nearly 240 km from Melkøya. The water depth is about 380m. Discovered in April 2011, the volumes are estimated to be around 250 million barrels of recoverable oil equivalents, with a considerable upside potential in the Skrugard. Production was originally planned to start in 2018.

This field is the northernmost oilfield in the present Arctic development portfolio. A series of Arctic problems that should be considered and which will influence the development plan will be faced during the exploit of the oilfield. These challenges include ice and icebergs management, construction and production in extremely low-temperatures, wind and waves, and winterization

The solutions is comprised of a floating production unit, with the capability of separate and storage the oil production of 95,000 barrels per day; and a 280 km pipeline to transport the production from Skrugard to Veidnes outside Honningsvåg.

The main functions of the floating production unit are offered on a platform for the treatment of the oil process.

- Disconnect the risers quickly in emergency condition.
- Separate the oil, water and gas on the facilities.
- Heat all equipment on the unit and insulate the work place.
- Pressurize and heat the oil for the pipeline transport
- The floating production unit, risers systems, and pipeline need special armor protection for the ice and icebergs.

6.2. Identification of hazard events and influence factors in offshore operations and maintenance

Many challenges in the present technological and engineering aspects confine the oil exploration and production in Arctic area.

a) The economic risk.

We know that it requires a huge investment to develop the Havis and Skrugard oilfield. The volatility of crude oil price will cause great impacts on the profit of the company.

b) Challenges of weather conditions.

The weather conditions are much harsher in the far north of the Norwegian Continental Shelf (NCS). The low temperature in the winter will freeze everything on the ocean. The floating unit will be covered by a heavy layer of ice and snow, and wind and waves could increase the ice. And also there will be extreme weather, polar low pressures, snow storms or hurricane, in the winter Arctic.

c) Risk of heating system and thermal isolator failure

In the cold winter, if the heating systems or thermal isolators are failing, there will be a big problem to the whole production process. Due to the extreme cold climate, the crude oil in the pipeline, the compressors, or the storage tanks may freeze and lose the flexibility. Wax formation appears to be a key problem in offshore oil pipelines. Because wax has a strong tendency to agglomerate and to adhere to the pipe wall and thereby plug the pipeline. This will choke the production process and lead to shut down and hazard.

d) Risks related to facility selection and maintenance.

The facilities or equipment used in the oilfield development should be of special design, with the materials withstanding the low temperature and the engineering maintenance design of the reliability, accessibility, maintainability, and supportability. As we know the properties of the steel will be fragile in the lower temperature, or the lube oil, rub, plastic may have different performance.

e) The breakdown time.

This may be a special risk in the cold climate. In the tropic or the temperate zone, it is easy and possible to execute the maintenance and repair, sometimes, outsourcing service may be available in one or two hours from the onshore. However, in the cold climate, it is not easy to get access to the failed equipment because of the ice, or the outsourcing service may be delayed for several days.

f) The pipeline challenge.

The long distance of the pipeline to deliver the oil is a high risk. Not only the pipe installation in the permafrost and lack of geological data and hard soil to trench are difficult, but also the heat of the pipe may affect the permafrost in its operation. The pipe is 280 km; it may need some extra heat or compression station. This will add to the difficulty in monitoring and inspection.

g) Risk of damage on the armored risers

Due to the cold climate, armored risers may not withstand the overload in big waves with ice, which may break the risers. The mooring lines should be armored too. Because the floating icebergs which have a bigger subsea part that may damage the risers and lines.

h) Threat of the oil spill and environmental pollution.

Oil leakage may occur in the process of transportation, pipeline, and oil tank collision. It may

cause much political attention and have a bad effect of the reputation of the company. Also the process waste water and gas should not be directly emitted to the environment.

i) Fire and explosion

Fire and explosion may be the most thrilling incident unacceptable at the offshore facilities, which may cause catastrophic consequences with respect to severe casualty, facility damage and environment pollution.

j) Project delay or failure

The project management needs an integrated plan for the whole work. And the installation and the construction, as well as the drilling work should be managed and organized in the summer and autumn times. Also the outsourcing service, the inspection and maintenance should be arranged during proper weather conditions. Therefore, too much uncertainty will be faced when performing the whole project.

k) Human error risk

Many operational work and maintenance jobs are accomplished by the workers, but humans might have an abnormal behavior in the harsh condition, winter darkness, heavy wind, low temperature, and heavy and slithery ice, which may increase the probability to be hurt or injured in the operation work.

