Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Risk Analysis of Dynamic Positioning (DP) System in Different Innovative Applications.

Master's thesis in Reliability, Availability, Maintainability, and Safety (RAMS).
Supervisor: Associate Professor Yiliu Liu
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Preface

This master thesis work has been carried out and submitted a report in relation to a mandatory requirement for the completion of master´s degree program in Reliability, Availability, Maintainability and Safety (RAMS) in the department of Mechanical and Industrial Engineering at NTNU during spring semester of 2021. This thesis work is a continuation of specialization project in fall semester of 2020.

The main objective of the thesis was to carry out risk analysis of dynamic positioning system in different innovative applications, which was done by using qualitative and statistical methods of risk analysis. For statistical risk analysis methods R studio with R version 4.0.3 have been used. Although, it has been tried to establish some understanding of basic concepts, but it is expected that readers of this report possess some prior knowledge of DP system and risk concepts.

Acknowledgement

I would like to express my gratitude and sincere thanks to everyone who has helped me directly or indirectly for the completion of this master´s thesis.

Particularly, I want to extend my special thanks to project supervisor, Yiliu Liu. He has been very kind and without his consisting and brightening supervision this thesis could not be completed. Yiliu, has ensured regular meetings during the course of this research journey which has helped tremendously to stick to the objective of the thesis.

I would also like to acknowledge significant contribution of co-supervisor and DNV representative, Also, R studio online community have helped me a lot to learn and implement R for statistical analysis carried out in this thesis.

Finally, I would like to thank my wife who have been very strong support for me throughout this phase of writing master´s thesis.

Abstract

Dynamic Positioning (DP) system has been around for many years but major attention to this technology was given by the oil and gas sector. When the hydrocarbon exploration was moving into deeper waters with a harsh environment where position keeping of vessel was more important than ever. Dynamic positioning emerged as a great solution for position keeping and heading of vessels. Many approaches and methods have been developed in managing the risks affiliated with this emerging technology.

A rapid increase of DP system application is not only in the oil and gas sector but in other sectors including the aquaculture industry. The biggest challenge in DP application is how to ensure its safe operation in an emergency or critical situation. There are two important factors that may impact DP safety, including the endurance of a DP in contradiction of drift-off from the required position and its ability to recover to the required position from loss of position.

Data analysis on DP incident data from IMCA shows that the occurrence of loss of position in DP vessel operation is not an uncommon event. This master´s thesis focus on risk analysis of DP system in different innovative applications. Failure modes and effects analysis has been used to investigate the risks from a qualitative point of view. While statistical methods have been used to predict the probability of DP system failures using IMCA incident data for nine years (2010-2018). While applying regression analysis for risk analysis, challenges like the low power of data have been addressed. Based on the results of risk analysis from FMEA and statistical methods, the thesis also discusses practices and measures for safe operations of DP system in aquaculture.

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Abbreviations

DP	Dynamic Positioning
DPS	Dynamic Positioning System
IMO	International Maritime Organization
DPCCS	DP Computer Control System
LoP	Loss of Position
DNV-GL	Det Norske Veritas Norway and Germanischer Lloyd
MODU	Mobile Offshore Drilling Units
IMCA	International Marine Contractor Association
ABS	American Bureau of Shipping
LR	Lloyds Register of Shipping
PID	Proportional Integral Derivative
BOP	Blow Out Preventer
MRU	Motion Reference Unit
VRU	Vertical Reference Unit
AC	Alternate current
IoT	Internet of Things
AI	Artificial Intelligence
ALARP	as low as reasonably practicable
ISO	International Organization for Standardization
RAC	Risk Acceptance Criteria
TQ	Technology Qualification
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
HAZOP	Hazard and Operability Analysis
DPC	Dynamic Positioning Committee
GPS	Global Positioning System
EQD	Emergency Quick Disconnect
UKCS	United Kingdom Continental Shelf
FTA	Fault Tree Analysis
ROV	Remotely Operated Vehicle
LoA	Level of Autonomy
APS	Acoustic Positioning System
DVL	Doppler Velocity Logs
STPA	Systems-Theoretical Process Analysis
SHERPA	Systematic Human Error Reduction and Prediction Approach
OR	Odd Ratio
CI	Confidence Interval
SE	Standard Error
SD	Standard Deviation

Chapter 1

Introduction

This chapter comprehends briefly that what is a Dynamic Positioning (DP) system, why risks in DP system is important along with research background and its objectives. In order to give an overview to the reader, the structure of the project will be presented later in this chapter.

