Technology management models for marine seismic acquisition projects

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Beijing, China

LEI LI

李磊

Abstract

A marine seismic exploration project is a high investment project with complex procedures, state of art management models should be implemented to solve the limitations and problems encountered in marine environment projects.

High investments in the seismic exploration need high working efficiency. So the specifics of technology for marine seismic acquisition should focus on how to improve the efficiency of marine seismic exploration,

Marine seismic data acquisition vessels are specialized vessels that towing a number of streamers (cables) and air guns, vessels characteristics and stability are all discussed and analyzed in this thesis.

Management strategy for equipment procurement and management of the spare parts that support the projects are crucial to any projects, they are the safeguard to make sure the marine seismic exploration follows the plan, and effective ways to reduce cost.

An advanced maintenance technology will save lots of money and will be welcomed by all project managers. Maintenance technologies are also discussed in this thesis to give managers a clear concept of equipment replacement, optimize their management.

Risk involved in the acquisition project management shall be emphasized by project managers and executors. Risks methodologies used to analyze risks in marine seismic data acquisitions should be concerned by all managers, in this thesis, we mainly focus on operational risk and environment risk.

Abstract in Chinese

海洋地震勘探项目是一个具有复杂程序的高投入的项目，这个特性决定了我们需要将先进的管理模式应用到项目的实施中，以解决实际操作中遇到的问题。

在地震勘探的高投资需要较高的工作效率，因此，海洋地震数据采集中的关键技术应将重点放在如何提高海上地震勘探的工作效率中。

海上地震数据采集船是经过专门设计的特种作业船，他在作业过程中会一直拖曳电缆和空气枪，作业方式决定了勘探船的独有特性，在本篇论文中，我们着重讨论和分析了勘探船的特性和稳定性。

设备采购和备件管理策略在项目实施中起到了非常关键的作用，这是保障项目顺利实施的基础，同时又是最立竿见影的减少项目成本的方法。

先进的维修技术将节省大量的金钱，因此会受到项目经理们欢迎。先进的设备维护保养理念会使管理人员能够更加深层的了解他们的设备，实现更加优化的管理。

项目管理人员应该在项目实施的过程中加强对项目的风险分析，管理人员应该重视项目风险分析的方法论，这篇论文中着重讨论了操作风险分析和环境风险分析。

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ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
DGPS	Differential Global Positioning System
DNV	Det Norske Veritas
IMO	International Maritime Organization
LCC	Life Cycle Cost
MAZ	Multi Azimuth
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
NAZ	Narrow Azimuth
NPV	Net Present Value
PSI	Per Square Inch
P wave	Primary Wave
PV	Present Value
RAZ	Rich Azimuth
S wave	Share Wave or Secondary Wave
WAZ	Wide Azimuth
VED	Vital &Essential &Desirable

Chapter 1 Introduction

1.1 Background

Marine seismic acquisition, which is used to acquire sub-surface image, has significant impact throughout the life cycle of oil and gas industry. As the increased demand of oil and gas in forward world, the demand of marine seismic acquisition is also increase at the same time.

However, marine seismic is also a high investment industry; the procedure of marine seismic is complex. Under fierce market competition, companies are dedicating to technology innovation and optimal management to improve their competitive position by four driving forces: the demand for high quality of seismic image, survey cost reduction, and environmentally friendly, working safety, personnel healthy (HSE).

As the investor, they always want to receive high quality image of subsurface, especially in areas with complex formation structure. Thus, marine seismic companies who have the ability to acquire high fidelity subsurface image will have advantage to win the bidding in market competition. Recently, many new technology on improve seismic image have already go into production, such as wide and multi-azimuth (WAZ and MAZ) seismic; broadband seismic, besides that, some companies also dedicate to design special vessel and streamers to achieve high quality image.

Seismic companies are dedicating to reduce cost to the greatest extent due to marine seismic acquisition is a high investment industry. During marine seismic project implementation, many ways are considered to address cost issues: such as design a vessel with fuel efficient; equipment procurement management based on life cycle cost analysis; optimal spare part management; effective fleet management and personnel management.

After the oil leakage disaster happened in Gulf of Mexico, companies who work in offshore realize the importance of environment protection. Crews (1994) stated that and equipment. Seismic exploration is the first step in the exploration and development process and usually provides more exposure geographically than other types of operations. If seismic crews demonstrate a proper regard for environmental protection and preservation, it is likely that others who follow to drill the wells, and then develop the necessary production and transportation facilities, will carry out their activities in a similar responsible and professional manner.

In project operation, series methods are implemented to protect the environment, streamer updated from fluid streamer into solid streamer, air gun soft start to protect fishes and animals in the sea and so on.

1.2 Objective and method

The objective of this thesis is to discuss how to improve marine seismic acquisition by technology innovation and cost effective management models. Under the implementation of technology and management models, risk analysis is discussed for marine seismic acquisition, because it is important to realize that risk management is critical for a successful marine seismic acquisition project, such as in the process of streamer deployment and retrieval, working in hazard environment.

The methods are mainly based on my work experience and what I have learned in the University of Stavanger. (UIS)

1.3 The scope of the work

The scope of the thesis will be limited in three dimensional (3D) marine seismic acquisitions, as 3D marine seismic acquisitions stay at a dominant position in geophysical activities. The primary scope of the thesis will be guided by four driving forces: the demand for high quality of seismic image, survey cost reduction, and environmentally friendly, working safety, personnel healthy (HSE):

- Some new technology and researches on improve high quality subsurface seismic data will be recommended in the thesis, such as broadband technology and wide azimuth technology.
- Management models throughout the life of marine seismic acquisition will be discussed, especially in procurement management, inventory management, and spare parts management. Life cycle cost (LCC) analysis is a cost effective method on equipment determination.
- Argue for maintenance technology and demonstrate the benefit of predictive maintenance technology.
- Implement qualitative risk analysis in marine seismic acquisition project to identify risk.

1.4 The structure of the thesis

The organization structure of this thesis will expand with 5 chapters: chapter 2 presents the overview of marine seismic acquisition. Chapter 3 illustrates the vessel characteristics of marine seismic vessel. Chapter 4 is about marine seismic data acquisition procedures and technology management, some management models throughout the acquisition will be detailed discussed. Chapter 5 mainly focuses on the risk analysis that involved in marine seismic acquisition. Chapter 6 summaries the Conclusions and recommendations for cost effective marine seismic acquisition projects

Chapter 2 Overview of marine seismic acquisition

2.1 Introduction and underlying principles

The word "seismic" comes from the Greek word which means an earthquake. It involves earthquake measurement, monitoring and prediction. Measure the energy waves created by the earthquakes and the effect of these waves close to where the earth's crust actually moved during the earthquake. (IAGC, 2002)

As the name suggests, marine seismic surveys use surface-induced seismic pulses to image subsurface formations. Basically, a seismic wave is generated underneath the earth's surface, and then picked up by sensors called "geophones" as the waves bounce off subsurface formations -- that is, layers of rock beneath the surface. This process becomes more complicated when there are hundreds or thousands of feet of water between the earth's surface and the geophones. (Rigzone, 2012)
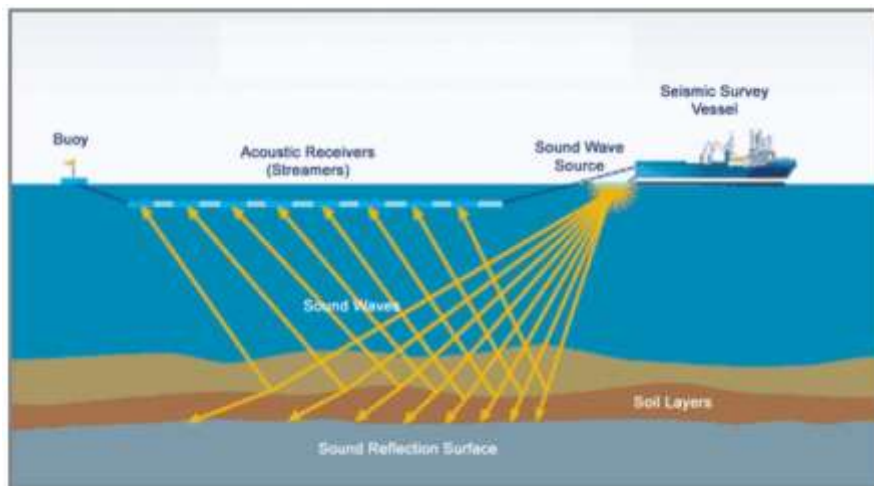
Figure 2. 1 Marine seismic acquisition principle (Odland, 2009a)

During marine seismic acquisition, Figure 2.1, pulses are generated by sources like air guns, water guns and some other kind of acoustic sources. After the pulses penetrate into the subsurface layer, reflection pulses which represent the layer formation will be picked up by geophones attached to the streamer towed by the seismic vessel. Then the information on the streamer will be transferred to the instrument room and stored in the logging system. Because the information picked by geophones is always analog signals, during the process of information transfer, analog signals will be converted into digital information. Digital information can be translated into maps which are used to reflect the structure of the subsurface, these maps help geologists analyze the structure of the survey area and provide the basis which investors can have confidence in decision making.

2.2 Propagation fundamentals

Marine seismic acquisition propagation fundamentals come from the research of earthquakes, from where seismic waves are used to determine the internal structure of the earth. The two main waves are body waves and surface waves. Body waves can travel through the layer of the earth, according to this characteristic, in marine seismic acquisition, body waves are used to acquire subsurface image. In this thesis, we mainly focus on body waves.

2.2.1 P waves theory

The first kind of body waves is called P wave, here P stand for primary, because they always the first to arrive, the P wave can move through solid rocks and fluids.

P waves are also known as compressional waves, because of the pushing and pulling they do. Subjected to a P wave, particles move in the same direction that the wave is moving in, which is the direction that the energy is traveling in, and is sometimes called the 'direction of wave propagation' (UPSeis, 2012). The motions of P waves just like the motion of a spring as figure 2.2 shows below, energy move in the same direction as the spring is moving in.

Figure 2. 2 *P waves simulation* (credit: Tech Museum of Innovation 2012)

2.2.2 S waves theory

The second kind of body waves is called S waves, as an S wave travels slower than a P wave, it is also called the second wave. On the contrast with P waves, S waves cannot penetrate any liquid medium, S waves can only penetrate through solid rock. The motion of S waves is different from P waves, The Tech Museum of Innovation (2012) illustrates that the P waves move in a compressional motion similar to the motion of a spring, while the S waves move in a shear motion perpendicular to the direction the wave is travelling. Figure 2.3 shows a simulation of S wave propagation by kicking a rope.
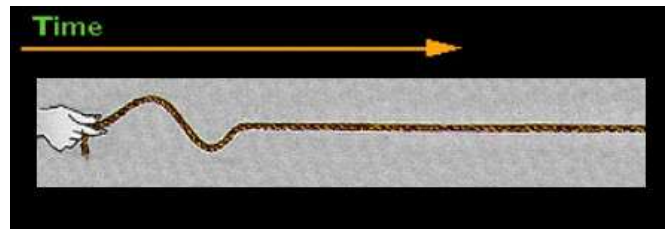
Figure 2. 3 S wave simulation (credit: Tech Museum of Innovation 2012)

In marine seismic acquisition, according to the characteristic of these two kinds of body waves, sea water will only propagate P waves during acquisition.

2.3 Towed marine seismic acquisition methods

With the increase of exploration activities in marine environment, two principal marine seismic acquisition methods are widely used, they are two dimensional (2D) seismic surveys and three dimensional (3D) seismic surveys.

2D can be described as a fairly basic survey method, which, although somewhat simplistic in its underlying assumptions, has been and still is used very effectively to find oil and gas, 2D work dominated in oil and gas until the beginning of the 1980s; while 3D surveying is a more complex method of seismic surveying than 2D and involves greater investments and much more sophisticated equipment than 2D surveying. In the late 1980s 3D surveys become the dominate survey technique with the introduction of improved streamer towing and positioning technologies. (OGP, 2011)

2.3.1 Towed 2D acquisition

During 2D acquisition, the traditional mode of operation is a single vessel which tows a single streamer with a single source (we will discuss streamer and source later). The data acquired are assumed to reflect the subsurface structure beneath the survey line that the vessel followed, and the data are always two dimensions- horizontal and vertical data, that is the reason the term '2D' come from.

Under actual operations, an angle will be generated between the sail line and the streamer due to the impact of current and tides in the sea, for this angle, we refer to the terminology as "streamer feather". Figure 2.4 shows a typical tow method of 2D seismic acquisition streamer and the real shape of the streamer caused by current and tides.
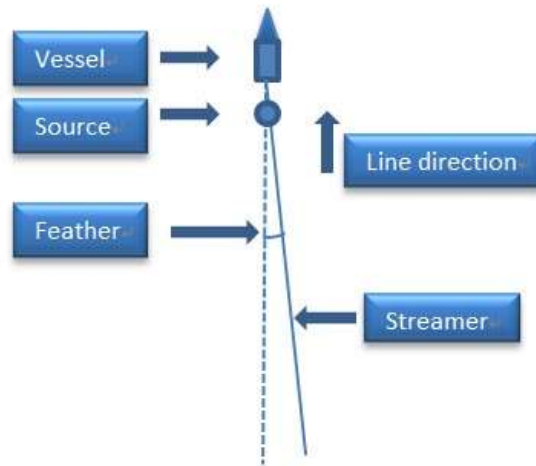
Figure 2. 4 2D acquisition feather

2.3.2 Towed 3D acquisition

Unlike 3D surveys, the traditional 3D marine seismic operation mode is that a special designed vessel tows a set number of streamers with certain sources. 3D seismic acquisitions have greater efficiency and quality than 2D surveys. 3D surveys are more expensive than 2D surveys; 3D produces spatially continuous results which reduce uncertainty in areas of structurally complex geology and/or small stratigraphic targets. (CGGVeritas, 2012)

A 3D survey covers a specific area, generally with known geological targets, which have been identified by previous 2D exploration. Prior to the survey, careful planning will have been undertaken to ensure that the survey area is precisely defined. (OGP, 2011)

In order to achieve the objective of the survey, a map with boundary coordinates and direction of survey lines should be expatiated before the activity of the seismic operation, all acquisition parameters involved in the operation configuration should also be defined.

Normally, survey lines are evenly distributed within the prospect, the separation of the survey lines are designed according to the vessel towing capacity, in other word, the number of streamers of the seismic vessel. Utilize more streamers and more than on source make the 3D survey method more efficient than 2D surveys. It is worth noting that large area surveys (that are over 3000 to 5000 square kilometers) always call for a high capacity vessel which is towing more streamers.

3D surveys are typically acquired as shown in figure 2.5, with a 'racetrack' pattern being employed. This allows adjacent sail lines to be recorded in the same direction (swath), whilst reducing the time necessary to turn the vessel to the opposite direction (OGP, 2011).

Normally, the turning radius of a 'racetrack' pattern is always designed by navigators according to the number and length of the streamers, current and tides, shape of the survey, obstructions. Let us take figure 2.5 for instance, a vessel towed 6 streamers, the distance

between each streamer is 100 meters, and the length of each streamer is 5000 meters; from figure 2.5, we know the turning radius is 4.5 kilometers. According to the 'racetrack' pattern, a prospecting is always divided into several small blocks, in most cases, how to divide the survey is decided by the client's chief and the chief navigator according to customer demand.
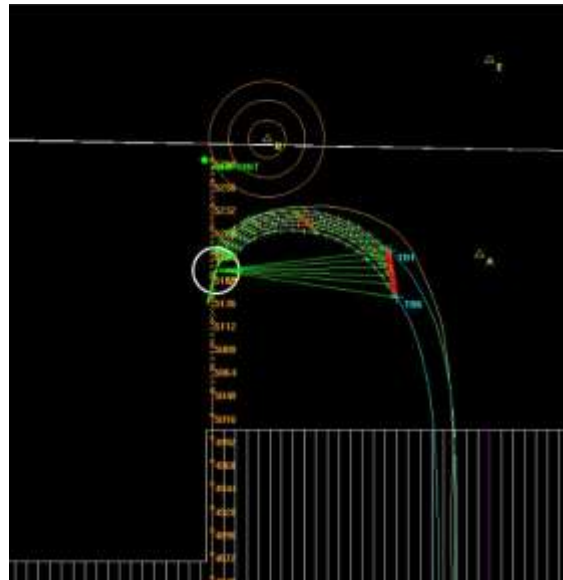
Figure 2. 5 3D survey with a 'racetrack' pattern (credit: HYSY718, GEO-COSL)

Data acquired are always logged by software systems like ORCA and SPECTRA, after processing and interpretation; an image that presents the subsurface structure will help the geoscientist evaluate the probability of the surveyed area to contain hydrocarbons. If the survey is documented as oil bearing structure, these data are also useful in the late stage, after a repeat 3D survey is implemented, these two 3D seismic data acquired at different times over the same area can be used to assess changes in this producing hydrocarbon reservoir. Repeated 3D surveys are also called 4D or 'Time Lapse' surveys.

2.4 Conventional marine seismic equipment

2.4.1 Seismic streamer

The seismic streamer plays a principal role in marine seismic data acquisition. Seismic streamers use hydrophones to detect and receive analog signals reflected from the subsurface, after these signals are received by hydrophones, these analog signals will be converted into electrical signals and then transmitted into the recording system onboard.

OGP (2011) stated that the streamer is mainly made up of five principal components:
● Hydrophones, usually spaced almost 1 meter apart, but electrically coupled in groups 12.5 or 25 meters in length.
● Electronic modules, which digitize and transmit the seismic data.

- Stress members, steel or Kevlar, that provide the physical strength required, allowing the streamer to be towed in the roughest weather.
- An electrical transmission system, which is designed for power to the streamer electronic modules and peripheral devices, and for data telemetry.
- The skin of the streamer in which all the above are housed.

The length of a single streamer is always designed to be 50-150 meters, which makes it convenient for modular replacement of damaged units. In both ends of a single streamer, there is a connector which is used to connect with other streamers; normally the total typical length of streamers is 5000-8000 meters long. Conventional towed streamers are fluid-filled streamers; normally the fluid is organic compound such as kerosene which can make streamers keep certain buoyancy in the sea environment. However, several weaknesses on working efficiency and environment makes that it will be replaced by advanced technology sooner or later:

- Fluid filled streamers are too sensitive to the weather and wave noise, this shorten the working windows especially in some harsh environments such as the North Sea or Arctic areas; and also influence the quality of the data of the subsurface structure.
- Marine seismic acquisition environmental conservation. Even the organic compound fluid in streamer has the characteristic of volatilization, if the skins of streamers are destroyed underwater, the fluid will leak into the sea, and these events will pollute the sea and cause bad influence to the sea animals.
- If fluid leakage happens, the speed of the streamer deployment always slow down by replenishment, sometimes these kind of work will last more than 20 hours, these activities will reduce work efficiency.