6.3. Severity class in risk analysis

According to Chapter 6.2 above, the main risk and challenges have been identified in the development of the Havis and Skrugard oil fields, Figure 6.3.1. The criticality of the challenge depends on the probability and the outcome. Here a simple risk matrix is used to indicate the severity of the consequences.

		Severity of the sequence				
		Very low	Low	Medium	High	Very high
Probability	Very high		k		b	
	High					c
	Medium		a		f	
	low	d	g	e		j
	Very low	i				h

Figure 6.3.1 Course analysis of risk involved in developing Havis and Skrugard oil fields

From the coarse analysis of severity of consequence above, we can identify the top 5 most critical operations and maintenance challenges.

c) Risk of heating system and thermal isolator failure

In the cold winter, if the heating systems or thermal isolators are at failure, there will be a big problem for the whole production process. Due to the extreme cold climate, the crude oil in the pipeline, the compressors, or the storage tanker may freeze and lose the flexibility. Wax formation appears to be a key problem in offshore oil pipeline. Because wax has a strong tendency to agglomerate and to adhere to the pipe wall and thereby plug the pipeline. This will choke the production process and lead to shut down and hazard.

b) Challenges of weather conditions.

The weather conditions are much harsher in the far north of the Norwegian Continental Shelf (NCS) than further south. Low temperature in the winter will freeze everything on the ocean. The floating unit will from time to time be covered by a heavy layer of ice and snow, and wind and waves could cause ice drift into the area. And also there will occasionally be extreme weather, polar lows, snow storms or hurricane, in the winter Arctic. All the equipment and systems are exposed in the cold climate in the Arctic. The design, construction, installation and operation should take the weather into account. The weather conditions require a higher standard in the design of reliability, availability, maintainability, and supportability.

f) The pipeline challenge.

The long distance of the pipeline to deliver the oil is high risk; see item f of Chapter 6.2

k) Human error risk

Many operational activities and maintenance jobs are accomplished by the workers, but humans might have an abnormal behavior in harsh conditions, winter darkness, heavy wind, low temperature, and heavy and slithery ice, which may increase the probability to be hurt or injured in the operation work.

h) Threat of the oil spill and environmental pollution.

Oil leakage may occur in the process of transportation, pipeline, and oil tank collision. It may cause much political attention and have a bad effect of the reputation of the company. Also the process waste water and gas should not be directly emitted to the environment.

j) Project delay or failure

For discussion, see j above in Chapter 6.2

6.4. Some methods used in cause analysis

6.4.1. Job safety analysis

Job Safety Analysis, also known as a JSA, Job Hazard Analysis, or JHA, is a very effective tool for reducing incidents, accidents, and injuries in the workplace. It is a simple qualitative and effective method helping to identify potential hazards with respect to the activities to be executed. Normally, a JSA sheet consists of task break-down, identification of potential hazards, and risk-reducing measures.

The job breakdown is performed by dividing the main job into several sub-jobs or tasks, which will be analyzed individually. The sub-jobs or tasks will be list in sequence and people involved in the specific operation must be familiar with all the steps of the task. Normally, a work site meeting, which clarify labor-dividing and responsibility, will be hold by the person in charge, and people involved or may be influenced will be informed in this meeting.

Identification of potential hazards is executed to reveal all the potential risks associated with the each step of the sub-jobs or tasks. What kind of hazards will be met and how severe the consequences are will be assessed and categorized in this column, according to the sub-jobs or tasks.

Risk reducing measures are given after evaluating the risks in the second column. Practical measures, requirements and actions will be prepared and announced to the persons involved in this operation to reduce or avoid risk.

Although JSA is a simple and effective risk analysis methodology used in identifying hazards in work assignment, it is a coarse method and usually accompanied by work permission system, which includes isolation sheet, cold work, hot work and entry to confined space. Because the job to be executed may be conflicted with other jobs and may cause risk to other person or system.

6.4.2. FMECA (Failure Mode Effects and Criticality Analysis)

FMECA (Failure Mode Effects and Criticality Analysis) is evolved from FMEA (Failure Mode and Effects Analysis), which has different definitions in different time.