After World War II, emergence of global economization happened with businesses, and researcher started to investigate ways to make things more rapid and safe. When oil and gas producer decided to expand, and look for oil in the deeper water, positioning of the drilling rigs and other vessels in harsh sea environment was a major challenge among many other challenges. Tools and techniques used in exploration of hydrocarbons in shallow water were not acceptable for offshore deeper waters due to punitive deep-sea environment. The need of novel methods and techniques opened an era of DP system to position the vessels and supplementary offshore installation in deeper waters. At present DP system is complex, advance and technologically well-equipped compared to its early days (1).

According to the International Maritime Organization (IMO) (2), DP vessel as "*a vessel that is able to maintain its position and heading, and to maneuver slowly along a predefined course, solely by means of its thrusters".* In general, a DP system consists of a DP computer control system (DPCCS), the thruster system and power system.

1.1 Research Background and Motivation

Demand of DP system has been on the rise since its success in the maritime operations. The technological novelties and broaden applications of DP system presents new challenges associated with overall safety and control of risk during its operations(3). Loss of position (LoP) of DP vessel from its required coordinate is considered to be the biggest risk in DP system. The consequences of LoP can be outsized but main consequences are subsea and topside blow out, damage to assets, life threat to on-job personnel, damage to environment etc. (4). In DP system, principally LoP accident can occur due to two failure modes of DP system that are drive-off and drift-off (5, 6).

To meet or exceed the expectations of the industry DP system is put to technological progressions, higher level of automation, advanced power system and thruster system (backbone of DP system) that is capable of an increased autonomy. Such autonomy and technological advancement has enabled DP system to interact at components level and information level (3). This means the risk analysis is even more important at early stage to avoid complete failure. For safe DP operation, international standards and DP classifications are in placed that DP users are bound to adhere to reduce the risk of accident during its operations (2, 7).

Despite of the fact that from last ten years' serious efforts have been made to make the world's environment better and safe for our planet. Even with such efforts world demand for oil and gas has not gone down and industry leaders are exploring for hydrocarbons further in deep and ultra-deep water. A successful introduction of DP system in oil and gas sector has made it relatively easy to achieve the objective of deeper water hydrocarbon exploration.

The application of DP system is yet to be recognized in aquaculture industry even Norway's aquaculture industry is second biggest industry only after oil and gas. Since Norway is one of the largest Salmon fish producers in the world. In order to meet the ever-increasing demand of Salmon, this will necessitate use of ocean resources, more space for farming, and production sites (8).

It can be challenging for aquaculture to adopt required planning and execution for its operation in ocean farming. However, petroleum industry, through many years of lesson learnt, has established and developed many standards, rules and regulations for different system required for safe marine operations. It will be very interesting to see to what degree aquaculture can adopt from petroleum industry.

1.2 Objectives

The main objective of this master thesis is to carry out risk analysis of Dynamic Positioning System in innovative applications. The secondary objectives of this master thesis are to

1- Establish better understanding of DP system and risks associated with DP system
2- Understand and review how DP system application can be seen in aquaculture environment.
3- Demonstrate risk analysis methods for DP system.
4- Qualify and quantify risks in DP system based on historical incident data and discuss result from both methods.

1.3 Novelty

The novel part of this thesis is that the author has analyzed the risk in DP system using statistical methods that are linear regression analysis, correlation analysis and logistic regression analysis. Later sections shows that a lot of research has been done on qualitative risk analysis in DP system but quantification of risk in DP system lacks. This thesis with the help of aforesaid methods quantify the risk in DP system based on IMCA incident data for nine years. The results from statistical methods are compared and discussed with results from qualitative method, FMEA, and suggest best practices for safe DP operations.