With the development of streamer technology, a new type of seismic streamer is moving away from fluid filled streamer into solid streamer, Figure 2.6. In a solid streamer, the organic compound is replaced by special designed foam. OGP (2011) stated this generation of streamer has many advantages in that it is more robust and resistant to damage, does not leak streamer ballast fluid when damaged either on the vessel or in the sea and is less sensitive to weather and wave noise. This has been achieved without reducing the sensitivity of the cable to the reflected signal.

Figure 2. 6 Fluid filled streamer (left) and solid streamer (right)
(credit: HYSY718 and HYSY720 GEO-COSL)

As the weather and the waves always affect seismic activities, the towing depth of streamers is always designed to escape from the influence of bad weather and noise; and is also designed according to the customers' demand. Normally the depth is designed within 6-10 meters.

During marine seismic acquisition, some traditional external devices are always attached on the streamers to achieve functionality, such as the acoustic unit (figure 2.7 left up) which is used to supply position service and compass birds (figure 2.7 down left) which are used to control the depth of the streamer; while lateral-control birds are used to control the movement in the horizontal direction.
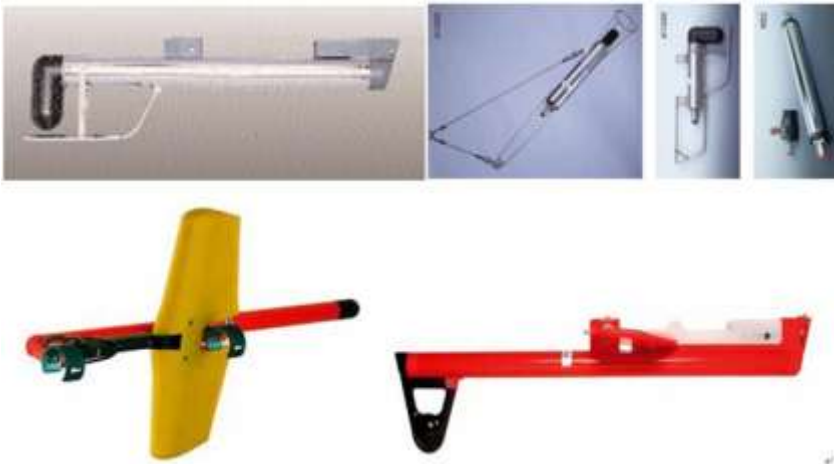
Figure 2. 7 Devices attached on streamers (credit: ION geophysical)

In the end of each streamer there is a tail boy (figure 2.8) used to house Differential Global Positioning System (DGPS) receivers that are used in the positioning solution for the hydrophone groups in the streamers. DGPS is a standard system used for positioning the vessel itself and relative DGPS used to position both source floats and tail buoys (OGP, 2011). As the top right acoustic units shown in figure 2.7, these acoustic are always housed on gun array and tail buoys, connecting with acoustic on streamer and DGPS systems, a specific acoustic network is generated, shown in figure 2.8.
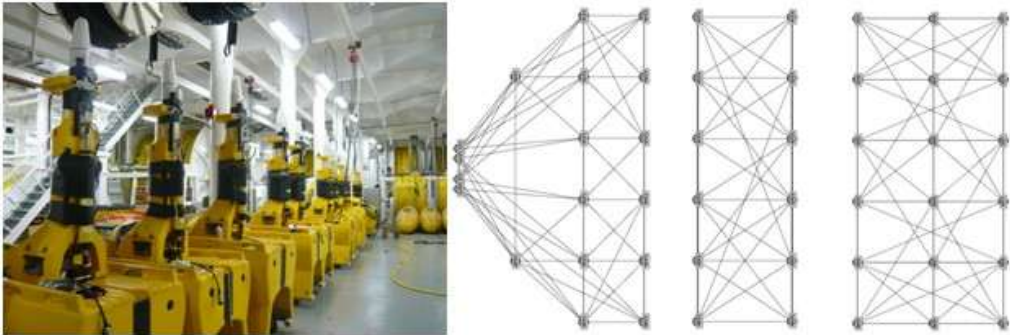
Figure 2. 8 Tailbuoy on board (left) and acoustic network (credit: HYSY720-GEOCOSL)

2.4.2 Seismic sources

In marine seismic acquisition activities, airgun arrays are high frequency used seismic sources. As airgun arrays consist of sub arrays with several multiple airguns, Krail (2010) stated that the airgun releases a high pressure bubble of air underwater as a source of energy to generate the acoustic/pressure waves that are used in seismic reflection surveys.

One type of airgun called G. Gun 150 designed by SERCEL Company is shown in figure 2.9, the operation of this type of airgun can be broken down into three phases: pre-fired phase; fire phase and return phase.
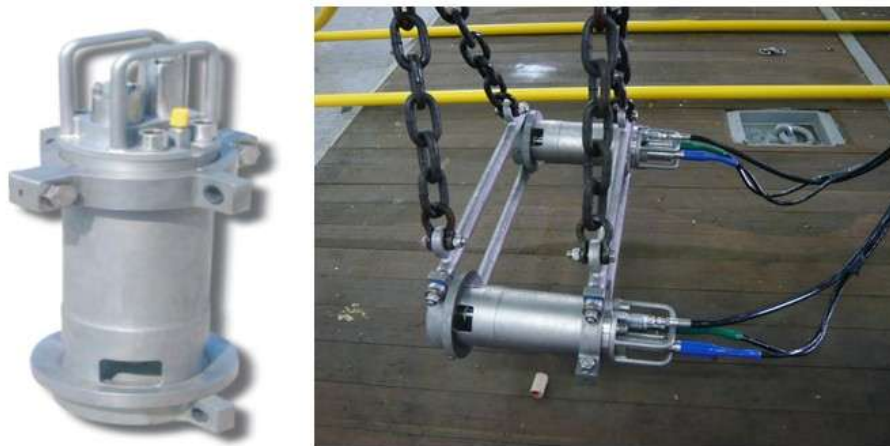
Figure 2. 9 A photo of G. Gun and suspended guns

Figure 2.10（left）describes the pre-fired phase, compressed air fills up the return chamber in the hollow shuttle to close and seal the main chamber. At the same time, the main chamber located between the casing and the shuttle is pressurized. When the solenoid valve is energized (figure 2.10 right), the triggering chamber is pressurized, allowing the shuttle to unseal and the shuttle larger area to be pressurized. The lightweight shuttle quickly acquires a high velocity before uncovering the ports. High-pressure air is then explosively released into the surrounding water to generate the main acoustic pulse (fire phase). When the pressure within the main chamber drops, the still fully pressurized return chamber returns the shuttle to its pre-fired position (SERCEL, 2006).
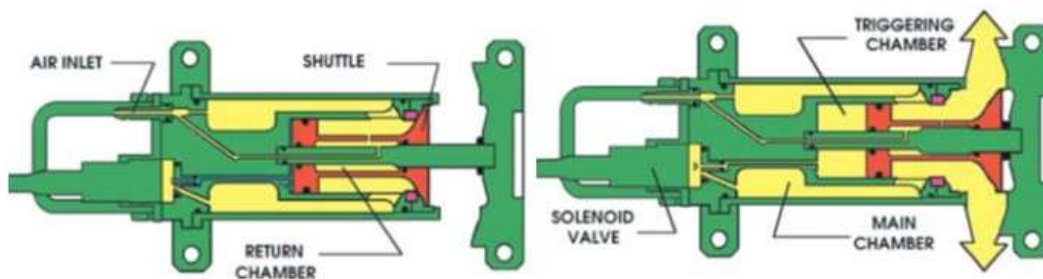
Figure 2. 10 Pre-fired operation and fired operation of airgun (credit: SERCEL company)

As we know, marine seismic sources are made up of sub-arrays, so the output pressure of the source is always proportional to the number and volume of the single airguns. The output of the sources are always different from survey to survey, normally it is designed by customer or client who has invested in the survey. Common surveys are always designed with 2000 to 3000 pounds per square inch (psi) pressure.

As there are several airguns in an array, the distribution and the size of airguns should be specially configured in order to make the source work smoothly. During this configuration, several elements should be concerned such as the interaction of airguns, the stability of airguns and the weather consideration. The depth of the airguns is always 6 meters: Figure 2.11 shows a configuration of airguns.
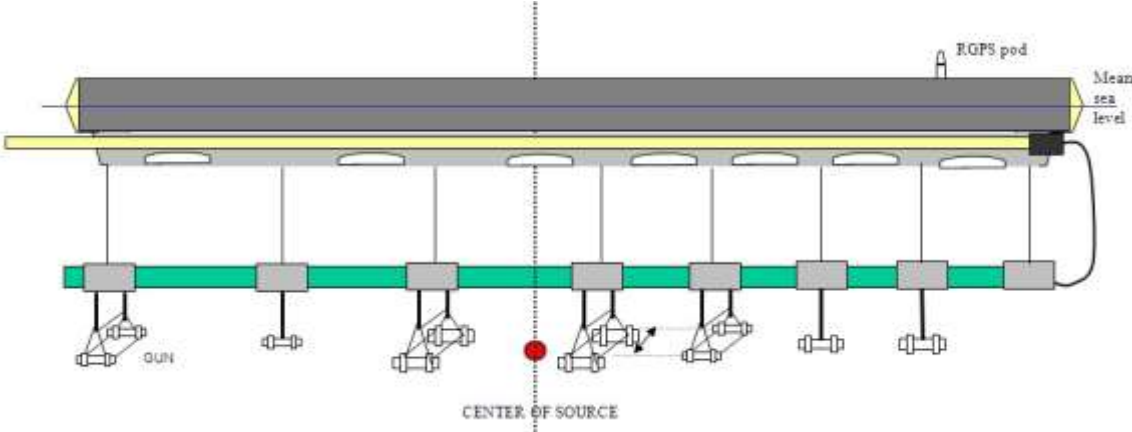
Figure 2. 11 Air gun array configurations (credit HYSY 719, GEO-COSL)

2.5 New developments and advance technologies

As we know, the fundamental goal for marine seismic is to acquire clear images of the subsurface. With marine seismic activities going into ever deeper water, so the R&D activities which are aiming at high-imaging resolutions are always welcome to improve seismic images. In this report, we will mainly focus on new developments and ongoing research in the marine seismic area, from which we can make clear orientation of our business.

In order to acquire clear images of the subsurface structure, it is important to record full range of frequencies, because broader bandwidths are acquired for clearer images of subsurface structures. Recent technologies are dedicated on getting broader bandwidths; several improvements are applied into practice such as the use of solid streamers, De-ghosting technology like novel streamer towing technology, dual-sensor streamers or variable-depth streamers.

2.5.1 Streamer technology improvement

A key element of this towed streamer broadband seismic technique is the streamer itself. Dowle (2006) describes some of the recent improvements in streamer technology. The new generation of streamer electronics can record hydrophone signals as low as 2 Hz, which add additional one or two octaves to the low-frequency end of the spectrum. Another key element is the design of solid streamers which can significantly reduce noise from streamers (Figure 2.12). This is done by isolating the hydrophone sensing elements from the strain member to reduce vibration noise sensitivity and using a solid foam fill which inhibits the transmission of noise wave modes along the streamer. This combination of low-frequency hydrophone recording and reduced noise make solid streamers an excellent platform for broadband recording. An additional advantage for this technique is that the solid streamer has a uniform density, stable buoyancy and is robust enough to operate at extreme depths (greater than 60m). This deep-tow capability facilitates streamer depth profiles which have significant ghost-notch diversity and optimal low-frequency recording (Soubaras et al., 2012).
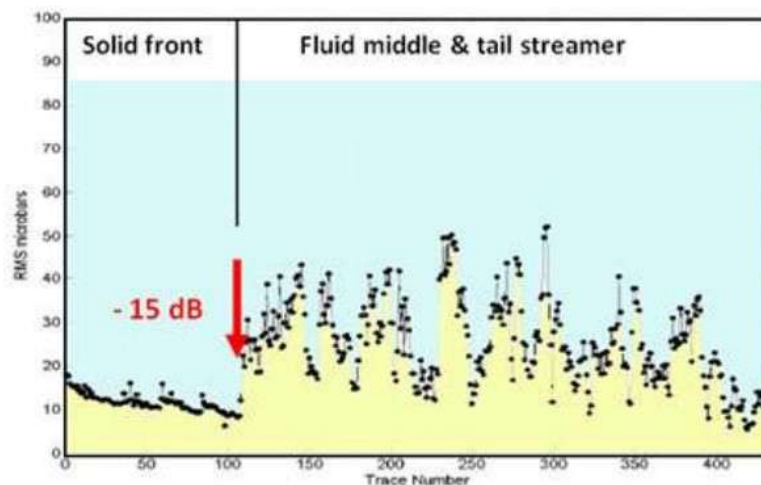
Figure 2. 12 Noise of solid streamer compared with fluid-filled streamer (credit: Soubaras et al*)*

2.5.2 De-ghosting technology

In marine seismic, we expect to have a good condition of the sea surface, which will to a large extent reduce the noise during our operation, however, the surface of the ocean acts as a mirror, which will cause "ghost" effects in recorded seismic data (refer to figure 2.13). The ghost affects both the source and the receiver which will generate source ghost and receiver ghost during a seismic survey, because signal reflected from subsurface will be recorded and interfere with the recording length of the record, these unwanted signals will reduce the quality of the seismic data.
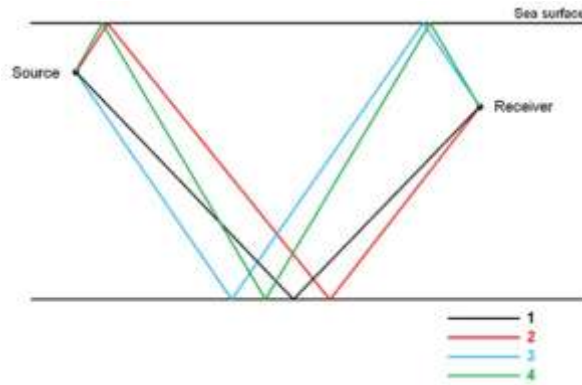
Figure 2. 13 Ghosting effect (credit: PGS)

With the development of De-ghosting technology, methodology like novel streamer towing technology, dual-sensor streamers or variable-depth streamers are widely used by many leading companies. The following figure 2.14 shows a configuration of a novel streamer towing techniques operated by GEO-COSL. The deployed configuration includes a different depth source array (6m and 12m), also with disparate streamer depth. This towing method highly reduces attenuation and increased bandwidth. In 2009, the seismic vessels HYSY718 and HYSY719 from GEO-COSL also implemented this research which clearly demonstrated the benefit of extending the low frequencies to improve deep imaging.
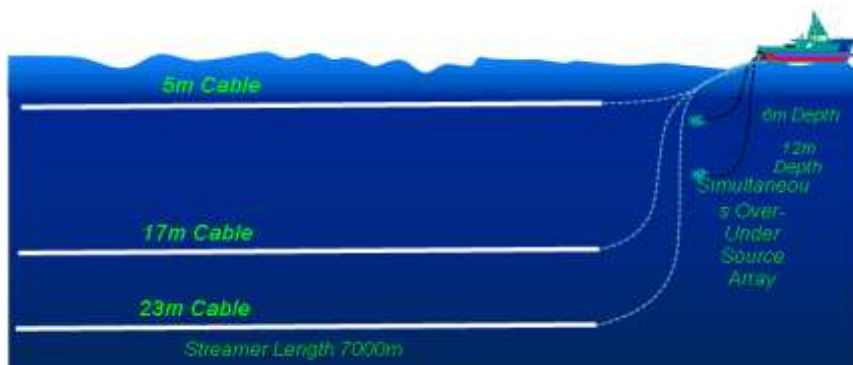
Figure 2. 14 GEO-COSL towing techniques (credit: HYSY 719, GEO-COSL)

2.5.3 More Azimuth Marine Acquisition

3D marine seismic data have traditionally been acquired by a vessel sailing in a series of parallel straight lines. These conventional streamer surveys are called narrow azimuth, or NAZ. This configuration suffers from an inherent problem in that the seismic ray paths are aligned predominantly in one direction. In the presence of complex geology, salt, volcanic layers or carbonates always exit in the overburden. Each of these so-called "penetration barriers" are associated with poor-quality seismic images contaminated with excessive noise, and ray bending can leave portions of the subsurface untouched by seismic waves and only a narrow range of source-receiver azimuths is recorded (WesternGeco,2012).

With the development of advanced acquisition techniques, acquisition methodologies such as multi-azimuth (MAZ), wide-azimuth (WAZ), and rich-azimuth (RAZ) are widely applied to address such illumination problems referred in narrow azimuth acquisition. Because these advance technologies will deliver better information of subsurface structures and improve signal-to-noise ratio during marine seismic data acquisition. In the following parts, we will give an introduction to these methodologies.