From Wikipedia, An FMEA is defined as “an inductive reasoning (forward logic) single point of failure analysis and a core task in reliability engineering, safety engineering and quality engineering”. It is a systematic techniques used in a system reliability study, by reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. In a FMEA, a specific worksheet will be presented to record the failure modes and their resulting effects on the rest of the system.

Gullo (2012) has defined FMEA as the following:

“A complex engineering analysis methodology used to identify potential failure modes, failure causes, failure effects and problem areas affecting the system or product mission success, hardware and reliability, maintainability, and safety”

FMECA, similar to FMEA, is also a systematic analysis of components and systems or subsystems with the additional quantitative criticality analysis by calculating the criticality of each failure mode. Gullo (2012) stated that FMECA is useful when applied to a design, for assessing the failure modes' criticalities and comparing design failure criticalities with each other and ranking the failures, or determining the criticality relative to a benchmark criticality or threshold level. Criticality in FMECA is used for calculating the RPN (risk priority number), and help to rank the failures according to priorities for taking measures to reduce the risks.

Omdahl (1988) defined FMECA as “a technique used to identify, prioritize, and eliminate

potential failures from the system, design or process before they reach the customer”.

Whatever the definition of FMECA is, the key points in FMECA can be summarized as following:

- Identifying all potential failure modes of the components or the parts of a system
- Identifying the effects that the failures may have on the system.
- Criticality analysis by calculating risk priority number and severity ranking by the calculations.
- Identify mitigating efforts or avoiding the effects of the failures on the system.

6.4.2.1. Types and usage of FMECA’s

There are several types of FMECA’s, which can be used in different situations. The different types of FMECA are presented in the following figure 6.4.2.1.

Types of FMECA	Usage description
System FMECA	Focus on system functions.
Design FMECA	Focus on eliminating failures during equipment design, taking into account all types of failures during the whole life-span of the equipment.
Process FMECA	Focus on problems from manufacturing, maintaining, operating and assembly processes

Figure 6.4.2.1. Types of FMECA

By using FMECA, we can select design alternatives with high reliability and high safety potential during the early design phases by identifying potential failures and the severity of their effects and develop proper criteria for the planning and requirements. FMECA helps to identify the potential influencing factors through the identification of failure modes and severity of the consequences, and formulate proper measures to mitigate the risks in offshore operations and maintenance processes.

6.4.2.2. FMECA methodology

The FMECA includes the following parts:

- 1) FMECA procedure
- 2) Worksheet preparation
- 3) Risk ranking and team review
- 4) Corrective actions

Rausand (2004) lists the main steps of FMECA, The FMECA procedure mainly consists of the following steps:

- a) FMECA prerequisites
- b) System structure analysis
- c) Failure analysis and preparation of FMECA worksheets
- d) Team review
- e) Corrective actions

And the risk ranking is often presented by a risk matrix (as shown in figure 6.4.2.2) or RPN (risk priority number). In the risk matrix, Rausand (2004) considered the risk associated with a failure mode as a function of the frequency of the failure mode and the potential end effects (severity) of the failure mode.

Frequency/ consequence	1 Very unlikely	2 Remote	3 Occasional	4 Probable	5 Frequent
Catastrophic					
Critical					
Major					
Minor					

Acceptable - only ALARP actions considered

Acceptable - use ALARP principle and consider further investigations

Not acceptable - risk reducing measures required

Figure 6.4.2.2 Risk matrix (Rausand, 2004)

Based on Kmenta (2002), the alternative method of risk ranking can be expressed by RPN (risk priority number), where

O = the rank of the occurrence of the failure mode

S = the rank of the severity of the failure mode

D = the rank of the likelihood that the failure will be detected before the system reaches the end-user/customer.

All ranks are given on a scale from 1 to 10. The risk priority number (RPN) is defined as

$RPN = S \times O \times D$. The smaller the RPN the better – and – the larger the worse.