1.4 Limitations

Due to time and resources constraint, it was not possible to get access to the reliable and realistic failure rate and other related data of DP components due to which the intensive and in-depth quantitative analysis on components level was not possible. Initial plans of the thesis were to work in DNV Oslo office for the whole semester and complete the thesis but due to COVID 19 this was not possible. That hinders the access to different tools and information which could have helped greatly to look other aspects of risk analysis in DP system.

Since, IMCA has their own system to collect the incident data from owners and DP system operators so the power of the data in terms of number of factors while incident happen (e.g., water depth, current, wind speed etc.) and number of years was not very strong. Data with more power and consistency can help predict the risk more effectively.

1.5 Structure of the Report

Chapter 1: Brief Introduction of DP system and structure of thesis.

Chapter 2: This chapter will cover background of DP system with detailed literature review.

Chapter 3: This chapter will give an overview of aquaculture industry and particulars of aquaculture in a sense of using DP system.

Chapter 4: This chapter will cover the detailed risk analysis methods for DP system. After establishing basic risk concepts, the chapter will analyze the nine years DP incidents data from IMCA. In next sections background of qualitative, FME(C)A, and statistical methods. Linear regression analysis, correlation analysis and logistic regression analysis, being used in the thesis will be discussed.

Chapter 5: In this chapter, FMEA and statistical analysis is carried out and results of both analyses are discussed and compare. Based on the results, this chapter will also include suggestions and recommendations for the safe operations of DP system in aquaculture.

Chapter 6: This final chapter will present conclusion and scope for the further study.

Chapter 2

Background of DP System and Literature Review

2.1 Dynamic Positioning (DP) System

DP technology was born back in 1960s in the US aiming to assist the vessel movement in horizontal degrees of freedom namely sway, surge and yaw. The first DP vessel was based on manual system developed for geologists to study the sliding of ocean plates on the seabed. But the advancements in the DP system started to emerge once oil and gas business began to show interest in it. For Norwegian sea, DP system has to travel long 17 years' journey from 1960 to 1977 and transformation from manual to automated under the supervision of prof. Jens Balchen with team of 12 in collaboration with SINTEF and Kongsberg in 1977 (9).

In order to ensure safe operations for oil and gas exploration activities in offshore floating units, a reliable station keeping system is one of the utmost important services. According to DNV-GL, application of DP has become vital and necessary part for position keeping of vessel and rigs operating offshore. Safe positioning is very important to avoid any personnel injuries, environmental pollution and damage to the assets in the field (1).

The DP system expanding its horizons in wider range of application, but typical applications in different type of vessels are not limited to only station keeping of mobile offshore drilling units (MODU), working in close vicinity to another vessel or structure, shuttle tanker operations, underwater operations, platform support vessels during loading and offloading to platforms, diving vessels, storing and offloading units, supporting diving operations, anchor handling, maneuvering of pipe layer vessels, passenger/cargo/heavy lift vessels and military vessels (3, 7).

Ocean fish farming is another growing sector particularly in Norway. The Norwegian government is very keen to ensure fish farming within natural limits that means ocean farming is becoming popular in Norway. With the introduction of larger scale ocean farming, DP system in the fish industry will play a very vital role in coming years. It can range from farm development of ocean farms to loading and offloading fish. In current practices for some vessel shaped fish farms, DP system has its application in connection with mooring system. The purpose of this duo system is to reduce hydrodynamic loads and possibility to disconnect in strict weather conditions (10).

Due to advancement in technology and needs, DP vessels are in great demand since ever. In the recent 35 years demand of DP vessels in aforementioned applications have increased abruptly (11). The trend of increasing number of DP vessels from 1980 to 2015 has been depicted in figure 1. There are varied forces acting on the DP vessels and DP system should manage to maintain its required positions. The forces acting on DP vessels can be strong waves, wind, and sea current.