2.5.3.1 Multi-azimuth (MAZ)

As we know, narrow-azimuth conventional surveys acquire data with one vessel with 'racetrack' pattern; this kind of pattern is referencing two directions, for instance, $7°$ and $187°$. Multiple-azimuth also uses one vessel but we acquire data in three to six directions. The following figure 2.15 shows a typical multi-azimuth design; the survey was shot in three complimentary azimuths, $7°$, $67°$ and $127°$.
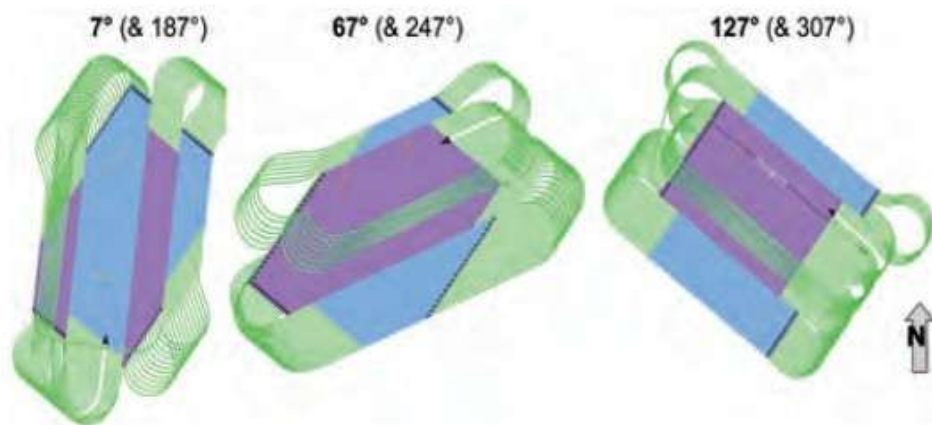
Figure 2. 15 Multi-azimuth planned vessel tracks (credit: WesternGeco*)*

Howard (2007) stated that MAZ has clear operational advantages since only a single source/recording vessel is required. It can be very cost effective because having multiple sailing directions gives flexibility in dealing with weather, currents, waves, or temporary surface obstructions and it eliminates the need for substantial infill. Thus, a MAZ survey with, say, six azimuths will cost much less than six times a conventional NAZ survey. Of course, it may cost nearly six times as much to process. In many areas, it may be a distinct advantage to have independent conventional surveys to processes. For example, small scale anomalies can be very difficult to resolve and build into a single velocity model, as would be required for depth imaging.

However, MAZ still have disadvantages during marine seismic acquisition. Because even when three to six directions' data are acquired, we cannot get full azimuth coverage, one vessel sailing three to six directions will acquire repeated data, which seems not so cost effective for a high investment project.

2.5.3.2 Wide-azimuth (WAZ)

Wide-azimuth is where we acquire data using several vessels, these vessels can be any combination between streamer vessels or source vessels, the source vessels can be configured at the starboard or at the port of the vessels. The following figure, 2.16, is designed by CGGVeritas with six-vessel arrangement; two vessels tow streamers in conjunction with four other source vessels configured at the starboard of these two vessels.
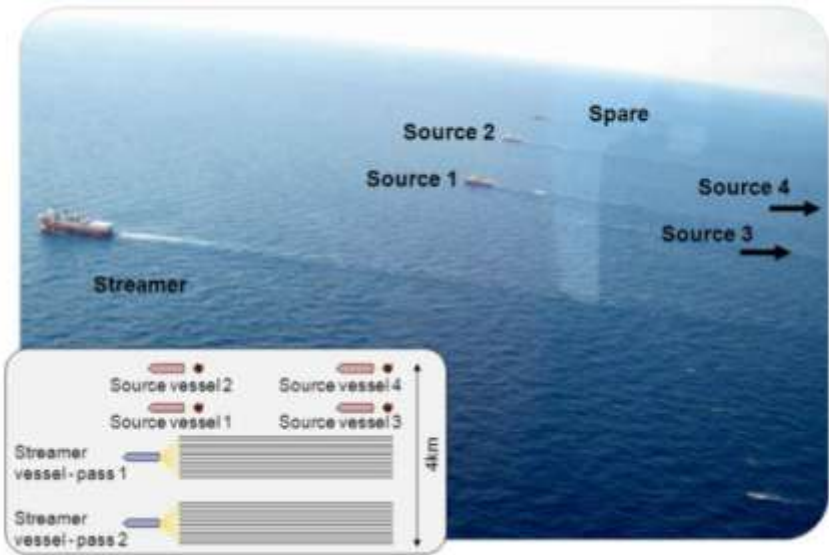
Figure 2. 16 Wide-azimuth seismic (credit: CGGVeritas)

WAZ gives better azimuth coverage than MAZ in one pass, which means, WAZ is an advanced methodology of improving seismic images. However, from figure 2.16 we know that this kind of acquisition will need several source vessels and streamer vessels, so a complicate working system will be needed for data transformation; the complicated system will increase the probability of downtime, which means this methodology may increase the risk of cost.

2.5.3.3 Rich-azimuth (RAZ)

Rich azimuth illustrates the concept: MAZ + WAZ = RAZ, it means the RAZ is a combination of multi-azimuth and wide-azimuth, figure 2.17. The configuration of RAZ is just like WAZ, and makes vessels sailing in multiple directions. Howard (2007) stated that RAZ combines the benefits of MAZ and WAZ and effectively avoids or mitigates many pitfalls. The RAZ design is a robust way to collect essentially full azimuth data in a small area for the purpose of field appraisal and development. It requires little modeling other than to choose the area of coverage needed for imaging at the target levels or to provide evidence that azimuth is a key issue.
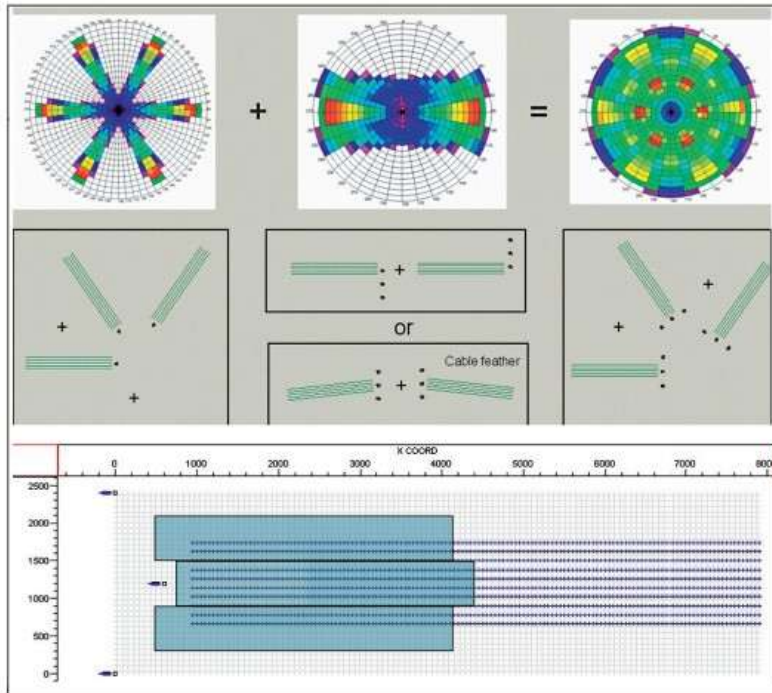
Figure 2. 17 A RAZ survey design (credit: Howard, 2007)

Chapter 3 Marine seismic vessel characteristics

This chapter is intended to provide an overview of marine seismic vessels and their characteristics. Our objective is to discuss how we can design advanced marine seismic vessels through analyzing stability and motions due to waves within a fixed budget.

3.1 What are marine seismic vessels

Sharda (2011) stated that seismic vessels are ships that are solely used for the purpose of seismic surveys in the high seas and oceans. A seismic vessel is used as a survey vessel for the purpose of pinpointing and locating the best possible area for oil drilling in the middle of the oceans.

Figure 3. 1 Seismic vessel HYSY720 from GEO-COSL

As oil drilling activities are high investment project, investors are very cautious to implement their project without acquiring the data about the area they want to drill, because these data that reflect the subsurface structure will give the investors' confidence whether they should drill or not. In this situation, seismic vessels which are used to acquire these data are considered critical. Besides that a seismic vessel is the one that is used to monitor the condition of the subsurface structure.

Along with people who have strong demand for oil and gas, it is indicated that marine seismic survey is a must, Sharda (2011) stated that in fact it can be said that every underwater operation requires a seismic survey with the help of seismic vessels. A seismic vessel is one of those technological developments that have the ability to enable more successes than

failures in fields where losses are far more costly than wins. And for this purpose alone, a survey vessel can be regarded as the pride of modern technological invention.

3.2 Vessel characteristics

Understanding marine seismic vessels is the first step in constructing an advanced vessel, this include general characteristics and vessel movements in the sea environment.

3.2.1 General characteristics

Different vessels have different sizes and shapes according to their functions. Typical physical inventory of marine seismic vessels should include build year and month, IMO number, propulsion type, speed, vessel classification, length, beam width, draft, height, fuel capacity, endurance, transit speed, accommodation, helideck, workboat. Figure 3.2 lists the specifications of Ramform Titan Class vessel from PGS:

Table 3. 1 Ramform Titan Class specification (PGS, 2012)

Name	Ramform Titan Class
Owner	Petroleum Geo-Services
Vessel Classification	DNV +1A1, SPS, ICE C, E0, HELDK, RP,CLEAN DESIGN, TMON, BIS, NAUT-AW,CLEAN DESIGN, TMON, BIS, NAUT-AW,VIBR, COMF-C(3) V(3)
Length	104.2 m
Breadth	70 m
Draft	6.4 m
Fuel capacity	6 000 m^3
Endurance(production/transit)	150 days
Transit speed	16 knots
Main propulsion system	Diesel electric
Propulsion type	Triple CP propeller plant with nozzle and propeller shaft, total 18MW
Engine plant	6 x 3840 kW
Accommodation (single berths)	60 single and 10 double cabins
Helideck	26m 15 t Super Puma/EH-101
Work boats	2 x 30' in stern cradle launching
Streamer winches	24 x 12 000m capacity

In order to achieve more efficient operations, marine seismic vessels have unique vessel characteristics in the following aspects:

- Special designed propulsion system according to the vessel towing capacity. Generally speaking, the towing capacity is increasing with the client's demand.
- Higher acquisition speed and transit speed to improve working efficiency and reduce recovery time.
- Higher fuel efficiency is always welcomed due to this higher investment projects.
- Longer endurance and comfort accommodations onboard.
- Faster streamer deployment and retrieval.
- Higher reel capacity.

3.2.2 Vessel design

With offshore operation properties, marine seismic vessels are integrated and independent. In order to work safely and orderly, equipment and facilities onboard the vessel should be laid out regularly. The basic difference between seismic vessels and other vessels are professional equipment or systems that are used for data acquisition; they are the streamer system, source handling system, towing system and auxiliary system. In the following figure, a seismic vessel designed by Rolls-Royce is shown, with detailed lay out of these systems onboard.
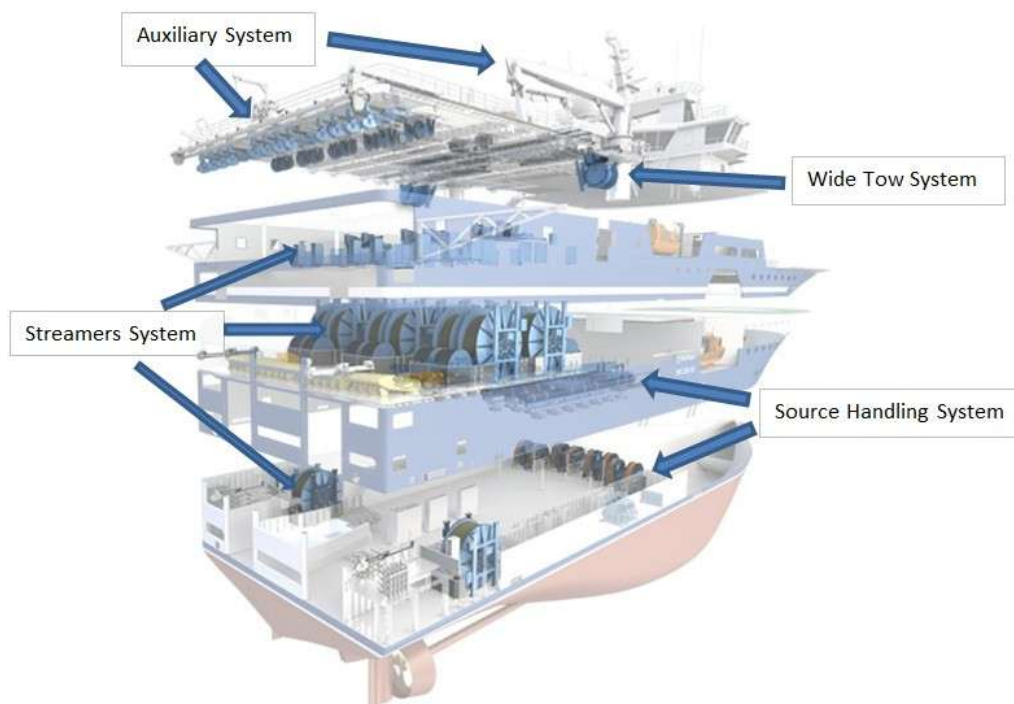
Figure 3. 2 Deck machinery for seismic vessels (credit: Rolls-Royce)

The streamer system and source handling system are core systems of these four systems. The streamer system and source system are always driven by electricity or hydraulic engineering. The streamer system is intended to deploy/retrieve streamers into/from the sea. It consists of streamer winch, spooling device and tow point (with Fairlead Block, see figure 3.3). The

Source handling system is used to pick up/deploy seismic sources from/into the sea. With implantation of science and technology into these systems, now streamer systems and source handling systems have the ability of remote and automated operation.
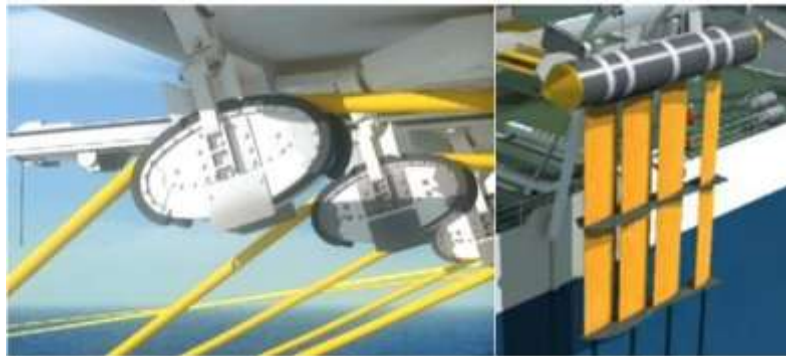
Figure 3. 3 Streamer tow point (left) and paravane (right) (credit HYSY 720, GEO-COSL)

The wide tow system is typically used to deploy and retrieve paravanes (used to extend the interval between streamers). This system mainly consists of towing winch and spooling devices.

The auxiliary system consists of various types of equipment that complements the main system; the auxiliary equipment can be delivered as a system and be integrated in the control system or delivered as standalone units. The system comprises the following units: Auxiliary winches, storage winches, spread rope winches, spooling racks, HP Air manifold, rope/wire blocks, various types of floats, handling booms, transverse multi-purpose winches moving vessel profiler, hydraulic power units (Rolls-Royce, 2012).

3.3 Vessel movements

A seismic vessel that is working in sea is always subject to the outer forces from winds, waves, currents and forces from streamers and sources and other equipment in the sea water. Generally speaking, all vessels in the sea will involve three types of linear motion: surge, sway and heave; and three types of rotational motion: roll, pitch and yaw, these types of motion are shown in figure 3.4. We should know that all these six types of motion are mainly generated by sea waves.
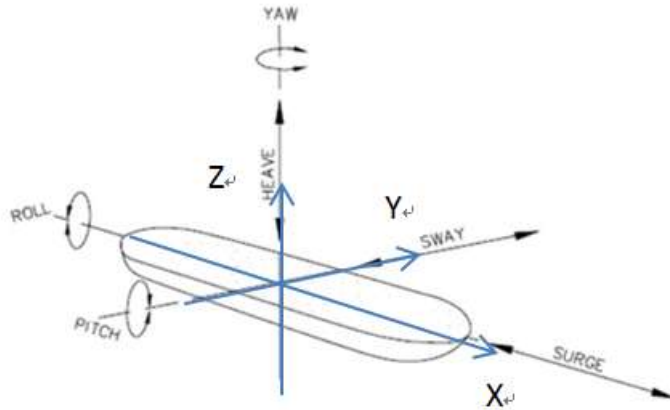
Figure 3. 4 Forces working on vessel (credit: USACE National Economic Development)

From figure 3.4 we know that rolling and surging moves around X axis. Rolling happens when waves strike the starboard or port side of the vessel, it is side to side movement; while surging happens when waves strike one end of the vessel, the vessel will be pushed in the direction of the wave.

Pitching and swaying moves around Y axis. Pitching happen when wave crest strike bow of the vessel, which will cause bow is lifted and stern is lower. Pitching is a rotary movement around Y axis. Swaying happen when wave strike the starboard side of the vessel, it will cause the vessel move in the direction to the port side, swaying is a linear movement.

Just like we discuss four movements upside, heaving and yawing moves around Z axis. Heaving happens when wave come from the bottom of the vessel, which make vessel moves up with the same direction of the waves, it is a linear movement; yawing happen when waves come from bow on starboard side, the vessel will be generated a rotary movement around Z axis.

3.4 Marine seismic vessel stability consideration

Under any circumstance, vessel stability is a fundamental principle to guarantee that the vessel will perform daily activity safely. Ship Hydrostatics (2002) stated that stability is the ability of a body, in this setting a ship or a floating vessel, to resist the overturning forces and return to its original position after the disturbing forces are removed. Actually, stability is to balance idealized ship weight against the external forces. According to Ship Stability (1997), these forces may arise from weather phenomena such as wind and waves, or from tow lines, shifting of cargo or passengers, or flooding due to damage.

Most seismic vessels are used for the purpose of marine seismic survey in deep sea and oceans. A marine seismic vessel is always special designed according to its functions. During seismic acquisition, these vessels always tow many streamers in the sea. In order to achieve convenient streamers deployment and retrieval, seismic vessels have wider stern than normal vessels, (see the following figure 3.5), which make marine seismic vessels especially need good initial stability.

Figure 3. 5 A marine seismic vessel (PGS, 2012)

O.T.Gudmestad (2012) has stated that initial stability is required for a small deviation from the original position; it means that the vessel will go back to its original position when the outer force goes away. From figure 3.1 we see that this marine seismic vessel can be considered as a triangular vessel, in the following part I will use knowledge learned from the Marine technology and design course at University of Stavanger to find the formula for the initial stability of this triangular vessel.