6.4.2.3. Application of FMECA in failure analysis in maintenance management

The Skrugard and Havis assets will have a common infrastructure. Production from Skrugard and Havis is suggested to be tied in to a semi-submersible floating installation through a subsea production system located in about 380 meters (1,247 feet) of water. The oil will be transported through a 280-kilometer (174-mile) pipeline from Skrugard to Veidnes outside

Honningsvåg. It will be piped directly to an oil storage facility and stored in two mountain caverns. (<http://www.greencarcongress.com/2013/02/skrugard-20130213.html>)

Before the oil, produced from the subsea wells, flows into the storage tanker, gas/water separation must be done to keep the stored oil stable. Thus, the separating processing is necessary in the plant. In addition, a boosting system must have the capability to pipe oil from the float facility to the terminal 280-km away. Related to the cold climate, the heating system is necessary to provide process heat. So a gas turbine with heat recovery and recycling unit will be installed.

From the background information, we know that the buffer storage tanks in the fluid transport system are required to provide stable and continuous flow to the next stage or to consumer. The simplified buffer storage tank is presented as the figure 6.4.1.

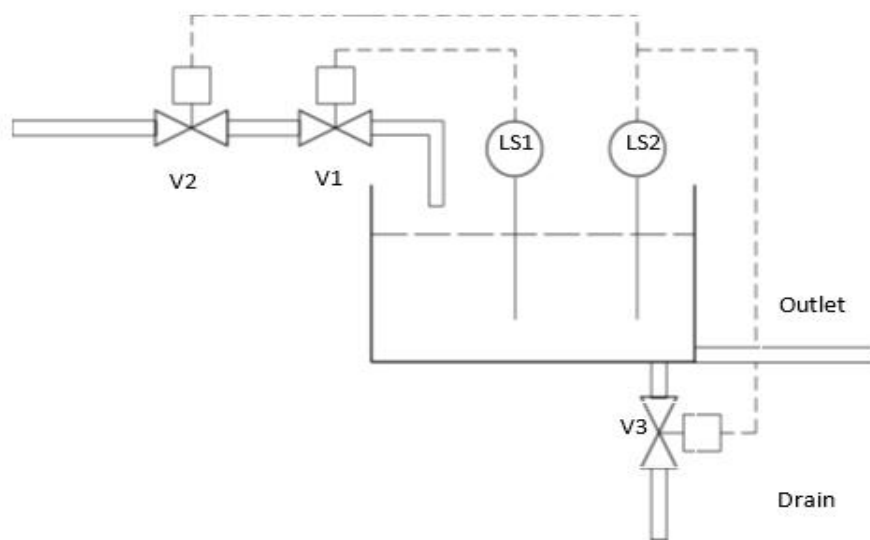


Figure 6.4.1 The simplified buffer storage tank

In this figure, V1, V2, and V3 represent valve 1, valve 2 and valve 3 respectively. LS1 and LS2 stand for liquid sensor 1 and liquid sensor 2 respectively. The level of the fluid in the tank is controlled by the valve V1, V2, V3. If the level is normally high, the level sensor 1 will send a signal to V1 then V1 will close, and the flow stops. If the level is extremely high, the level sensor 2 will send a signal to V2, then V2 will close and V3 will open at the same time in order to prevent the tank to be overfilled.

According to occurrence rankings (Ben-Daya, 2009) in figure 6.4.3 , the severity rankings (Ben-Daya, 2009) in figure 6.4.4 and detection rankings (Ben-Daya, 2009) in figure 6.4.5, the Failure Modes, Effects and Criticality Analysis is presented in figure 6.4.2 and the ranking of undesired consequences by risk number is listed in the figure 6.4.7. Finally, a risk matrix is presented in figure 6.4.8.

Figure 6.4.2 Failure Modes, Effects and Criticality Analysis

Equipment: Buffer storage tank												
Description of unit		Description of failure			Effects of failure		Failure frequency (P)	Severity ranking (S)	Detectability (D)	Risk NO. (P)*(S)*(D)	Corrective measures	comments
Ref. No	Function and Operational state	Failure mode	Failure cause	Detection of failure	On the sub-units	On the system						
1.	Stop the fluid supply when level is normal high. V1 is normally open	Does not close on signal	V1 failure Or get stuck	The LS2 is active and V2 works	LS2 is activated and send signal to V2, then V2 close	The liquid level may increase above limit	6	1	1	6		A
V1		Close when not intended	LS1 sends signal when the level is not high	The level does not increase		No supply from the inlet and no stable flow in outlet	1	4	1	4		B
2.	Stop the fluid supply when level is abnormally high. V2 is normally open	Does not close on signal	V2 failure or get stuck	The level is abnormally high	V3 works	The fluid is drained and no outflow	8	7	1	56		C
V2		Close when not intended	LS2 sends signal when level not abnormally high	The level does not increase while V1 is open		No supply from the inlet and no stable flow in outlet	1	5	1	5		D