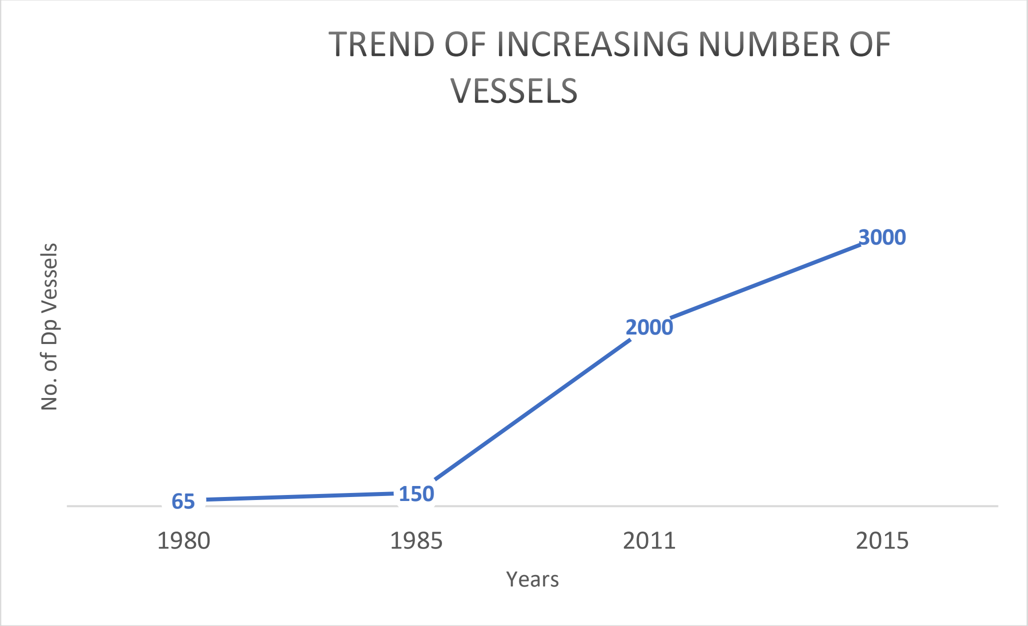


Figure 1: Increasing trend of DP vessels utilization with time (6, 11)

There are number of factors which decide the accomplishment of DP vessels utilization in different industries. Following are the main factors associated with the success of DP vessels:

(i) Training and skills level of DP operators
(ii) Reliability of equipment (computer, power system, thruster etc.)
(iii)Analysis of risk and methods to mitigate associated risk

Although, there are many different standards, laws and regulations in place for the design and operation of DP vessels (12, 13) but still many accidents happened in the past. The risk of accident to happen may occur due to operational or technical fault. The basic definition of accident in DP system is loss of position (LOP) of the vessel from its required reference or coordinates. The consequence of LOP incident includes subsea and topside blowouts, leakage of drilling mud which may cause significant harm to the environment, personnel on job and assets. Drilling with the use of DP vessel is considered as a dangerous operation therefore it is utmost important to study and investigate how blowout may develop and find methods to reduce the risk (4).

According to the International Marine Contractor Association (IMCA), operator error is the second largest contributor in main and third largest contributor in secondary causes for LOP incidents. Here main causes are defined as “ a fault that leads to a failure of a system or subsystem leading to loss of position” and secondary causes are defined as “attributes that provide foundation to the incident or confuse the position loss recovery” (14). Figure 2 shows the main and secondary incident causes reported by IMCA.