According to DNV (one of the world's leading classification societies) rules for classifications of ships, typical requirements for barge transport as shown in table 3.2, here GM is the distance from the center of gravity to the metacenter. DNV Rules for Ships, which announced in January 2005 demonstrated typical requirements for barge transport, see table 3.2:

Table 3. 2 Typical requirements for barge transport (DNV, 2005)

	Freeboard (f)	$\overline{GM}$
Inshore transport (In fjords)	0.2 m	0.15 m
Offshore transport (Open sea)	0.5 m	0.30 m

Now let us look at a vessel model shown in figure 3.6 (left), in order to achieve a simple analysis of the initial stability of the marine seismic vessel. We assume this vessel with all sides equal to a value b, the hull draft is d, the height is h and the total weight M, the vessel is designed as having its weight uniformly distributed, let us try to find the formula for the initial stability of this vessel.
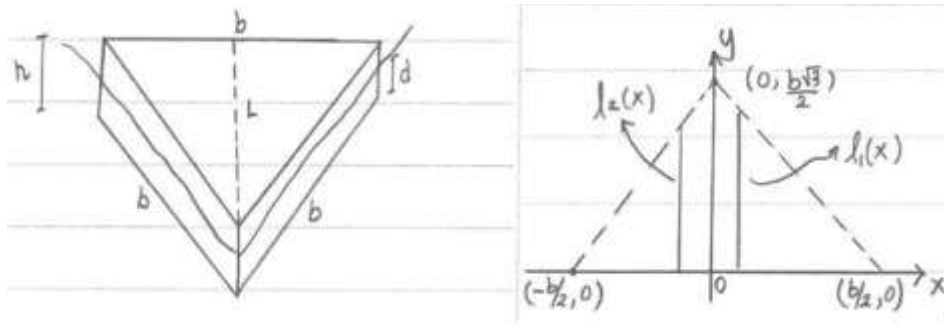
Figure 3. 6 A marine seismic vessel model
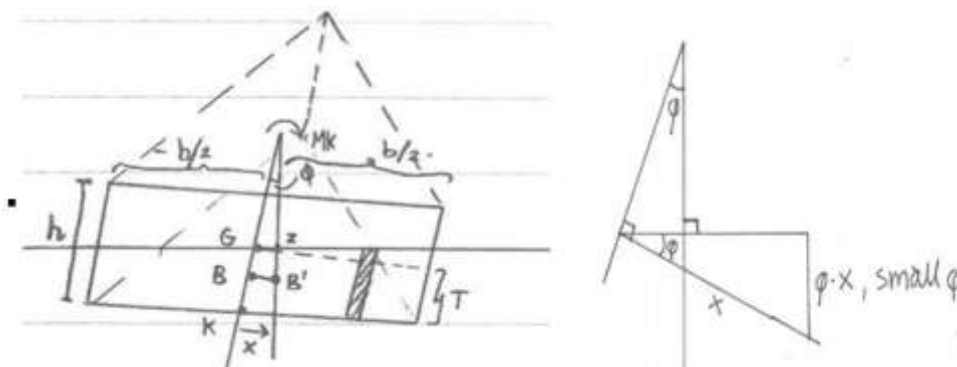
Figure 3. 7 Vessel stability analysis

For this analysis, we consider the inclined vessel in figure 3.7, here we have:

• B is the original position of the center of buoyancy

• G is the center of gravity

• ϕ is the angle of inclination

• B is the center of buoyancy in inclination mode

• K is the keel

• M_k is the moment causing the inclination

The metacenter radius $\overrightarrow{BM}$ is the distance between the center of buoyancy B and the metacenter M, whereas the metacenter height $\overrightarrow{GM}$ is the distance from the center of gravity to the metacenter, we mainly focus on the center of gravity to the metacenter $\overrightarrow{GM}$, as we know when $\Phi \rightarrow 0$, $\sin\Phi = \tan\Phi \approx \Phi$, and $\cos\Phi = 1$, hence:

$$\overrightarrow{BB'} = \overrightarrow{BM} \cdot \sin\Phi \approx \overrightarrow{BM} \cdot \Phi$$

$$l_1(x) = \frac{b\sqrt{3}}{2} - \sqrt{3}x, \; l_2(x) = \frac{b\sqrt{3}}{2} + \sqrt{3}x$$

First, let us consider the term $\overrightarrow{BB'} \cdot \rho \cdot g \cdot \nabla$, from geometry, we have that:

$$\overrightarrow{BB'} \cdot \rho \cdot g \cdot \nabla = \int_{-\frac{b}{2}}^{0} \sqrt{3}x \cdot \rho \cdot g \, (T + x\Phi)\left(\frac{b}{2} + x\right) dx + \int_{0}^{\frac{b}{2}} \sqrt{3}x \cdot \rho \cdot g \, (T + x\Phi)\left(\frac{b}{2} - x\right) dx = \sqrt{3} \cdot \rho \cdot g \int_{-\frac{b}{2}}^{0} (\frac{b}{2}Tx + Tx^2 + \frac{b}{2}\Phi x^2 + \Phi x^3) dx + \sqrt{3} \cdot \rho \cdot g \int_{0}^{\frac{b}{2}} (\frac{b}{2}Tx - Tx^2 + \frac{b}{2}\Phi x^2 - \Phi x^3) dx$$

$$= \sqrt{3} \cdot \rho \cdot g \, (\frac{bT}{4}x^2 + \frac{T}{3}x^3 + \Phi\frac{b}{6}x^3 + \frac{\Phi}{4}x^4)_{-\frac{b}{2}}^{0} + \sqrt{3} \cdot \rho \cdot g \, (\frac{bT}{4}x^2 - \frac{T}{3}x^3 + \Phi\frac{b}{6}x^3 - \frac{\Phi}{4}x^4)_{0}^{\frac{b}{2}}$$

$$= \sqrt{3} \cdot \rho \cdot g \, (-\frac{bT}{4}\frac{b^2}{4} + \frac{T}{3}\left(\frac{b}{2}\right)^3 + \Phi\frac{b}{6}\left(\frac{b}{2}\right)^3 - \frac{\Phi}{4}\left(\frac{b}{2}\right)^4 + \frac{bT}{4}\frac{b^2}{4} - \frac{T}{3}\left(\frac{b}{2}\right)^3 + \Phi\frac{b}{6}\left(\frac{b}{2}\right)^3 - \frac{\Phi}{4}\left(\frac{b}{2}\right)^4$$

$$= \sqrt{3} \cdot \rho \cdot g \, (\frac{b^4\Phi}{48} \cdot 2 - \frac{b^4\Phi}{64} \cdot 2) = \sqrt{3} \cdot \rho \cdot g \, \frac{b^4\Phi}{96}$$

Here ∇ is the submerged volume of the vessel, we have $\nabla = \frac{1}{2}\left(b \cdot \frac{\sqrt{3}}{2}b\right) \cdot d = \frac{\sqrt{3}}{4}b^2 d$

So: $\overrightarrow{BB'} \cdot \rho \cdot g \cdot \frac{\sqrt{3}}{4}b^2 d = \sqrt{3} \cdot \rho \cdot g \, \frac{b^4\Phi}{96}$ we get $\overrightarrow{BB'} = \frac{b^2\Phi}{24d}$

$$\overrightarrow{BB'} = \overrightarrow{BM} \cdot \sin\Phi \approx \overrightarrow{BM} \cdot \Phi$$

We know $\overrightarrow{BM} = \frac{\overrightarrow{BB'}}{\Phi} = \frac{b^2}{24d}$ $\qquad \overrightarrow{KB} = \frac{d}{2}, \qquad \overrightarrow{KG} = \frac{h}{2}$

$$\overrightarrow{GM} = \overrightarrow{KB} + \overrightarrow{BM} - \overrightarrow{KG} = \frac{d}{2} + \frac{b^2}{24d} - \frac{h}{2}$$

As we know, GM is the distance from the center of gravity to the metacenter, according to typical requirements from DNV rules, if vessels transport is in open sea, after check on this figure from the DNV roles, $\overrightarrow{GM}$ should meet the need that

$$\overrightarrow{GM} = \overrightarrow{KB} + \overrightarrow{BM} - \overrightarrow{KG} = \frac{d}{2} + \frac{b^2}{24d} - \frac{h}{2} > 0.3m$$

This formulate demonstrate the relationship among draft, side and height. Design of vessel geometry should be based on this formulate when investors want to follow DNV standard.

3.5 Vessel operational constraints

Unlike other vessels, marine seismic vessels tow amount of underwater equipment, the length of streamers are several kilometers long, the width normally more than one kilometer, under this condition, marine seismic vessel have some constraints during data acquisition.

3.5.1 Turning radius constraint

As we stated above, streamers towed behind a seismic vessel are always several kilometers long, if the vessel need to turn to another direction, it is definitely different from other kind of vessels; during turning, an appropriate radius is needed to help underwater equipment keep in a safety position, that is why marine seismic data acquisition should follow a racetrack pattern. Normally the turning radius is rough estimated according to the length of the streamers, for example, if the streamer is 5 kilometers long, the turning radius with 2 kilometers is appropriate.

3.5.2 Vessel speed constraint

During marine seismic acquisition activities, we ask for a faster transit speed, which will save time for a high investment project, while to a certain extent, the acquisition speed is restrict by a specific acquisition parameter such as a given acquisition length, too fast speed will cause data lose.in some manual specification, acquisition speed cannot be exceed 5 knots (1knot =1.852 kilometer/hour).

3.5.3 Ambient environment constraint

Every investor call for an ideal acquisition area during acquisition, however, deal and reality always has a gap, almost every survey will be influenced by ambient environment, which will slow down vessel acquisition efficiency.

Fishing activity in the survey is major challenge for data acquisition, this will highly constraint vessel operations. If fishing activities involve in marine seismic survey, under water equipment will be damaged if they entangle with fishing net or auxiliary equipment, probability of physical confrontation will be increased between fishing personnel and acquisition personnel, even acquisition personnel undertake notification to fishing personnel, sometimes, acquisition vessel need to slow down the speed to wait fishing activities, which will lower working efficiency.

OGP (2012) summarized that the presence of shipping in the survey can restrict vessel operations due to physical access constraints such as proximity to harbors, data acquisition in shipping lane area such as the English Channel, or due to excessive noise contamination from other vessels. The effect of such vessel noise can require portions of the recorded data to be re-recorded, which necessitates the vessel repeating a sail line. Although seismic vessels are flagged to indicate that they are towing equipment in the water, and employ guard vessels to try to ensure that other vessels do not sail across the submerged streamers, other vessels do not always respond and the depth control bird have to effect and emergency dive to lower streamer below the keel depth of the transgressing vessel when this happens, this results in

data acquisition having to be aborted and the vessel having to circle to re-acquire the line, starting some distance back from where the incident occurred to ensure proper overlap of subsurface data coverage.

Fixed obstacles such as drilling rigs or platforms in and around the survey are also constraints for vessel operations. For these kinds of obstacles, seismic vessel has to escape from these obstacle in order to make the underwater equipment safe, this will cause a data lose near the obstacles

The seismic interference from other seismic vessels in ambient area is also vessel constraint during operation. The degree of influence by seismic interference depends on the direction and source energy of ambient vessels.

3.6 Class notation for seismic vessels

In the summer of 2012, DNV announced a new class notation for seismic vessels after consulted with three leading geophysical companies WesternGeco, PGS and Fugro-Geoteam. The new notation focuses on the requirement to hull arrangement and hull strength, as well as certification requirement of system and equipment; all of these will increase the availability of the vessels' operations.

The class notation has taken the DNV concept for redundant propulsion one step further so that any failure on board will not lead to loss of more than 50 per cent forward trust. This is sufficient to maintain a minimum speed of a few knots and will protect any high cost air guns and streamers deployed (Richardsen, P, W., 2012).

In the new class notation, from pipe arrangement to pressure relief valves arrangement, all parts in the high pressure systems are all given specific instructions, all of which are used to ensure safe deck operations.

For more details about class notation for seismic vessels, please refer to appendix 2: DNV Class notation of seismographic research vessels.

Chapter 4 Acquisition project management

In order to achieve an effective marine seismic data acquisition project, some project management models are recommended. In this chapter, we mainly discuss some models used in project initiation, procurement, operation and maintenance.

4.1 Creating a project network

During marine seismic data acquisition, many activities are involved in the project. Defining the logical relationships between these activities will save time and budget, especially for this high investment acquisition project. In this part, we will therefore discuss how a project network will save time and budget in the acquisition project. We assume the duration of every activity has already been estimated (normally we use historical data for the, time the activity takes or we use a probabilistic method). Under this assumption, we define activity dependencies and create a project network.

4.1.1 Sequencing activities

Gardiner, P, D (2005) suggested a method to define the logical relationships between activities. If activities in the project are independent of each other and can be done at the same time, these activities are sequenced in parallel (see figure 4.1(a)), if these activities are dependent on each other and must follow one after the other, these activities are sequence in series (see figure 4.1(b)).
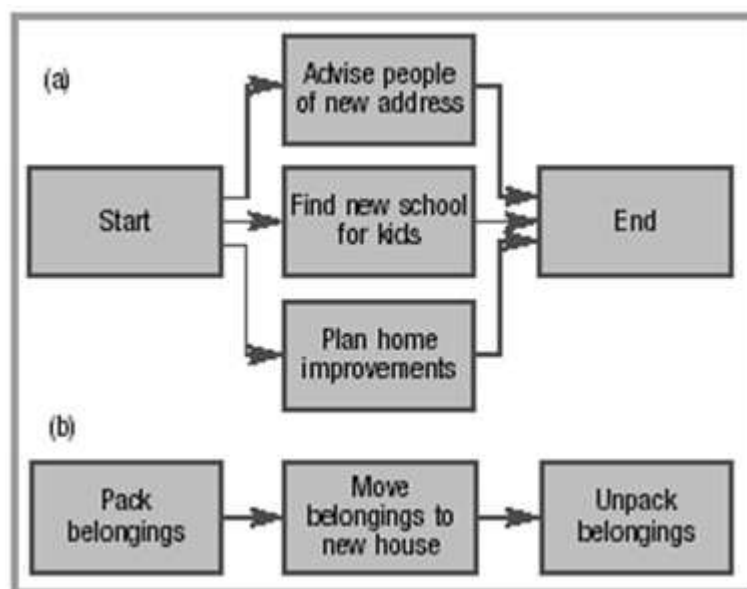
Figure 4. 1 Relationship between activities (credit: Gardiner, P, D)

4.1.2 The network diagram

Gardiner, P,D (2005) stated that a network diagram not only shows the relationships between activities but can be used to reveal which activities are time-critical, and so warrant greater management attention. So a network diagram is very important for a project management.

Before we draw a network diagram, we should know that each activity should have seven attributes as shown in figure 4.2, activity name and code, earliest start time, duration, earliest finish time, latest start time, float/slack, latest finish time. This box which is used to display these attributes is called the activity box.
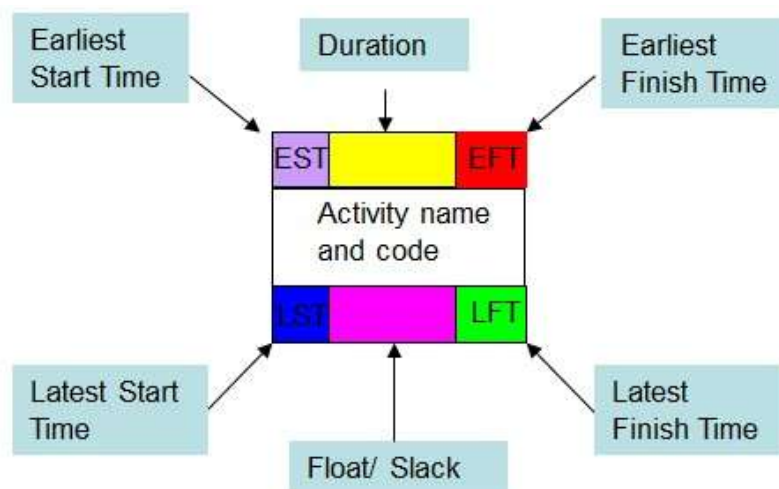
Figure 4. 2 Standard labelling for an activity box (credit: Gardiner,P,D)

Now, there is one consideration before we draw a diagram, how many kinds of relationships are there between activities? Totally there are four relationships between activities (for example between A and B), they are finish-to-start; start-to-start; finish-to-finish and start-to-finish, and the diagram of relationships is shown in figure 4.3.
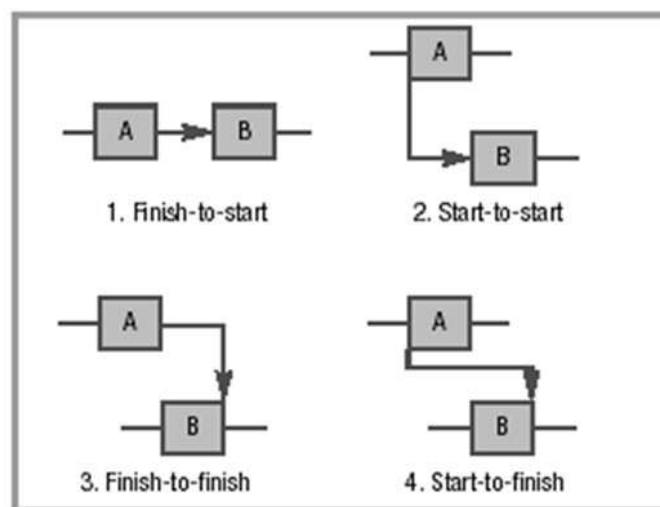
Figure 4. 3 Relationships between activities (credit: Gardiner, P, D)

Finish-to-start means activity A must finish before activity B has permission to start; Start-to-start means once activity A has started, activity B must also be started; Finish-to-finish means activity A must be finished before activity B can finish; Start-to-finish means as long as activity A has started, we can proceed to finish activity B. For these four relationships, a time lag can be written on the arrow to indicate if there must be a delay between A and B (Gardiner, P, D, 2005). We should know that, during marine seismic data acquisition project, Finish-to-start relationships are the most common used relationships in the project network.

4.1.3 Creating a network

Creating a network will give managers a holistic overview of relationships between all activities that are involved in a project, and a network will help managers to find which activities are critical and which activities cannot be delayed, here these activities which cannot be delayed are called "critical activities".

We should know that critical activities have zero float, these critical activities generate a critical path which have the longest duration in the network. In order to find critical activities, the first step is to carry out a forward pass through a network, it begins from the first activity until we reach to the last activity, and the EST of the first activity is always zero. If an activity can be started after several activities, the EST is taken from the activity that has the highest EFT. After finishing forward pass, we should write down EST and EFT. The EFT for the last activity is the expected duration of the project.

After finishing the forward pass, the next step is to continue backward pass, it start from the last activity, the LFT is equal to EFT, and the LST= LFT- duration, the float = LFT-EFT = LST-EST.