3.	Drain the fluid when the liquid level is abnormally high. V3 is normally closed	Does not open on signal	V3 failure	The level is abnormally high and increasing, no drain		Overfill if V2 is not closed	7	8	1	56		E
		Open when not intended	LS2 sends signal while the level is not abnormally high	V1,V2 is open while the level dropping		The fluid is drained and no stable flow to the outlet	1	5	4	20		F
4.	Send signal to V1 if the liquid level is high	No signal sent out when the level is high	LS1 failure	LS2 is activated and V2 is closed	V1 is still open	level may increase above limit if V2 does not close	8	2	2	32		G
		Send signal when level is not high	LS1 failure	The level of liquid not increase and V2,V3 are normal	V1 closes when not intended	No fluid supply from inlet	6	4	2	48		H
5.	Send close signal to V2 and open signal to V3 when the level is abnormally high	No signal out when level is abnormally high	LS2 failure	The level is abnormally high and V2,V3 are normal	V2 does not close and V3 does not open	overflow	8	8	4	264	A spare LS2 should be installed	I
		signal when the level not abnormally high	LS2 failure	level is decreasing and v2, v3 are abnormal	V2 closes when not intended and V3 open when not intended	No fluid supply and no flow from the outlet	6	5	2	60		J
V3												
LS1												
LS2												

Ranking	Failure Rate	Comment
1	1/10,000	Remote probability of occurrence; unreasonable to expect failure to occur
2	1/5,000	Very low failure rate. Similar to past design that has, had low failure rates for given volume/loads
3	1/2,000	Low failure rate based on similar design for given volume/loads
4	1/1,000	Occasional failure rate. Similar to past design that has had similar failure rates for given volume/loads
5	1/500	Moderate failure rate. Similar to past design having moderate failure rates for given volume/loads.
6	1/200	Moderate to high failure rate. Similar to past design having moderate failure rates for given volume/loads
7	1/100	High failure rate. Similar to past design having frequent failures that caused problems
8	1/50	High failure rate. Similar to past design having frequent failures that caused problems
9	1/20	Very high failure rate. Almost certain to cause problems
10	1/10+	Very high failure rate. Almost certain to cause problems

Figure 6.4.3 Occurrence rankings (Ben-Daya, 2009)

Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on Safety, Health, Environment or Mission
2	Very Low	Minor disruption t facility function. Repair to failure can be accomplished during trouble call
3	Low	Minor disruption t facility function. Repair to failure may be longer than trouble call but does not delay Mission
4	Low to Moderate	Moderate disruption to facility function. Some portion of Mission may need to be reworked or process delayed
5	Moderate	Moderate disruption to facility function. 100% of Mission may need to be reworked or process delayed
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. Moderate delay in restoring function
7	High	High disruption to facility function. Some portion of Mission is lost. Significant delay in restoring function
8	Very High	High disruption to facility function. All of Mission is lost. Significant delay in restoring function
9	Hazard	Potential Safety, Health or Environmental issue. Failure will occur with warning
10	Hazard	Potential Safety, Health or Environmental issue. Failure will occur without warning

Figure 6.4.4 Severity rankings (Ben-Daya, 2009)