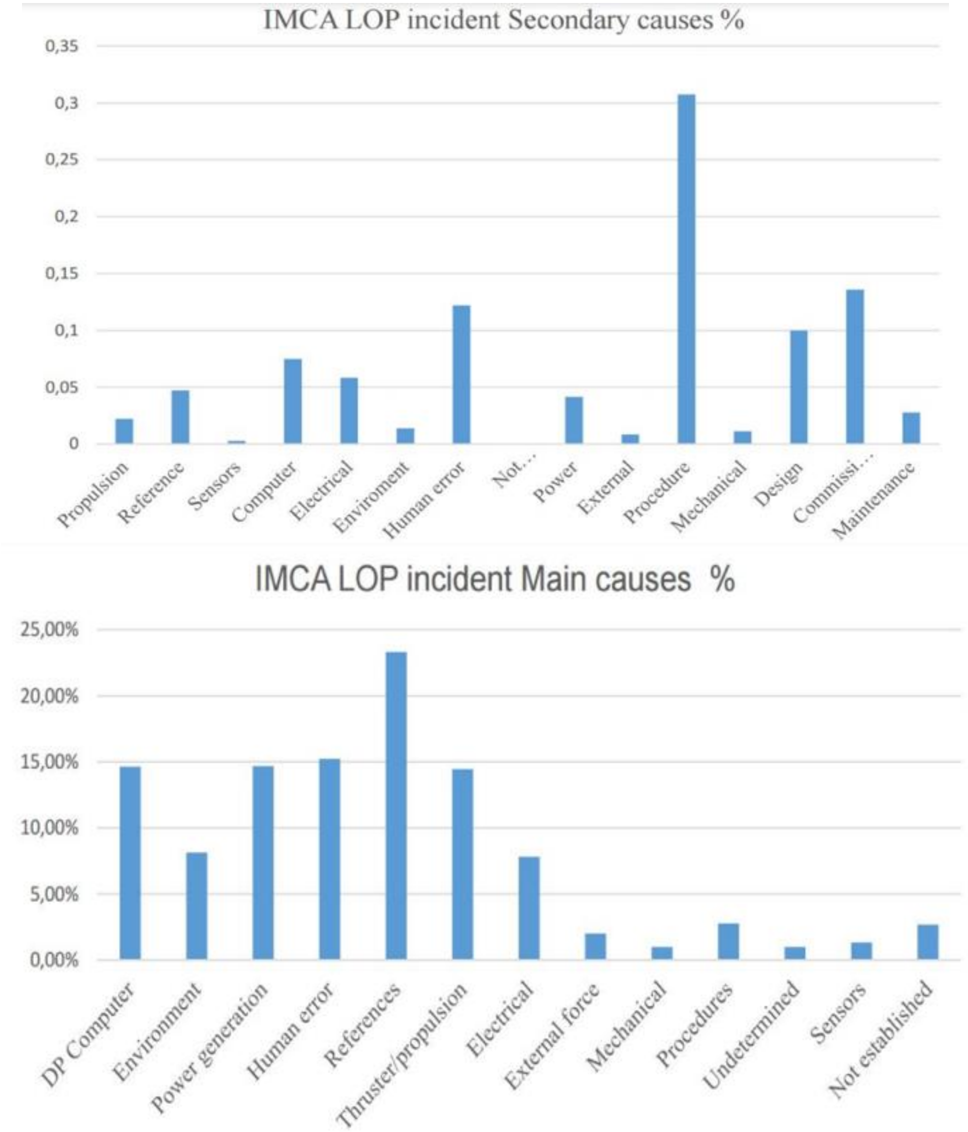


Figure 2: Main and secondary causes for LoP reported by IMAC (14)

The main causes are based on 620 incidents based on IMC categorization while secondary causes are based on 361 incidents. It is important to note that human errors in both the cases are relatively high. The other noticeable trends are references, DP computers and thrusters in main causes while procedures and commissioning in secondary causes. Further in the thesis it has been tried to go into deeper risk analysis to postulate better understandings why and which parts of DP system are commonly involved in failure and need more attentive attention for safe operations.

According to Verhoeven et al. (15) there are three type of failure modes of loss of position in DP vessels (i) drive-off (ii) drift-off and (iii) force-off. Moreover, time loss is mentioned as a third mode in addition to drive and drift-off (14, 16). Mainly, the first two failures modes have been discussed more extensively in the literature (5, 6).

Drift-off *refers to the state when vessel loss its position due to fractional or complete loss of thruster leading the DP vessel to drift.*

Drift-off can happen due to power failure, system failure, DP control system failure, operator error, etc.

***Drive-off** failure is referring to the state when loss of position is due to an inadequate and unwanted forces applied to the DP system or DP control system failure leading the DP vessel or installation to move on a hostile direction.*

Drive-off can be in any direction (17).

Because of the nature of the failure mode, forces convoluted in the process of drive-off are more significant than in case of drift-off. As a result, the damage in drive-off situation will be greater. Therefore, more literature and in-depth analysis of drive-off incidents is found compared to drift-off. It is also highlighted in literature that DP control system failure is the root cause involved in all the incidents (18).