If an activity has more than one immediate successor, the LFT is taken from the path having the numerically lowest LST (Gardiner, P, D, 2005).

According to description above, we give an example and try to find the critical path and the duration of the project. Assume there are eight activities involved in a project, activity H can start when the activities E, F and G are completed. Activity D and E can start when activity B is completed. Activity F can start when the activity C is completed, and activity G can start when the activity D is completed. Activity B can start when A is completed, and activity C can start 2 weeks after A is completed. The duration of each activity is given in table 4.1.

Table 4. 1 Duration of each activity

Activity	Duration (in weeks)
A	4
B	6
C	8
D	8
E	10
F	11
G	4
H	10

With this information given above, a network diagram is shown in figure 4.4, in which the duration is 35 weeks and the critical path is A-C-F-I.
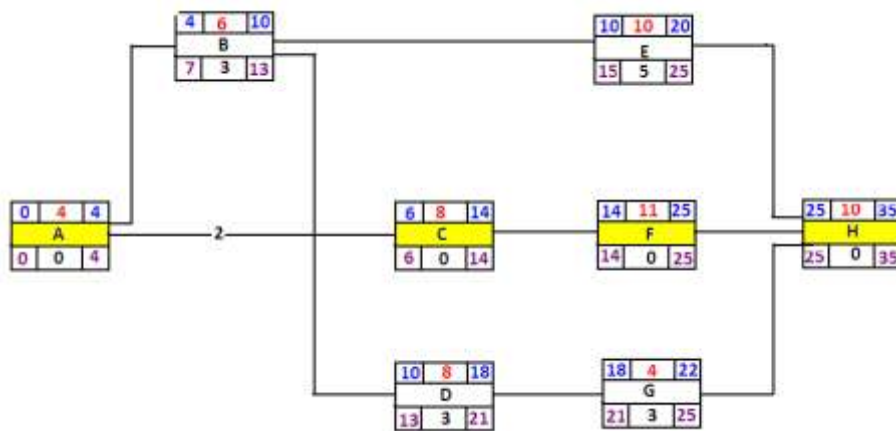
Figure 4. 4 An activity network

Applying network diagrams in marine seismic data acquisition project will help managers schedule and plan resources for the project, network diagrams will help managers concentrate on managing those activities which could cause delays to the whole project.

4.2 Procurement management

Project procurement management includes the processes required to acquire goods and services, to attain project scope, from outside the performing organization (PMI, 2000:8).

In this thesis, we mainly discuss a procurement strategy based on a life cycle cost consideration. We will take streamer procurement as an example to illustrate LCC procurement strategy.

In the past, comparisons of asset alternatives are mainly based on initial capital costs, however, usually the cost of operation, maintenance, and disposal exceed all other first costs many times over (supporting costs are often 2-20 times greater than the initial procurement costs) (Barringer, 2003) .

The Life cycle cost (LCC), Figure 4.1, is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission (SAE 1999). LCC analysis is a tool for economic analysis and engineering analysis. It is used as a measurement and comparison tool to evaluate the life cycle cost among all alternatives and make choices accordingly. It is a reliable method to reveal which equipment or system is cost-effective throughout the life cycle of a project.

Figure 4. 5 Life Cycle Cost Analysis, (PMstudy, 2012)

NORSOK Standard O-CR-002 clarifies three functions of LCC for production facilities:

➢ Optimizing the production facility
➢ System optimization during the engineering phase
➢ Modification projects and optimization during operation

In this part, we use NORSOK Standard O-CR-002 to make a LCC analysis for the selection of marine seismic streamers which are supplied from different suppliers. During the LCC analysis, the Net Present Value (NPV) methodology will be used to determine which kind of streamer is most cost effective. The Net Present Value (NPV) of an investment is the present value (PV) of the expected cash flows, less the cost of the investment, NPV= PV- Cost. While PV mean the present worth of a future value, it is calculate by a discount of future value, PV=future value/discount rate.

NORSOK Standard O-CR-002 defines LCC as being equal to the sum of the operating cost, capital cost and deferred production cost. We will apply this method to perform a LCC analysis of a marine seismic project. Table 4.2 shows the major costs and potential loss factors involved in the LCC analysis which are referred in NORSOK Standard O-CR-002:

Table 4. 2 LCC structure (NORSOK Standard O-CR-002)

LCC	Capital cost	equipment cost
		installation cost
		commissioning cost
		capital insurance cost
		reinvestment cost
	Operating cost	man hour cost
		spare parts and consumable consumption
		logistic support cost
		energy consumption cost
		operating insurance cost
		onshore support cost
	cost of deferred production	cost of deferred oil production
		cost of lost gas export

The processes of LCC analysis are shown below:

● Identify two alternatives and focus on economic consequences to look for solutions.

● Cost estimate and select cost calculation module (NPV method).

● Use selected module (NPV method) to calculate cost profile for each alternative.

● Performing an uncertainty analysis with the sensitivity analysis method (Tornado chart) to evaluate the impact of changes in the key variables.

● Make reasonable assumptions and connect with Norsok standard O-CR-002, to calculate the uncertainty.

Here we select a streamer as an example to illustrate how to use LCC analysis to compare selection from different suppliers. Suppose a marine seismic vessel A has to procure streamers, and there are two alternatives which meet the needs. Both the two kinds of streamers are designed for maintenance and the life span for both are 15 years. The price of streamer 1 is lower than for streamer 2, but the maintenance cost will be higher than for streamer 2. In the appendix, some assumptions and detailed calculations are given to calculate the LCC using the NPV method. After the sensitivity analysis, we state:

➢ LCC analysis demonstrated that streamer 2 has a higher NPV than streamer 1.

- Streamer 1 has lower capital cost than streamer 2, but operation cost are much higher than for streamer 2. Man hour costs and spare parts and consumable consumption are key factors to make the operation cost higher, higher man hour cost and needs for more spare parts and consumable consumption means that streamer 1 will have more failures which induce more operation and maintenance cost; and downtime costs to carry out maintenance and repair during its lifecycle.
- Tornado chart is a risk analysis method to uncover the key factors and demonstrate how these key factors affect the LCC of the two alternatives.
- Streamer 2 is more cost effective than streamer 1.

In this case study, the whole life cycle costs are considered in equipment selection, rather than only the procurement costs. Based on a payback period, LCC analysis helps investors maintain budgets, reduce their cost and present decision making in financial perspective to select streamers to achieve the lowest long term cost.

4.3 Equipment maintenance technology

Maintenance costs always occupy a large propotion of the total costs during equipment operation. Recent researches indicate that more than 30 percent of all maintenance cost are wasted due to unconscionable maintenance technology. From this point of view, we can judge that an advanced maintenance technology will save lots of money and will be welcomed by all project managers. In this part, two maintennace technology are discussed to help project managers reliazed the importance of maintenance technology.

4.3.1 Preventive maintenance

Preventative maintenance is a program of routine equipment inspections, maintenance tasks and repairs which are scheduled to ensure that degradation of equipment is minimized. A well-designed preventative maintenance program slightly over-maintains equipment because scheduling is designed for the worst case operating conditions. The overall objective is to prevent operating problems or failures, and ensure reliable operation of a facility (Okrasa, R 1997)

Figure 4.6 is a typical bathtub curve illustrates the reliability of a product. The early life period of the bathtub curve indicates that a new machine has a high probability of failure because of installation problems during the first stage of operation. After this initial period, the product will be operated in a normal life period, in this period the probability of failure is relatively low. After this normal machine life period, the probability of failure increases and goes into the end life of wear out period.
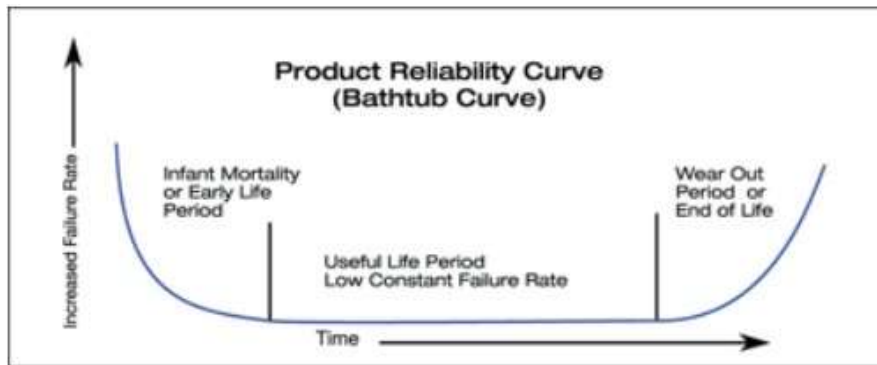
Figure 4. 6 Typical bathtub curve (credit: Astrodyne and Mansfield, 2009)

All preventive maintenance management programs assume that machines will degrade within a time frame, from the picture, we know that it represents a likelyhood of failure over the life of an asset. For example, an acoustic CMX will normally run 6 months before it must be replaced. Using preventive management techniques, the CMX would be removed from service and replaced after 6 months of operation. The problem with this approach is that the mode of operation and variables directly affect the normal operating life of machinery. The normal life are not the same for all CMX that handles. In this exam, the CMX may not to be replaced after 6 months. Therefore, the labor and material used to make the repair was wasted. According to my experience, we always use preventive maintenance in our operations, and we are trying to find advanced solutions to achieve cost effective operation in marine seismic acquisition.

4.3.2 Predictive Maintenance

Predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation. A comprehensive predictive maintenance management program uses the most cost-effective tools (e.g., vibration monitoring, thermography, tribology) to obtain the actual operating condition of critical plant systems and based on this actual data schedules all maintenance activities on an as-needed basis (Okrasa, 1997).

From the definition we know that predictive maintenance is a condition-based preventive maintenance program, in order to acquire the real time condition of an equipment, some monitoring and diagnostic techniques should be include in a comprehensive predictive maintenance diagram, normally, these techniques include vibration monitoring, thermography, tribology (refer to wear oil analysis and lube oil analysis), process parameters, visual inspection, ultrasonics, and other nondestructive testing techniques. Table 4.3 highlight some typical applications of predictive maintenance.

Table 4.3 Applications of predictive maintenance (credit:NASA, 2000)

Technologies	Applications Pumps	Electric Motors	Diesel Generators	Condensers	Heavy Equipment/ Cranes	Circuit Breakers	Valves	Heat Exchangers	Electrical Systems	Transformers	Tanks, Piping
Vibration Monitoring/Analysis	X	X	X		X						
Lubricant, Fuel Analysis	X	X	X		X					X	
Wear Particle Analysis	X	X	X		X						
Bearing, Temperature/Analysis	X	X	X		X						
Performance Monitoring	X	X	X	X				X		X	
Ultrasonic Noise Detection	X	X	X	X			X	X		X	
Ultrasonic Flow	X			X			X	X			
Infrared Thermography	X	X	X	X	X	X	X	X	X	X	
Non-destructive Testing (Thickness)				X				X			X
Visual Inspection	X	X	X	X	X	X	X	X	X	X	X
Insulation Resistance		X	X			X			X	X	
Motor Current Signature Analysis		X									
Motor Circuit Analysis		X				X			X		
Polarization Index		X	X						X		
Electrical Monitoring									X	X	

Let us consider this condition based predictive maintenance applys in a marine seismic data acquisition project, typical benifits will be included:

● Estabilish a scheduled maintennace planning
● Minimize equipment downtime and unexpected failures
● Reduce maintenance cost and overhaul time
● Optimize spare part inventory.
● Increase useful life period

4.4 Maintenance interval calculation models

In practical operations, many failure caused by replacement occurs in every phase, we now look at some models for calculating optimal maintenance intervals. We assume that maintenance either means replacement or perfect repair; here perfect repair means the component is as good as new after maintenance, now we will list three models to calculate maintenance replacement intervals.

4.4.1 Age replacement model

In the "Age replacement model", the component is replaced at failure, or at age u, here u is a fix time (see following chart, figure 4.7), whichever comes first.
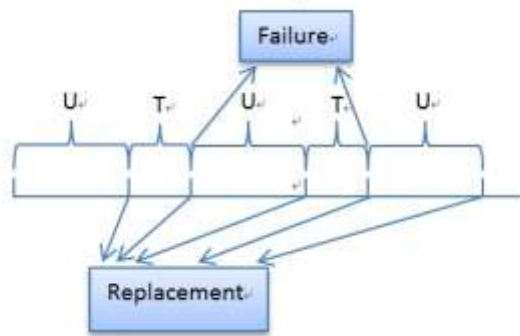
Figure 4. 7 Age replacement model(credit: Abrahamsen,2012)

If T is the lifetime of the component, the expected time between each replacement becomes:

$$EX = E(\min(T, U)) = \int_o^u tf(t)\, dt + \int_u^\infty uf(t)dt$$

$$= \int_o^u tf(t)\, dt + u\big(1 - F(u)\big) = \int_0^u R(t)dt$$

If we assume the cost by corrective replacement (at failure) is k_c, the preventive replacement (at age u) cost is k_p, the expected cost per replacement is then:

$$E(\text{cost}) = kcP(\text{corrective}) + kpP(\text{preventive}) = kcF(u) + kpR(u)$$

Then the expected replacement cost per time unit becomes:

$$K(u) = \frac{kcF(u) + kpR(u)}{\int_0^u R(t)dt}$$

For Age replacement only old or failed components are replaced, but we must keep an over view of all failure or replacement times.

4.4.2 The Block replacement model

For this replacement model, the component is replaced at failure and at fixed times u, 2u, 3u..., which is shown in figure 4.8
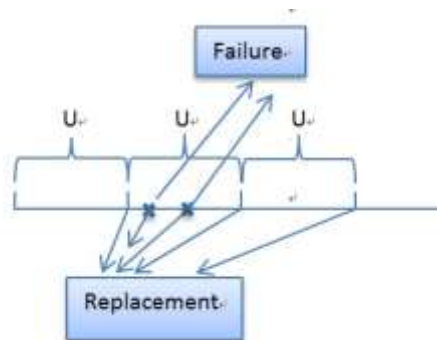
Figure 4. 8 Block replacement model(credit: Abrahamsen, 2012)

Let N (t) be the number of failures in the period (0,t). The cost of corrective and preventive replacements are as before kc and kp, the expected cost per preventive replacement then becomes: E(cost)=kcE(N(U))+kp. Actually, in our daily maintenance, the Block replacement model is most frequently used.

The Block replacement model does not need to keep an overview of all failure times. But some "young" components are replaced

4.4.3 Minimal repair block replacement

The component is replaced at fix times u,2u,3u,… failures between the replacements are repaired by a minimal repair, which is shown in figure 4.9.
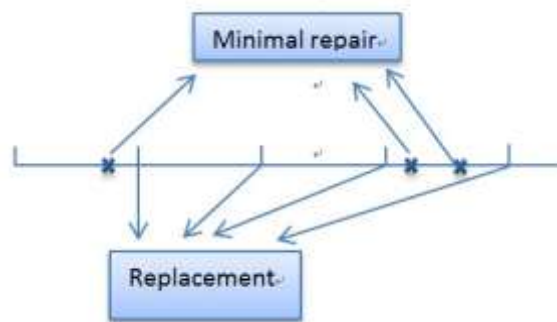
Figure 4. 9 Minimal repair block model(credit: Abrahamsen, 2012)

The occurrence of failures between the replacements is described by a non-homogeneous Poisson process. Recall that for a non-homogeneous Poisson process

$E(N(t))= \int_o^t \lambda(u)\, du$, where $\lambda(t)$ is the intensity, let km be the cost of a minimal repair and kp the cost of a preventive replacement. The expect cost per time unit is then:

$$K(u) = \frac{km \int_o^u \lambda(t)\, dt + kp}{u}$$

With these three models, according to our experience, we will have a tool to calculate which is optimal for our maintenance replacement.

For Minimal repair model, only old components are replaced and we do not need to keep an overview of all failure times.

4.5 Spare parts management

Smith, S, E (2003) stated that spare parts management is the maintenance of key spare parts at strategic locations so they will be available when needed. Decisions about which parts to keep in stock and where to keep them require a careful evaluation of current and future needs. In some cases it may be more cost effective to order a part when it is needed, while in others, it

is necessary to keep a spare part on hand to prevent down time in the event of breakage or problems.

Spare parts management is used to achieve part availability when failure or wear out have happened, effective spare parts management will face three questions: What spare parts to store? How many spare parts to store? Where to store the spare parts? In this part, we will solve these three problems with some models and theory.

4.5.1 What spare parts to store?

Spare parts are also called service parts, Business dictionary (2012) defines a spare part as "Replaceable component, sub assembly, and assembly identical to and interchangeable with the item it is intended to replace". Spare parts management plays a crucial role in any organization as optimal spare parts supportability and stock levels will increase working efficiency and to some extent reduce cost. When we decide what spare parts to store, several factors that are involved are needed to be considered:

- The criticality of item application regarding mission success.
- The quantity, reliability and availability of the item.
- Lead time of spare parts procurement.
- Various characteristics such as the operation condition, the annual consumption value and the unit cost.
- Maintenance and inspection requirement.

The most crucial factor, the criticality of items, which is based on its function in the system, always, specify item levels and determines what to store. Reliability and availability condition of the production equipment/facility, when a working component will fail and need to be replaced by a spare part. Some spare parts will be decided to store or not according to the lead time, if the lead time is short it may be not necessary to store, however, the spare parts which have a long lead time have to be stored to reduce the waiting time. The operation and consumption condition will require some spare parts to be stored to meet the requirements of operation and consumption. As well, if some overhaul or annual inspection will be implemented, some spare parts will be required to be stored ahead of the overhaul and inspection. The required spare parts could be standard spare parts or spare parts needed to be manufactured according to specification.

There are several methods for classification about what spare parts to store. These are based on the frequency of issues (FSN Analysis), the annual consumption value (ABC Analysis), the criticality (VED Analysis), the lead time (SDE Analysis) and unit price (HML Analysis). In marine seismic exploration, I think VED Analysis is quite appropriate, because the criticality of items always occupies a larger weight on the decision of what spare to store.