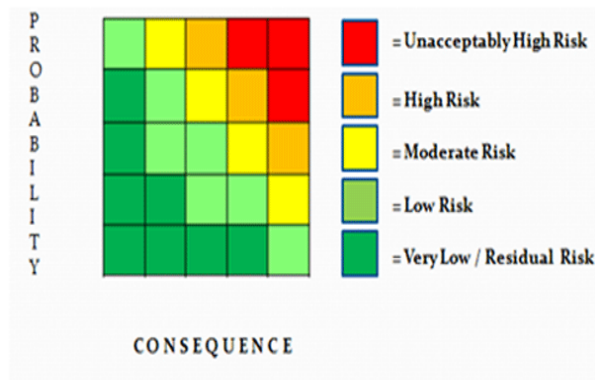
Ranking	Effect	Comment
1	Almost Certain	Current control(s) almost certain to detect failure mode. Reliable controls are known with similar processes
2	Very High	Very high likelihood current control(s) will detect failure mode
3	High	High likelihood current control(s) will detect failure mode
4	Moderately High	Moderately high likelihood current control(s) will detect failure mode
5	Moderate	Moderate likelihood current control(s) will detect failure mode
6	Low	Low likelihood current control(s) will detect failure mode
7	Very Low	Very low likelihood current control(s) will detect failure mode
8	Remote	Remote likelihood current control(s) will detect failure mode
9	Very Remote	Very remote likelihood current control(s) will detect failure mode
10	Almost Impossible	No known control(s) available to detect failure mode

Figure 6.4.5 Detection rankings (Ben-Daya, 2009)

Number	Undesired consequences	Risk number
A	The liquid level may increase above limit	6
B	No supply from the inlet and no stable flow in outlet	4
C	The fluid is drained and no outflow	56
D	No supply from the inlet and no stable flow in outlet	5
E	Overfill if V2 is not closed	56
F	The fluid is drained and no stable flow to the outlet	20
G	level may increase above limit if V2 does not close	32
H	No fluid supply from inlet	48
I	overfill	264
J	No fluid supply and no flow from the outlet	60

Figure 6.4.6 Ranking of undesired consequences by risk number

Risk Matrix:



		Hazard severity				
		Negligible 1-2	Slight 3-4	Moderate 5-6	High 7-8	Very high 9-10
Likelihood of occurrence	Very unlikely 1-2	A	B	D F		
	Unlikely 3-4					
	Possible 5-6		H	J		
	Likely 7-8	G			C E I	
	Very likely 9-10					

Figure 6.4.8 Risk matrix

According to the example above analyzed by FMECA, the top undesirable events and the severity of consequences can be clearly identified by quantitative analysis. The failure modes and the effects on the whole system can also be identified by FMECA. For each undesirable event, other risk analysis methods like FTA (fault tree analysis) and ETA (event tree analysis) will be used to find out the root cause or influence factors in order to propose proper measures to reduce the risks.

6.4.3. Fault tree analysis

From the discussion above in 6.4.2.3, the most undesirable events in this case is overfilling of buffer storage tank. A fault tree analysis is used to illustrate the relation between undesirable events, system failure, components failure, and system barriers. By using fault tree analysis, we can easily find the direct cause and contributors of the top events. In other words, factors contributing to undesirable events can be found by fault tree analysis. In this example, fault tree analysis for the top event “overfilling” will be list in figure 6.4.9.

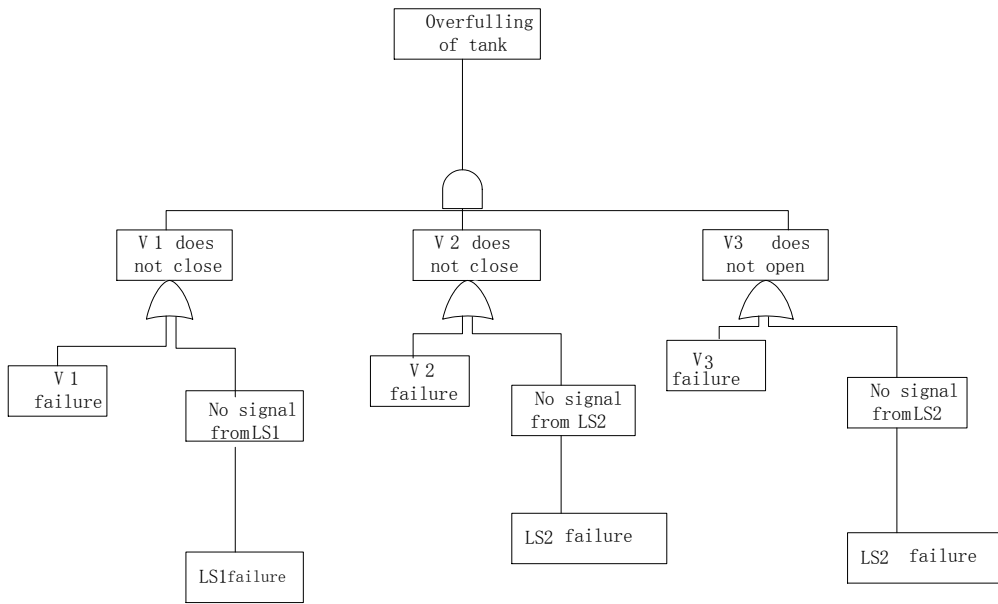


Figure 6.4.9 Fault tree analyses for the top event “overfilling”