In order to find out the critical items, Gajpal et al. (1994) suggested a three step hierarchy process which is called the Analytic hierarchy process (AHP) to determine the criticality of the items. The decision model is a breakdown structure; it is based on structuring the problem into a hierarchy with the overall objective (or focus) at the top level 1. Criteria that are used to evaluate the criticality of spare parts are located in the middle level 2, and the alternative modes characterizing each of the criteria are located in the bottom level 3. For example, three alternative of spare can be standard spare available off the shelf; standard spare but availability not certain; non-standard spare to be fabricated according to specifications. (Gajpal et al., 1994).
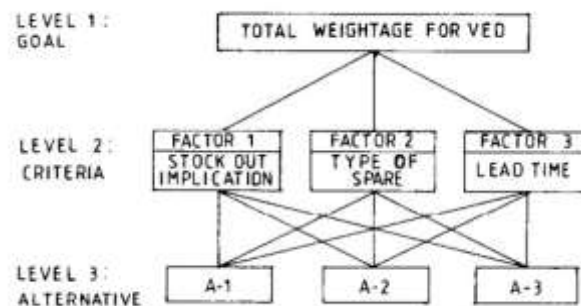
Figure 4. 10 Analytic hierarchy processes (Gajpal et al., 1994)

Based on the reliability and availability of different machines and equipment, we can classify the items for a VED Analysis into a Vital, Essential and Desirable hierarchy, and to determine the criticality of an item and its effect on production and other services, then we make a classification of what spare parts to store.

4.5.2 How many spare parts to store?

Blanchard (2004) stated that "spare parts quantities are a function of demand rates" and included the consideration of the following:

1) Spare and repair parts converting actual item replacement occurring as a result of corrective and preventive maintenance actions.
2) An additional stock level of spare parts to compensate for repairable items in the process of undergoing maintenance.
3) An additional stock level of spare parts to compensate for the procurement lead times required for item acquisition.
4) An additional stock level of spare parts to compensate for the condemnation or scrap age of repairable items.

Calculation factors:

1. The reliability of items to be spared (expressed as fail, removal, replacement or inversely as mean time between failures, MTBR, replacements).

2. The number of items installed.
3. The required probability that a spare part will be available when needed; normally, to determine the quantity of spare parts, the probability P should satisfy: 90%<= P <=95%

The reliability of a system is the most important indicator of the required quantity of spare parts, so we here focus on the calculation of system reliability. Then we calculate the quantity of spare parts according to the result of the reliability of the system.

Fukuda, J (2008) stated that Poisson distribution is a quite frequently used forecasting technology in spare parts quantity determination. It takes use of reliability analysis with the following formula:

$$P = \sum_{x=0}^{n} \left[\frac{(\lambda t)^x e^{-\lambda t}}{x!} \right]$$

Where λ=failure rate

t = time considered (or total operation period of all items involved).

x = number of failures.

λt = number of failures in time t.

Fukuda (2008) stated that spare parts can be divided in non-repairable and repairable parts. For non-repairable parts, the number of failures equal to the number of spares. The quantity of spare parts is the minimum value of n which satisfies the following formula:

$$P <= \sum_{x=0}^{n} \left[\frac{(\lambda t)^x e^{-\lambda t}}{x!} \right]$$

For repairable items the number of failure is different from the number of spares, because the spares are used when the replaced items are under repair. We can apply Palm's theorem to calculate $\lambda t = \frac{t}{MTBR} = \frac{A*N*M*T}{MTBR}$ where MTBR means Mean Time Between Repair. For the repairable items, the n need to be replaced by (n-1). So the formula for repairable items will be expressed as

$$P <= \sum_{x=0}^{n-1} \left[\frac{(\lambda t)^x e^{-\lambda t}}{x!} \right]$$

Besides what we discussed above, Inventory system should also take into considerations about the quantities of spare parts. An optimum balance (not too much or too little) must be sought between the inventory on hand, the procurement frequency, and the procurement quantity based on the budget. The following figure 4 shows the general deterministic inventory process:
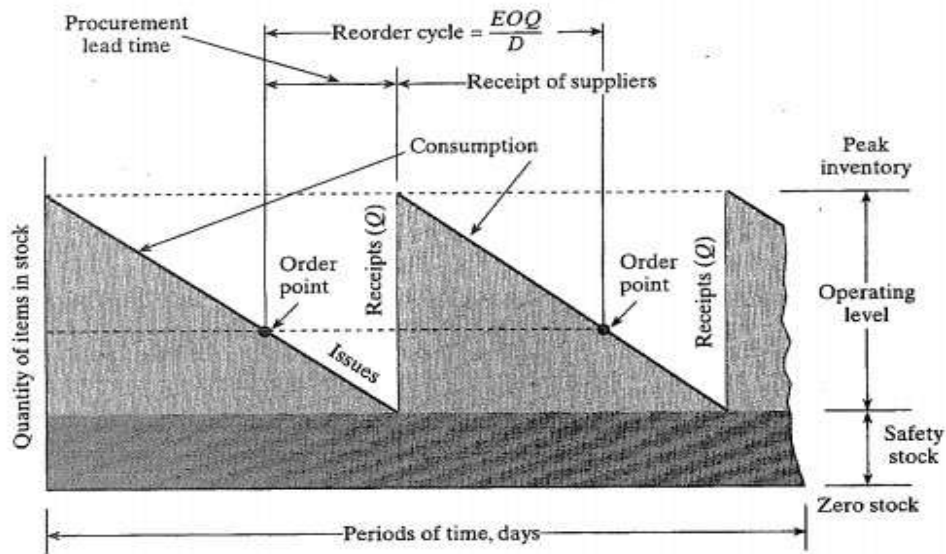
Figure 4. 11 Inventory considerations: (Blanchard, 2004)

The main objective of inventory considerations is to have enough amounts of spare parts to support that a normal operational system goes smoothly versus MTTF (mean time to failure), also to have successful repair times, and procurement lead times, and to be able to reply to some unexpected failures and unforeseen delays. All of these activities are aiming at lowest total cost.

Sometimes the customer satisfaction is another element of inventory consideration, because the cost of storage will make customer satisfied in the form of short lead time and less risk of downtime which will cost him more money.

4.5.3 Where to store the spare parts?

In offshore marine seismic industry, according to the hierarchy of the items in the VED Analysis, it is suggested that there are three locations that will be suitable to store spare parts:

Onsite（On board or in offshore depot）: Spare parts that are vital (for frequent use and all that with high criticality) should be stored on board to ensure normal system operation. The onsite storage could be a decentralized storage or centralized storage. The spare parts require some special methods to store, will be stored in a centralized way; the spare parts which are heavy and large dimensions, not easy to transport, or required to be available at any moment when failures occurs, will be stored in a decentralized way.

Onshore warehouse: spare parts that are essential (not so frequently used and extra parts more than needed) could be stored in an onshore warehouse. As the onshore warehouse could provide a better protection to the spare parts and has enough space to store large dimension and heavy spare parts, this is also a very important method to store the spare parts. Most onshore spare parts will be stored in the main warehouse near to the head quarter of the

company, but some would be stored in the warehouse close to the vessel and could easily and quickly be transported to the vessel if needed.

Manufacturer warehouse: for the spare parts considered to be desirable (very few used but the unavailability of which when needed would be significant), storing them in manufacturer's warehouse is a good selection, these spare parts can be accessed and traced by an online condition monitor system.

Chapter 5 Risk analysis and management

Almost all projects will experience risk, thus how to deal with risk affects project implementation. This chapter will discuss the importance of risk in marine seismic data acquisition project and discuss the risk assessment process and risk management method.

5.1 Risk and risk analysis methodology

Before we analyse risk, we should know the definition of risk. The 2000 edition of the *Guide to the Project Management Body of Knowledge* (PMI, 2000) states that a project risk is: An uncertain event or condition that, if it occurs, has a positive or negative effect on a project outcome.

Charette (2000) stated that close to half of the respondents (49%) use the traditional definition of risk, in which risk is a "negative," and that risk management primarily deals with negative consequences of some event. Nearly the same number (44%) is evenly split between the definition of risk that could include positive consequences of some event, as well as negative aspects. (See figure 5.1 below.)
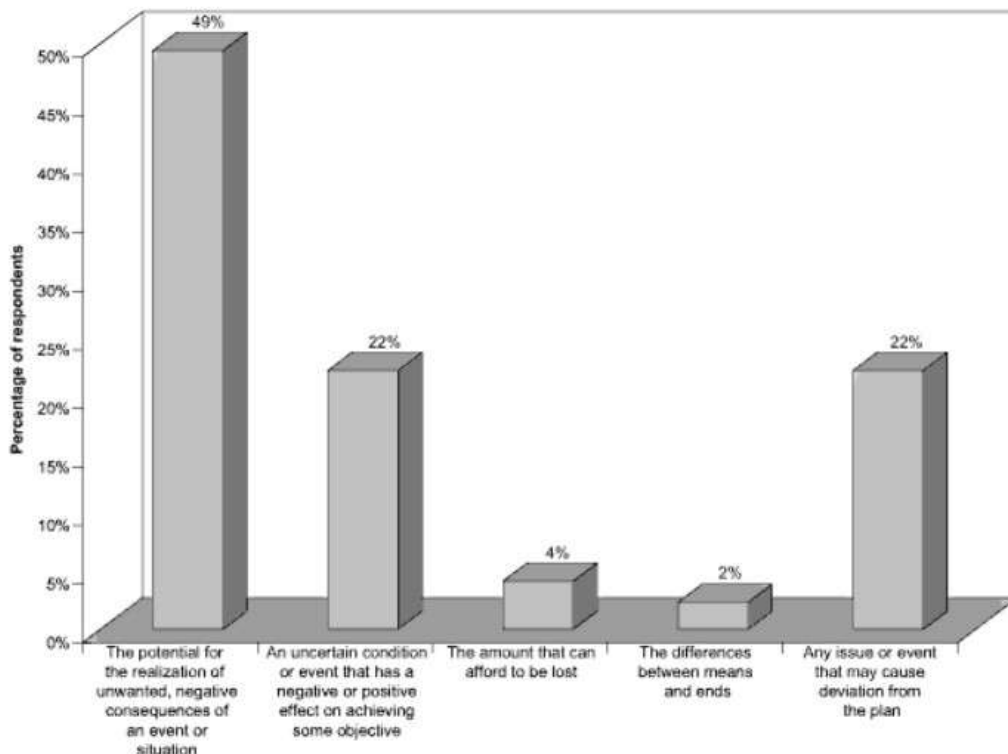
Figure 5. 1 Definition of risk (Charette, 2000)

From this definition, we can clearly see that involvement in a marine seismic data acquisition project itself represents an interpretation of risk, first, people invest in these kinds of project

just like buy a stock, and the consequence will be a loss (no hydrocarbon) or a profit (find hydrocarbon). So, an investment in a data acquisition projects have a positive or a negative outcome, so we can consider this as a speculative risk; during project implementation, some activities will only meet negative effects. For example, deploying streamers and guns will only involve the chance of equipment damage in the sea, so these risks are pure negative risk.

Aven (2008) illustrate a bow-tie diagram to express the risk picture, see figure 5.2.
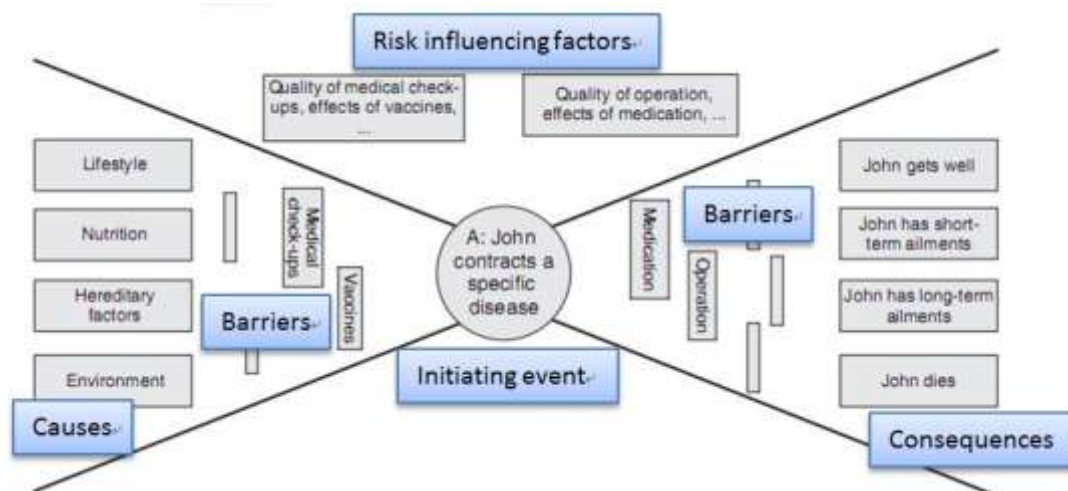
Figure 5. 2 An example of bow-tie diagram (based on Aven, 2008)

We can schematically describe an incident with a bow tie diagram:

- The probability related events are to the left and are hindered by barriers
- The possible consequences are to the right and are also hindered by barriers
- The issue is then to ensure a sufficient number of barriers to hinder any possible negative event to escalate into an unwanted consequence.

From the bow-tie diagram, we know that the risk analysis focuses on establishing a risk picture by analyzing causes and consequences of the initiating events, in marine seismic data acquisition project, the initiating events can be a hazard/threat which has a bad influence to the project, or the opportunity to find a hydrocarbon structure. Some causes and consequence barriers that effect on the initiating event are demonstrated and listed in this diagram; risk influencing factors that are critical to the risk are also identified.

In all activities there is a risk, and in order to reduce risk to the minimum extent, we cannot completely avoid hazard and risk during any operation, what we can do is reduce risk as much as we can, in this condition, we introduce ALARP principle.

ALARP means the risk should be reduced to a level that is As Low As Reasonably Practicable. This principle means that the benefits of a measure should be assessed in relation to the disadvantages or costs of the measure. This means that an identified measure should be implemented unless it can be documented that there is a "gross disproportion" between costs/disadvantages and benefits (Aven,2008).

In the use of ALARP method, we can set a series of accept criterias for barriers during an activity implementation. Table 5.1 lists criteria suggested by Gudmestad (2012).

Table 5. 1 Barrier acceptance criteria (Gudmestad, 2012)

Evaluated Risk	Criteria
Acceptable	Requires a minimum of one effective primary barrier in place for all threats
	Requires a minimum of one effective primary barrier in place for each identified consequence
Tolerable (ALARP)	Requires a minimum of two effective primary barriers in place for all threats
	Requires a minimum of one effective primary barrier in place for each identified consequence
	Requires a minimum of one effective secondary barrier all barrier failure / decay modes
Intolerable	Requires a minimum of three effective primary barriers in place for all threats
	Requires a minimum of two effective primary barriers in place for each identified consequence
	Requires a minimum of one effective secondary barrier all barrier failure / decay modes

Aven (2008) stated that the analysis results provide a basis for

- Choosing between various alternative solutions and activities while in the planning phase of a system
- Choosing between alternative designs of a solution or a measure. What measures can be implemented to make the system less vulnerable in the sense that it can better tolerate loads and stresses?
- Drawing conclusions on whether various solutions and measures meet the stated requirements
- Setting requirements for various solutions and measures, for example, related to the performance of the preparedness systems
- Documenting an acceptable safety and risk level

5.2 Risk management methodologies

Risk management is defined as all measures and activities carried out to manage risk. Risk management deals with balancing the conflicts inherent in exploring opportunities on the one hand, and avoiding losses, accidents and disasters on the other hand (Aven and Vinnem, 2007).

Risk management is used to manage risk, so risk analysis should be the central part of risk management. A comprehensive risk analysis will help managers manage risk involved in the projects. Raz & Michael (2001) stated that the management of risk in projects is currently one of the main topics of interest for researchers and practitioners working in the area of project management.

5.2.1 Hazard identification

Before we implement a risk analysis methodology, we should first talk about hazard identification.

Maragakis et al. (2009) stated that Hazards identification is the act of recognizing the failure conditions or threats (Safety Events), which could lead to Undesirable Events and defined the characteristics of theses undesirable events in terms of their potential Safety Outcomes and of the magnitude of these safety outcomes' Consequences.

Aven (2008) stated that it is difficult to avoid or to reduce the consequences of events that one has not identified. For this reason, the identification of the initiating events (here we talk about hazard) is a critical task of the analysis. Figure 5.3 lists the process of hazard identification, and lists some hazard identification techniques which are based on qualitative analysis.
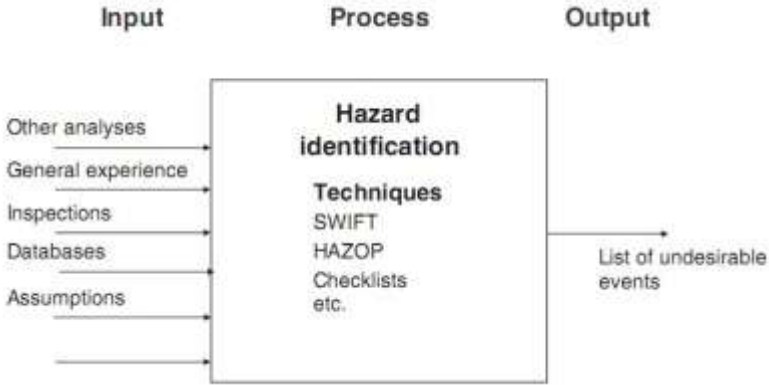
Figure 5. 3 Hazard identification (Aven, 2008)

In order to identify all the hazards which may occur during an operation, it is recommended to apply methodically techniques during hazard identification. Normally, there are two kind of methodologies used to identify hazard; they are the qualitative and quantitative risk analysis.

Investopedia US (2013) stated that qualitative analysis uses subjective judgment based on no quantifiable information, such as management expertise, industry cycles, strength of research and development, and labor relations. This type of analysis technique is different than quantitative analysis, which focuses on numbers. Due to the marine operation of seismic data acquisition projects, in this thesis, we mainly discuss qualitative analysis.

5.2.2 Qualitative analysis

Smith et al. (2006) state that a typical qualitative risk management usually includes the following aspects:

- A brief description of the risk;
- The stages of the projects when risk may occur;
- The elements of the project that could be affected;
- The factors that influence risk to occur;
- The relationship with other risks;
- The likelihood of risk occurring;
- How risk could affect the project.

In the following part, we will discuss several qualitative risk methodologies; all these risk methodologies are based on Aven (1992).

5.2.1.1 Checklist

Checklists are lists of known hazards or hazard causes that have been derived from past experience. The past experience could be previous risk assessments of similar systems or operations or from actual incidents that have occurred in the past (Maragakis et al., 2009). Checklist methodology is a previous knowledge and experience based technique, hazard that have never happen before may be missed, and it has limitation in novel systems.

5.2.1.2 Job Safe Analysis (JSA)

JSA is usually based on checklists; it is used to identify potential hazards during every step involved in implementing a specific job, analyzing and taking actions to make the job avert from hazards.

Special forms are always designed for job safety analysis. In the form, potential hazards are analyzed and measures are demonstrated in advance. JSA will help people realize that everyone's safety is the first priority; job safety analysis usually decomposes a task into several sub-tasks, and analyzes each task respectively. Table 5.2 is a typical job safety analysis form.

Table 5. 2 Job safety analysis form (NWP103A, 2012)

Job safety analysis

Safety information for sampling and testing		
Names of personnel		
Title of job or task Sample the local wetland water		

Task	Hazards	Controls
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		

Phone numbers:	Required Personal Protective Equipment (PPE):
Colleague:	
Supervisor/Manager:	
Emergency response: 000	

Other Information: See your Supervisor/Manager for other information
Contributors: Names of those undertaking this JSA
Date:
JSA Number:

5.2.1.3 Failure Modes and Effects Analysis (FMEA)

Aven (2008) summarized that Failure Modes and Effects Analysis (FMEA) is a simple analysis method to reveal possible failures and to predict the failure effects on the system as a whole. The method represents a systematic analysis of the components of the system to identify all significant failure modes and to see how important they are for the system's performance.

This method considers what will happen to the system if a component fails, this method only investigate that one component fails at a time, other components are expected to work under smooth operation, however, during system/equipment operation, failures caused by several components always happen, in this condition, FMEA is not a practical methodology. FMEA create a detailed hazard identification process for every component involved in the system, but this will be time consuming and expensive.

5.2.1.4 Hazard and operability (HAZOP) study

A HAZOP study is a systematic analysis, it is mainly based on the theory that assume risk events are caused by deviations from the design specification, and then one identify and analyze these deviations (which may cause hazards) by taking use of series guidewords. The following guidewords are commonly used: Not/No, More of/Less of, as well as, Part of, Reverse and Other than, Early, Late, Before, After. These guide work are critical for a HAZOP study, according to the IEC Standard 61882 (2001):

The identification of deviations from the design intent is achieved by a questioning process using predetermined "guide words". The role of the guide word is to stimulate imaginative thinking, to focus the study and elicit ideas and discussion.

The main job of HAZOP is analyzing the causes and consequences of these deviations. The procedure of a HAZOP can be illustrated in the following figure 5.4.
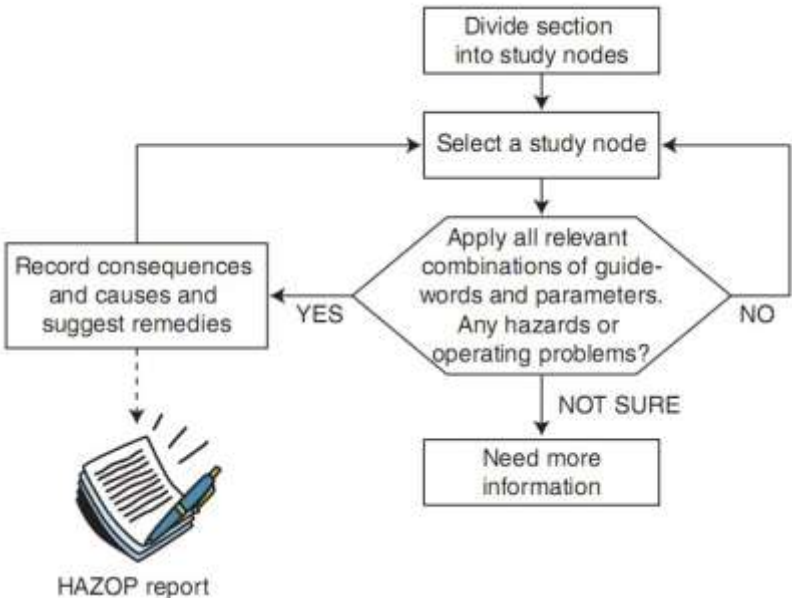
Figure 5. 4 A HAZOP procedure (Rausand, 2005)

5.2.1.5 Structured What-If Technique (SWIFT)

SWIFT is a systematic technique for hazard identification. It is just like HAZOP, it is also using predefined checklists to identify deviations from normal operations, SWIFT analyze deviations from normal operation is based on brainstorming, it is beginning with "what if" and "how could". It relies on a higher level the opinions from experts to identify hazard.

In a word, all these five qualitative methods are cost effective methodologies for hazard identification, we can also consider these methods as risk reduction methods. According to DNV-OSS-121:

The results of hazard identification and evaluation present a good opportunity for targeted risk reduction. In assigning classification, DNV expects that such risk reduction will be undertaken wherever significant and practicable opportunities are identified.

Hazard identification and evaluation is most effectively initiated at concept design stage where risks can be avoided or reduced. For existing installations where this is not possible, hazard identification and evaluation should be used to address hazards and optimising the protection measures to manage them. In order of importance, this means measures to prevent, detect, control and mitigate against hazards.

5.3 Risk involved in marine seismic exploration

An investment in data acquisition projects is an activity with speculative risk, although marine seismic data acquisition projects themselves are risk reduction measures for oil drilling projects, implement these projects always involve different kinds of hazards or risks. In this part, the mainly risks involved in data acquisition projects are discussed in details.

5.3.1 Personnel operational risk

Joshi (2012) stated that a good survey design, technology, resources (equipment, software, and hardware), financial back up etc. can be easily ruined by deputing non suitable personnel in the key position and there is no way to cover up this risk once the project is complete. Personnel at every stage of the job always play a crucial role in the life cycle of a project, especially in a complicated working environment.

From 1993 to 1997, UKOOA (1998) as cited in Nick &Gatwick (1999) stated that an investigation relating to LTI (Lost Time Injuries) in marine seismic business demonstrated that the back deck operations are the most hazardous work area, see table 5.2. The reason being that although air-gun deck and streamer decks are designed in different floors, some deflector systems are mixed with numerous towing winches and handling systems. At the same time, personnel is challenged to deploy and operate an increasing number of auxiliary equipment packing on the streamers, that is why back deck operation occupy such a big proportion of risk.

Table 5. 3 Lost Time Injuries by work area (Nick &Gatwick, 1999)
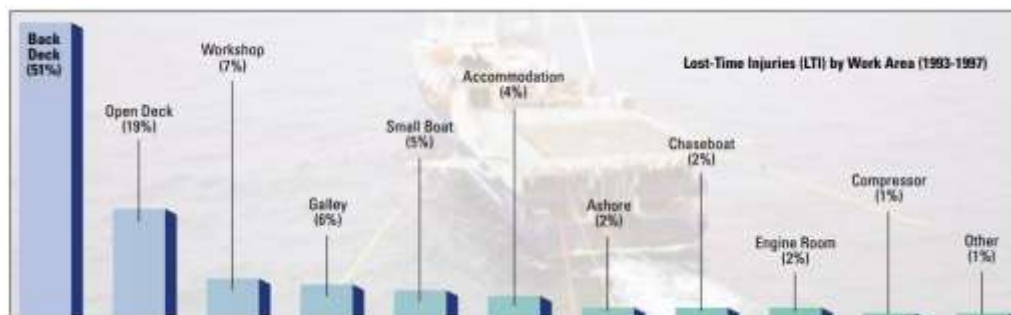
In order to eliminate operational risk during marine seismic business, a HAZOP can be used as a risk reduction methods, Swinstead (2004) suggested several principles to undertaken:

- Eliminate safety hazards with the work area by redesigning deployment equipment and working practices. Such as: a dynamic streamer tow-point system, which will retract and lower streamers to a comfortable operation; taking use of remote control device to make a safety distance between human and equipment.
- Only standard and certified equipment is accepted for the whole fleet.

- Improve training methods so that potentially hazardous situations can be anticipated and acted upon before they arise.
- Improve communications between the back deck environment and the navigation and data acquisition activities undertaken in the instrument room, also the bridge.
- Standard operation regulations should be established and enforced.
- Seismic vessels back deck should be divided into different areas according to function and all these areas should be marked clearly.
- Operators in the instrument room should have a holistic overview of the back deck operation.

5.3.2 Environmental risk

During marine data acquisition, towed streamers and airguns will be deployed into the water; personnel will live and work on board the vessel; there are also some chase boats and supply vessels work in the survey, all of these will increase the risk to the environment, the main potential hazard associated with the projects include:

- Fuel and oil leakage from seismic vessel and equipment.
- Seismic sources that cause physical disturbance to biota such as marine mammals, turtles, fishes and sharks.
- Interference with commercial fishing activities.
- Garbage disposal to marine environment.
- Refuel activities that could pollute the water.
- Risk of introducing marine pests into the water.

In order to mitigate operation risk to the environment, we introduce the ALARP process to reduce risk. Figure 5.5 illustrates the principle of ALARP.
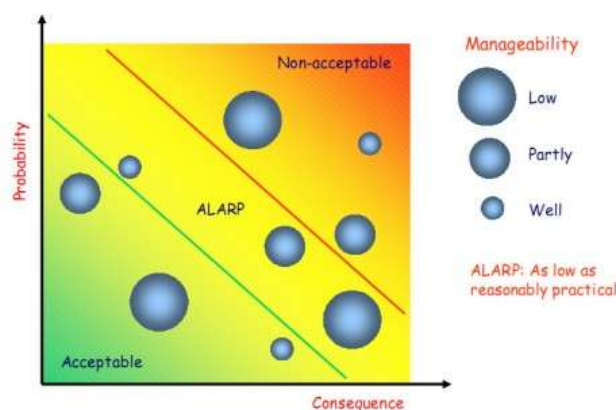
Figure 5. 5 Risk matrix – balloon diagram (Odland, 2009b)

with the ALARP principle, measures and activities should be implemented to achieve risk As Low As Reasonably Practicable. Table 5.3 lists some activities to protect the environment during 3D seismic data acquisitions.

Table 5. 4 Environment protection based on ALARP (Apache Energy Ltd, 2011)

Activity	Requirement
Operational Environmental Awareness	➢ Through inductions and educational material present on the vessels, ensure that all personnel are familiar with the environmental requirements of the environment plan to ensure these guidelines and procedures are being followed. ➢ Ensure all personnel sign off on the vessel register book confirming their induction.
Minimize risk of adverse effect to marine biota and the marine environment.	➢ "Soft start" procedures and Interaction procedures in place and adhered to. ➢ Supply vessel used to assist in keeping watch for whales ➢ Responsibilities for monitoring, responding to and recording challenging sightings clearly identified and conveyed to vessel personnel.
Deck drainage, Liquid Discharges chemical storage and management	➢ All discharges, including sewage, black and grey water, brine, cooling water, bilge, ballast water, deck drainage, to comply with legal requirements, including MARPOL (Maritime Agreement Regarding Oil Pollution) Regulations ➢ Maintain good housekeeping practices. ➢ Store chemicals in enclosed areas away from open drains and chemical containers are to be intact. ➢ Use drip trays under all machinery and fuel points and valves. ➢ In the event of a spill, take all actions to control the spill and divert deck drainage to on board containment tanks for treatment through the oil in water separator. ➢ Ensure absorbent material is on board to use in soaking up chemical or oil spills on deck. ➢ Maintain oil water separators regularly to ensure 15 ppm oil concentration alarm is functional, in accordance with MARPOL 1973/78 requirements.
Sewage discharge	➢ Treat sewage to secondary level prior to discharge through the sewage plant (aerates, macerates and chlorinates). ➢ Sewage facilities to meet MARPOL 1973/78 requirements. ➢ Maintain the sewage treatment plant in order to ensure effective treatment.
Solid waste management : ➢ Food scraps (including putrescible galley waste) ➢ Garbage, Litter Scrap metal and wood etc.	➢ Disposal of food scraps in accordance with MARPOL 1973/78 – no disposal of un-macerated food within 12 nm from coast ➢ Do not dispose of debris, garbage or litter into the sea (ships need covers to prevent wind-blown rubbish – especially plastics and cups). ➢ Segregate industrial waste (scrap metals / drums etc.) wherever possible for appropriate disposal onshore. ➢ Do not use polystyrene cups. ➢ Reduce, reuse and recycle waste wherever practicable. ➢ Record the volume and type of waste taken off vessels and forward to the Environmental Department at the end of the

	seismic survey.
Minimize risk of introducing marine pests into surveyed waters	➢ Vessel log book records a full ballast water exchange at sea prior to entry into Australian waters. ➢ Compliance with National Biofouling Management Guidelines for Commercial vessels and National biofouling management guidance for the petroleum production and exploration industry.
Maintain air quality	➢ Include inspections and tuning of engines and equipment on a regular maintenance schedule. ➢ Verify that vessel procedures comply with requirements of MARPOL.

5.3.3 Weather risk

No one will deny that weather is one of the most common risks in marine seismic operations; a better weather condition will increase the work window of marine operations. It is clear that acquisition in areas with typhoons or monsoons have lower working efficiency than area without them, because weather will reduce the data quality and generate delays to the working plan. For a contract where the clients do not pay for the standby caused by weather condition, weather influence is an indirect way to increase survey cost. So before implement an acquisition project, an SWIFT should be discussed and analyzed regarding what will be the consequences if bad weather exists in and around the survey area.

5.3.4. Supply chain risk

Smooth supply chain activities among suppliers and receivers are used to ensure profitability and continuity of a specified project. Events caused by supply chain risk always bring substantial negative consequence to the system. Tang and Nurmaya Musa (2011) summarized several risks may happen in the supply chain:

● Material flow risk. When we talk about material flow risk, the first disaster come into our mind is Ericsson's inability of reacting to a supplier's fire accident is the consequence of single sourcing risk (Peck et al., 2003). In order to avert this single sourcing risk, many companies turn to multi-suppliers. However, when we switch suppliers between different suppliers, changing supplier will also bring new risk in to the system.
● Financial flow. Financial flow risk involves the inability to settle payments and leads to improper investment. The common risks are exchange rate risk, price and cost risk, financial strength of supply chain partners and financial handling/practice.
● Information risk. Supply activities are always triggered by the information transmission between suppliers and users, we should make sure the information is accurate during decision making in supply chain.

In order to reduce supply risk in marine seismic acquisition activities, a cost-benefit method which is based on NPV (Net Present Value) consideration will be helpful in decision making. In appendix 1 we show a clear LCC analysis under the NPV methodology.

Chapter 6 Conclusions and Recommendations

A marine seismic exploration project is a high investment project with complex procedures. In order to achieve a cost effective project, methods concerned with how to reduce cost and improve working efficiency is appreciated by every project manager and operator. The thesis only covers a few aspects related to marine seismic vessel design, management models and risk reduction measures.

As the marine seismic exploration goes into deeper waters, advanced technologies are required to meet the needs, and narrow azimuth acquisition methods will be replaced sooner or later. Advanced technologies such as broadband, WAZ, MAZ and RAZ will be the predominant methodologies in the future. Besides these methodologies, high volume air guns, longer streamers, and novel streamer towing technology, dual-sensor streamers or variable-depth streamers will be widely applied in practice.

Seismic vessels are the main vehicles for the marine seismic data acquisition project, for towing of equipment in the water, for handling of systems and for supply of accommodations for personnel and so on. Due to the high investment, special designed vessels should focus on absolute safety and high working efficiency. In this thesis, a detailed stability analysis of a marine seismic vessel is discussed. Special vessel characteristics are discussed under the consideration of some operational constraints.

Marine seismic data acquisition projects always include plenty of activities, a network diagram is recommended to achieve an easy management plan. LCC analysis, minimal repair block model and the VED analysis model are recommended to achieve a cost-effective project management.

Risk in marine seismic acquisition projects may bring disasters as acquisition activities are always far away from the land; thus, identifying hazard in advance will reduce the probability of bad consequences, five qualitative risk analysis methodologies are recommended in managing risk involved in marine seismic acquisition projects.

With the acquisition activities going into deeper water and more complex environment, further study should also focus on technology and management of harsh environment operations, such as operations in arctic areas.

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Appendix 1: LCC analysis

Table A1.1 BASIC ASSUMPTIONS FOR STREAMER 1 and STREAMER 2

BASIC ASSUMPTIONS FOR STREAMER 1 and STREAMER 2		
	Streamer 1	Streamer 2
investment year	2012	2012
start of production	2013	2013
operating hours per year	8400	8520
Man hour cost	60000	16000
cost of deferred production per hour	7000	7000
spare parts and consumable consumption	40000	10000
discount rate	10%	10%
streamer life span (years)	15	15
cost of fuel per kW+CO_2 tax cost per kW	0.6	0.3

We assume the power requirement is equal each year, the unit is NOK

The formula to calculate average annual energy consumption cost of single equipment is shown as below:

Annual average energy consumption= power requirement*time in operation*cost of power

Table A1.2 Annual average energy consumption calculation

	Streamer 1	Streamer 2
power requirement (kW)	3	4
operation time per year (hours)	8400	8520
cost of power (NOK/kWhour)	0.6	0.3
average annual average energy consumption (kW)	15120	10224

The formula for production loss on the streamer is as follows:

$PL_t = E*p*L*D$ Where:

PL_t =Production loss in year t

E=average number of critical failures per year

p=probability of production reduction

L=quantity of production loss per time unit

D= duration of production reduction

Table A1.3 Cost of deferred production calculation

	streamer1	streamer2
E	0.2	0.2
p	5%	5%
D (hours)	360	240
L	0.8	0.8
PL	2.88	1.92
cost of deferred production (NOK)	20160	13440

Evaluate the economic consequences of streamer 1 with LCC analysis.

Table A1.4 LCC analysis for streamer 1

	For streamer 1	Detail cost	Year 2012	Year 2013-2027
LCC	Capital cost (NOK)	equipment cost	-1500000	
		installation cost	-200000	
		commissioning cost	-100000	
		insurance cost	-50000	
		reinvestment cost	-150000	
	Operating cost (NOK)	man hour cost		-60000
		spare parts and consumable consumption		-40000
		logistic support cost		-10000
		energy consumption cost		-15120
		insurance cost		-30000
		onshore support cost		-25000
	Cost of deferred production (NOK)			-20160
		Total cost per year		-200280
		Discount rate (10%)		0.1
		PV	-2000000	-1523345.604
		LCC	-3523345.6	

Then we will use a Tornado Chart to determine how changes in key variables impact LCC, and evaluate how the variables influence the LCC when they increase/ decrease by 10%.