The top event “overfilling” can occur only if the three valves V1, V2, and V3 are closed at the same time. And the next level is the possible events that may directly cause top event failure. In this figure above, V1 failure or no signal from LS1 will cause V1 failure. It is similar to V2 and V3 failure. By using fault tree analysis, the factors contributing to failure or risk can be obviously found and improvement for increasing system reliability can be made when we perform maintenance strategy and design a system.

6.4.4. Event tree analysis

From the information above, we know that the production from Skrugard and Havis will be tied in to a semi-submersible floating installation through a subsea production system located in about 380 meters (1,247 feet) of water. The oil will be transported through a 280-kilometer (174-mile) pipeline from Skrugard to Veidnes outside Honningsvåg. Thus, the most undesired event in this situation is oil spill in the arctic. Now the consequence of overfilling will be analyzed by ETA. (As shown in 6.4.9-1)

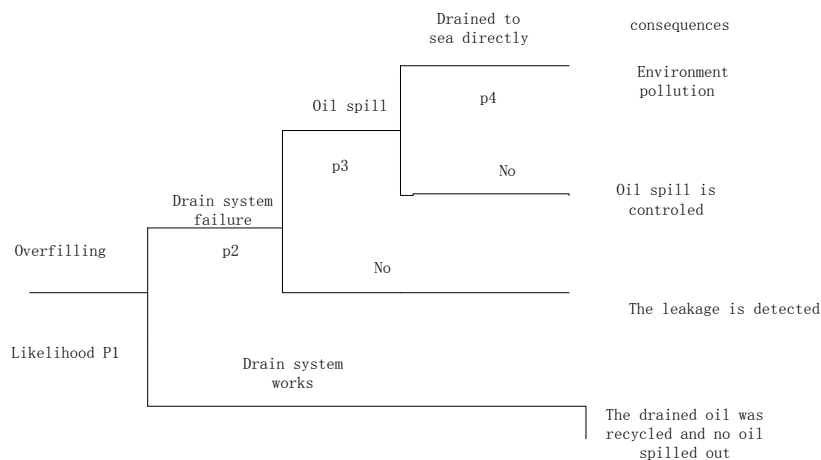


Figure 6.4.9-1 Event tree analysis for overfilling

Here, the P1, P2, P3, P4 denotes the probability of events occurrence. And we can calculate the probability of consequences of the initial event overflowing of the tank if it is assigned specific numbers.

6.5. LCC analysis in offshore maintenance

6.5.1. Life Cycle Costing (LCC):

LCC analysis is an important engineering and economical optimization method applied in the selection of alternatives which are more cost-effective by evaluating relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost over a specific period of time. These factors refer to life time costs, time value, lifetime, uncertainty and risk. LCC, as a useful tool supporting decision-making, is used in selection for machine and equipment and maintenance design alternatives.

Research shows that 60% to 70% of system failure can be attributed to the design and construction, 25-30% to operating procedures, and 5-15% to maintenance (Kumar, 1990), in other words, most of the failure or problems can be tracked down to the design phase. Therefore, RAMS (reliability, availability, maintainability and safety) should be planned and designed into the system from the beginning at the conceptual phase. When designing the equipment or machine, the designers have to consider the work load or profile and working environment the equipment will be subjected to. As for the oilfield we discussed, maintainability and reliability of equipment in cold climate should be designed at the conceptual phase. Some risk and uncertainty also should be considered.

6.5.2. Identification of cost elements

By consulting the “Norsok standard O-CR-002”, (1996) the cost elements included are:

Capital cost: Design and administration cost; Equipment and materials purchase cost; Fabrication cost; Installation cost; Commissioning cost; Insurance spares cost; Reinvestment cost.

Operating cost: Man-hour cost; Spares and consumables consumption cost; Logistic support cost; Energy consumption cost; Insurance cost; onshore support cost.

Cost of deferred production.

6.5.3. Uncertainty and risk analysis in LCC application.

From my perspective, LCC analysis is not only about calculating the visible data collected from the available sources, but also concerning some hidden uncertainties and risk. Some useful tools and methods, such as FMECA, event tree analysis (ETA), fault tree analysis (FAT), and hazard and operability analysis (HAZOP), are introduced in design phase to reduce or eliminate uncertainties and risk.

6.5.4. Assumptions.

Because the LCC costs we will calculate is relevant to many internal or external factors and have different performance under different scenarios, some assumptions must be made when

applying LCC analysis. For instance, we have to consider the discount rate, interest rate, and variation of energy price, materials price, labor costs and lifespan of equipment or project.

6.5.5. Evaluating the results and selection for alternatives.

The results of LCC analysis based on considering lifetime costs, time value of money and uncertainty and risk provide a strong and visualized information support for decision making between possible design or overhaul alternatives, within the limits of the available data.

6.5.6. Application of LCC in selection of spare parts or equipment in offshore maintenance

Let me take a pumping system to illustrate the application of LCC analysis. In the Johan Castberg field concept, the oil produced from the well will be piped to the onshore terminal 280 km away from the float facility. Therefore, a powerful and reliable boosting system must be required. For instance, we have there pump suppliers who have the capability to provide the equipment we required. Here we use A, B, C representing the products of three pump suppliers respectively. Before we settle a purchase, we have to select from the alternatives by comparing their performance, RAMS, and life circle cost.

$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{re}$, where

C_{ic} = initial costs, purchase price

C_{in} = installation cost

C_e = energy costs (considering pump efficiency and energy efficiency)

C_o = operation costs (labor cost of normal system supervision)

C_m = maintenance and repair costs

C_s = down time costs (loss of production)

C_{re} = reinvestment cost

In order to compare A, B, C, at an equal basis, future LCC has to be discounted to present value. Here is a question about the result of LCC. We calculated the LCC by the date given, however, these date are influenced by many factors such as price of energy, relevant products, materials and market risk (discount rate, interest rate), in other words, there are many potential uncertainties existing to affect the calculation. Therefore, uncertainty and risk analysis is necessary in LCC analysis. By doing sensitivity analysis and scenario analysis, we can determine which factors affect the LCC most and chose the alternative from A, B, and C according to the sensitivity and scenario analysis.

7. Discussion

Approach for identifying influence factors in offshore operations

As the huge demand of energy is rapidly increasing worldwide, offshore operations with regarding to oil and gas exploration & production are moving forward year by year. However, incidents related to personnel fatalities, environment issues and big loss of economy accompany the process of offshore operations. To keep safe is the priority that is accepted by any oil companies in the oil and gas industry. Hence, it is necessary and important to realize the potential threats to offshore operation safety and identify the factors influencing factors on offshore safety. As discussed in the thesis, factors influencing offshore operations can be categorized into the environmental, cultural, and regard geographical aspects.

As for environmental and geographical aspects, weather, cyclone, waves, wind, temperature, climate, and water depth are influencing factors to be considered in all phases of offshore operations. From the beginning of design to closure of an operation, analysis of these factors should be involved and analyzed to take risk reducing measures to ensure the safety of personnel, equipment, environment, and operations. Cultural factor is another aspect different from the external sides like environmental and geographical factors. In cultural factors, safety culture and safety climate have a great impact on the safety performance of an organization. Besides, organizational culture and managerial culture are also important parts in culture creating of an organization.

What matters is not only to analyze the influencing factors, but also to establish a systematic method on how to identify these influencing factors and take effective risk reducing measures. An effective mean to identify influencing factors is using risk analysis methods. Qualitative ways such as bow tie picture and risk matrix are parts of the risk expression. As discussed in this thesis, the potential threats or undesirable events in the offshore operations must be firstly identified when we try to find the internal or external influencing factors. And then risk analysis methods consisting of coarse analysis, job safety analysis, cause and consequence analysis, FMECA, fault tree, and event tree analysis can be used to find the root causes and possible consequences of the failures. Contributing factors, consequences, and barriers of an initial event can be revealed during the analysis process.

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