Table A1.5 OPEX decrease and increase 10%

	OPEX decrease 10%	OPEX increase 10%
capital insurance cost (NOK)	-5000	5000
logistic support cost (NOK)	-7606.1	7606.08
commissioning cost (NOK)	-10000	10000
energy consumption cost (NOK)	-11500.4	11500.4
reinvestment cost (NOK)	-15000	15000
cost of deferred production (NOK)	-15333.85	15333.86
onshore support cost	-19015.2	19015.2
installation cost	-20000	20000
operation insurance cost	-22818.23	22818.24
spare parts and consumable consumption	-30424.31	30424.32
man hour cost	-45636.47	45636.48
equipment cost	-150000	150000
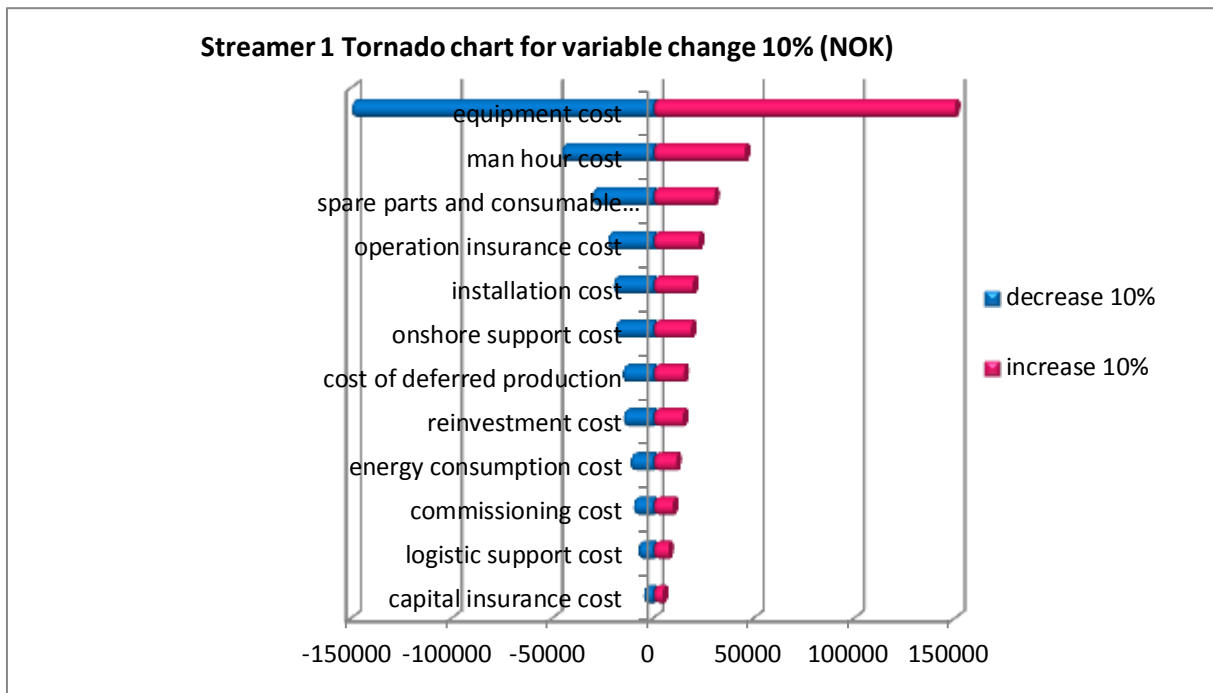
Figure A1.2 Streamer 1 Tornado chart

Table A1.6 LCC analysis for streamer 2

	For streamer 2	detail cost	Year 2012	Year 2013-2027
LCC	Capital cost (NOK)	equipment cost	-2000000	
		installation cost	-300000	
		commissioning cost	-150000	
		insurance cost	-70000	
		reinvestment cost	-100000	
	Operating cost	man hour cost		-16000
		spare parts and consumable consumption		-10000
		logistic support cost		-5000
		energy consumption cost		-10224
		insurance cost		-30000
		onshore support cost		-25000
	Cost of deferred production			-13440
		Total cost per year		-109664
		Discount rate (10%)		0.1
		PV	-2620000	-834113.103
		LCC	-3454113.1	

Table A1.7 OPEX decrease and increase 10%

	OPEX decrease 10%	OPEX increase 10%
logistic support cost	-3803	3803
Capital insurance cost	-7000	7000
spare parts and consumable consumption	-7606	7606
energy consumption cost	-7776	7777
reinvestment cost	-10000	10000
cost of deferred production	-10222	10223
man hour cost	-12170	12170
commissioning cost	-15000	15000
onshore support cost	-19015	19015
Operation insurance cost	-22818	22818
installation cost	-30000	30000
equipment cost	-200000	200000
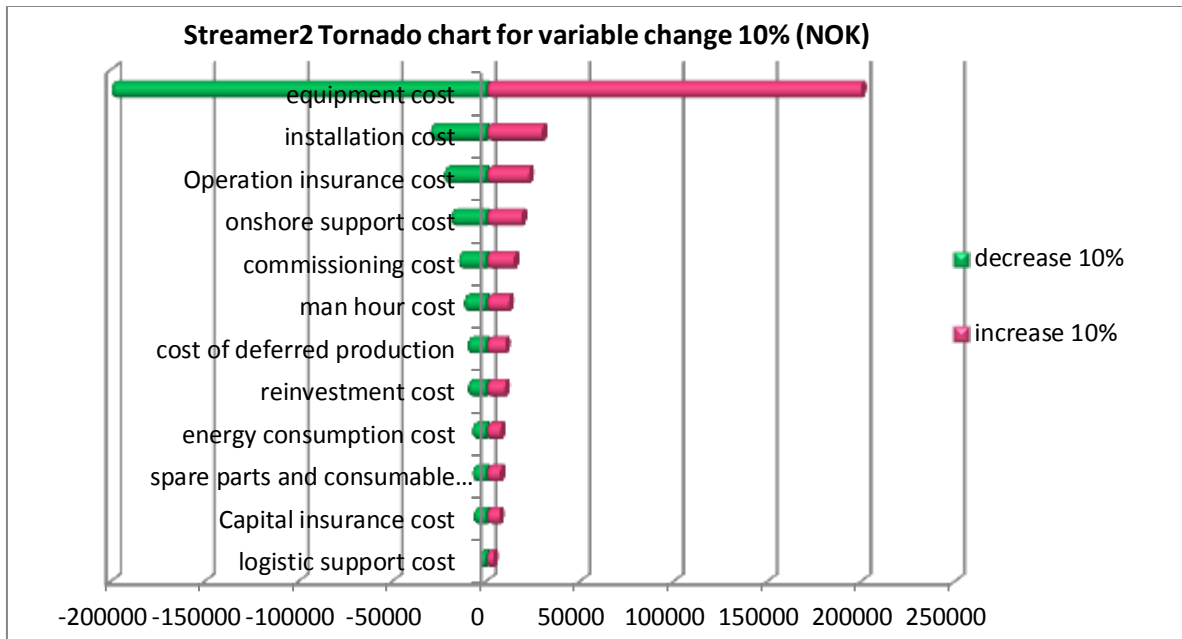
Figure A1.3 Streamer2 Tornado chart

Table A1.8 Cost Summary for alternative streamer 1 and streamer 2 (NOK)

streamers	streamer 1	streamer 2
Capital cost per year		
equipment cost	-1500000	-2000000
installation cost	-200000	-300000
commissioning cost	-100000	-150000
insurance cost	-50000	-70000
reinvestment cost	-150000	-100000
Total capital cost per year	-2000000	-2620000
Operation cost per year		
Man hour cost	-60000	-16000
Spare parts and consumable consumption	-40000	-10000
Logistic support cost	-10000	-5000
Energy consumption cost Insurance cost	-15200	-10224
Onshore support cost	-30000	-30000
	-25000	-25000
Total operation cost per year	-180120	-96224
Cost of deferred production	-20160	-13440
Total LCC	-3523345.6	-3454113.1

Appendix 2: DNV Rules for Ships

SEISMOGRAPHIC RESEARCH VESSELS

A. General

A. General

A 100 Introduction

101 The requirements in this section apply to vessels designed especially for seismographic research operations.

A 200 Objective

201 The objective of this section is to provide a design standard enabling safe and reliable operation of seismographic research vessels with particular focus on the robust design of the seismic equipment hangar; the ability to maintain propulsion power and vessel maneuverability through adapted bridge design and navigation systems.

A 300 Scope

301 This section contains requirements to hull arrangement and hull strength, systems and equipment applicable to seismographic research vessels.

A 400 Application

401 Vessels built in compliance with the requirements as specified in Table A1 will be assigned the class notations as follows:

Table A1 – Class notations				
Class notation		Qualifier		Requirements
Name	Description	Name	Description	
Seismic vessel	Vessel purpose seismographic research	<None>	Hull arrangement and strength	A and B
		(A)	Systems and equipment	C

402 Qualifier **(A)** is optional.

403 Vessels with qualifier **(A)** shall hold the following additional class notations:

— **RP (+) or RPS (+),** see Pt.6 Ch.2; or **DYNPOS-AUTR** or **DYNPOS-AUTRO**, see Pt.6 Ch.7; or

    DYNPOS-ER, see Pt.6 Ch.26

— **E0** or **ECO**, see Pt.6 Ch.3

— **NAUT- OSV(A),** see Pt.6 Ch.20

A 500 Documentation Requirements

501   Documentation shall be submitted as required by Table A2.

Table A2 Document requirements			
Object	Documentation type	Additional description	info
Seismic handling equipment	C010 – Design criteria	Design loads (safe working load, fleet angles, brake rendering load and wire breaking load as relevant). Self-weights of equipment in operational and in transit modes.	F1
	Z030 Arrangement plan	Heavy machinery in hangar and on deck and equipment for handling and storage and mooring at sea.	F1
	Z030 Calculation report	Hangar: Design loads and racking calculations covering operational and transit modes.	F1
Seismic equipment supporting structures	H050 Structural drawing	Including foundations. Design loads, footprint loads and fastening details.	AP
Work boat davits	C060 – Mechanical component documentation	Including: Safe working load, heel/trim if applicable and dynamic factor if above 1.5.	AP
	Z160 – Operation manual		F1
	Z170 – Installation manual		F1
	Z180 – Maintenance manual		F1
Work boat davit winches	C060 – Mechanical component documentation	Including: Safe working load, heel/trim if applicable and dynamic factor if above 1.5.	AP
	Z160 – Operation manual		F1
	Z170 – Installation manual		F1
	Z180 – Maintenance manual		F1

Work boat davits and winches supporting structures	H050 Structural drawing	Including foundations. Design loads, footprint loads and fastening details.	AP

B. Hull Arrangement and Strength

B 100 Design Loads for Seismic Equipment Hangar

101 Loading conditions and load combinations are to be as specified in the Table B1 for transit vessel mode (fully loaded deck equipment in stowed condition) and operational mode (seismographic equipment is deployed).

Table B1 Loading conditions and load combinations on the seismic equipment hangar

Load combination	Transit			Seismic operation	
	Vertical	Transverse	Longitudinal	Vertical	Transverse
$(g_0+0.5a_y)M$	X		X		
g_0M		X		X	X
$0.67\,a_tM$		X			
$0.67\,a_lM$			X		
Equipment load				X	X
Sea pressure	X			X	

Guidance note:

Accelerations are to be according to Pt.3 Ch.1 Sec.4. In no case transverse accelerations $(0.67a_t)$ are to be less than $0.5g_0$.

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102 The total weight M is to include steel weight of the hangar, weight of the deck cargo and fully loaded equipment. For the operational conditions the weight of the equipment can be reduced by the weight of deployed cables.

103 Combinations of equipment loads are to include maximum operational loads on seismographic handling equipment (winches, towing points, etc.) which are assumed to be at least one line with breaking load and remaining lines with safe working load times the dynamic factor.

In case of maximum transverse loading, safe working load on towing points times dynamic factor is to be combined with maximum breaking strength on at least one line in the most

unfavorable position (normally the outermost line). Similar for maximum vertical loading the breaking load is normally to be applied to the mid-span line and combined with SWL time's dynamic factor for the remaining lines.

If the design specification should include combinations with more than one piece of equipment with breaking load then this is to be included in the load specification of the seismic equipment hangar.

104   Breaking load need not to be taken greater than the force causing the winch to render.

105   A design dynamic factor of not less than 1.3 shall be applied to the static SWL of the seismic handling equipment.

106   For the lowermost deck on semi- enclosed hangars, the design load shall be taken as the greater value of the Rule sea pressure and specified deck load (when below $2t/m^2$) in combination with sea pressure. The sea pressure does not need to exceed $30kN/m^2$, when it is used in combination with the deck load. For the remaining decks on semi enclosed hangars, the design load shall be taken as the greater value of the Rule sea pressure and deck load. For open weather deck located over 1.7Cw (ref. Pt.3 Ch.1 Sec.4) above the Summer Load Waterline, the design load shall be taken as the greater value of the Rule sea pressure and deck load.

107   Allowable stresses:

—Normal stresses: 160 f_1 N/mm^2

—Shear stresses: 90 f_1 N/mm^2

B 200 Supporting Structures for Seismic Handling Equipment

201   Local structural strength in way of the equipment foundation is to be in compliance with Pt.3 Ch.3 Sec.5.

202   In case the winch is supported by two deck levels, then local support at one deck level shall be capable of bearing all vertical loads from the winch.

203   When part of the equipment is acting as structural hull support (i.e. winch frame providing pillar support for the decks) it is to comply with the strength requirements as for the main structure with respect to the design loads and Rule acceptance criteria.

204   In cases when equipment is being used as hull structural support this is to be stated in Memo to Owner (MO) and Appendix to Class Certificate.

B 300 Strengthening for Side-By-Side Mooring

301 The SWL for the mooring bollard shall be at least 3 times the minimum breaking load of the mooring lines according to the vessel's equipment letter, or based upon the designer's specification for the minimum breaking load to be used for side-by-side mooring lines.

302 The mooring line specification and restrictions on operation of the mooring bollards are to be stated in the Appendix to Class Certificate and in a Memo to Owner.

303 The strength of supporting deck structure is to be based on the mooring bollard's SWL times 1.5.

304 Allowable stresses:

—Normal stresses: $160 \, f_1 \, N/mm^2$

—Shear stresses: $90 \, f_1 \, N/mm^2$

C. Systems and Equipment

C 100 Certification Requirements

101 Components shall be certified as required by Table A3.

Table A3 Certification requirements			
Object	Certificate type		Additional description
Work boats	NV-P	DNV product certificate	DNV Standard for Certification 2.21 – Craft
Wide tow equipment	NV-P	DNV product certificate	DNV Standard for Certification 2.22 – Lifting Appliances, normally as 'Industrial crane'
Handling and towing booms	NV-P	DNV product certificate	
Work boat davits	NV-P	DNV product certificate	
	NV-M	DNV material certificate	EN 10204
Work boat winches	NV-P	DNV product certificate	
	NV-M	DNV material certificate	EN 10204

102 For a definition of the certificate types, see Pt.1 Ch.1 Sec.4 B.

C 200 Work Boat Davits and winches

201 Where fitted, work boat davits and winches, unless otherwise required by national authorities are to comply with SOLAS 1974 and the LSA Code, with the following exceptions:

—No requirements to heel or trim unless specified by operator.

—Stored mechanical power not required, however lowering in dead ship condition shall be possible.

—No requirements to hoisting or lowering speed.

—If estimated dynamic factor exceeds 1.5, shock damper arrangement is required.

202 In addition to strength requirements given in above regulations, fatigue according to a recognized standard to be considered.

203 Testing at factory and after installation on board shall be performed in line with IMO MSC. 81(70) part 2.

C 300High pressure air system

301 The piping system shall comply with the requirements in Pt.4 Ch.6. In addition, the requirements specified in 302 to 311 are to be fulfilled.

302 High pressure pipes shall not be installed in the vicinity of gangways or other spaces which are in normal use by personnel. If this cannot be avoided, shielding or equivalent arrangement shall be applied.

Any manifold and pressure relief valve shall be shielded to safeguard any operator. The pressure relief valves shall be arranged for venting to exhaust or overboard.

Guidance note:

 Example of appropriate shielding may be punched steel shields. The shielding may also be removable in order for accessing de-pressurized equipment.

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303 Pipes should be inclined relative to the horizontal. Water pockets in the pipeline shall be avoided as far as practicable. If this cannot be avoided, means of drainage shall be arranged.

304 All manifolds and other locations where liquid may accumulate shall be arranged with possibilities for efficient drainage. Automated drains shall be arranged for air receivers, with additional possibility for manual operation.

305 Lubricating oil points for the air guns shall not be located in the vicinity of manifolds. If this cannot be avoided, there shall be arranged automatic shutdown of lubrication pumps when the high pressure air system is not pressurized.

306 All valves shall be automatically operated in order to prevent adiabatic compression or water hammer in the system. Alternatively, the system shall always be de-pressurized before operating any valves.

Guidance note 1:

Opening time of a valve shall be at least 10 seconds.

Controlled pressure adjustment before opening a high pressure valve may, in some cases serve as an equivalent to automatically operated valves. By adjusting the system pressure to 1:8 of design pressure, the risk of generating high temperatures through adiabatic compression is negligible.

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Guidance note 2:

In cases where automatic operation is not possible to install, each valve shall be permanently marked with warning against rapid opening.

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307   Air intakes for the compressors shall be so located as to minimize the intake of oil or water contaminated air.

308   Pipes from air compressors with automatic start shall be fitted with a separator or similar device to prevent condensate and HP piping must be done in a way to prevent condensate from draining back into compressors.

309   Cylinder banks shall be located in areas which are not in normal use by personnel. The area shall be arranged for high pressure air to expand in case of an explosion.

Guidance note:

Proper shielding of connected piping and valves may be considered as an equivalent solution if designated areas cannot be arranged.

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310   There shall be at least one burst disc installed at the manifold, and one at the cylinder bank. The discs shall be directed away from working areas.

311   The piping shall be hydrostatically tested for at least 30 minutes in the presence of a DNV surveyor after installation on board with the following test pressure:

$$PH = 1.5 \ p$$

PH = test pressure in bar

p = design pressure in bar as defined in Pt.4 Ch.6 Sec.7 A303.

The test pressure need not exceed the design pressure by more than 70 bar.