The nature of the LOP event depends on the kind of failure happens. DP operator can prepare and manage to take effective and better actions to avoid worst consequences provided he has better knowledge or information about the effect of failure. This information can be very critical and might have great significance in risk assessment process if vessel get into a situation where it has to operate with faulty components.

As mentioned in the aforesaid text, DP vessels have large range of application in offshore marine operations therefore risks triggered by DP vessels in offshore marine operation are not marginal. In the recent two decades, a lot of research work has been carried out in identifying and assessing risk associated with DP vessels. In chapter 4 more details of risk aspect of DP system is be covered.

2.2 Historical Viewpoint of DP System

Since the introduction of DP system, there exists different definitions of the system with little variation but the objective and aim of the system remains same. According to IMO and DP class certifying bodies (DNV-GL, ABS, LR, etc.) DP is defined as a vessel that maintains its position and heading by mean of active thrusters (2, 12). As mentioned earlier and according to Fay the first commercial DP was announced in 1960 which was aim for the motion in horizontal manners only namely surge, sway and yaw. The first DP system was using principle of single input and single output PID (proportional integral derivative) control algorithms in combination with low-pass and notch filter (19).

The concept of wave filtering technique derived from the Kalman filter theory used for the first time by Balchen, Jenssen and sælid (20) is thought to be the major revolution in marine control system largely. The concept has further motivated many other marine control applications (21). Balchen and team (20) extended their work and presented more cutting edge control methods cantered around multivariable optimal control and Kalman filter theory. This research provided the basis for the concept and later this work was improved in a comprehensive way by many researchers in the field of dynamic positioning (21, 22).

Since the marine resource exploration is being done at a higher continuous rate, as a result research scientists and companies are investing more time and resources to look for advance technology and ways in which they can perform their work in the sea more effectively. In this quest, a DP system has become a backbone of the activities in the sea where control of position is necessary (23) .

DP system has voyaged a long journey and now a days DP system has more mature computer control system that plays a very vital role in the vessel positioning system. Now a days DP vessel are equipped with more than one computer system for redundancy purpose. If one computer fails the sensors can alert the operator while function requirements are fulfilled by the redundant computer system ensure DP vessel provide required accurate positioning (24, 25).

As mentioned in aforesaid text that traditional anchoring methods were failing and to address these failing methods the DP system was introduced on the vessels. The first ever drillship using concepts of dynamic positioning was called CUSS1. It was basically a joint venture of Continental, Union, Shell and Superior Oil. The CUSS1 was equipped with moveable thrusters that were capable of rotation/moving through a full circle. The speed and direction of the ship ere manually controlled from a central location (26). Figure 3 shows a pictorial view of the CUSS1.

Figure 3: CUSS1 first vessel to use dynamic positioning (26)

After CUSS1, Shell oil decided to develop a first DP system loaded vessel from the scratch. The vessel was named Eureka, it was built with more power to the thrusters. Yet, the speed and direction of the vessel to be controlled manually at first. Position was to be measured using oscilloscope and heading of vessel using gyrocompass. For Eureka, it was observed that the planned manual thruster control was a risk to the objective of Eureka. Shatto (26) quickly realised the position control need to be automatic for Eureka to succeed. Eureka then become the first DP vessel with automatic position control. In 1971 Shell oil built the first DP rig for oil well using riser and blow out preventer (BOP), the rig was called SEDCO 445. Figure 4 shows the pictorial view of the DP loaded vessel Eureka and first DP rig SEDECO 445 (26).

Figure 4: Eureka DP equipped vessel (top) and SEDECO 445 first DP rig (bottom) (26)

2.3 Classification of DP System

DP system reliability mainly depends on its ability to keep the required position. According to Rokseth et al. (3) the main concern in DP vessel is loss of position keeping ability of the DP system. The DP system is classified based on consequence of loss of position keeping ability. If the consequence is higher, the DP system must be more reliable.

According to IMO, DP system is categorized as per DP control system, thruster system and power system. In order to classify the designed equipment DP system is categorized into three different classes (2).

DP Equipment Class 1: This class does not have any redundancy and loss of position may occur due to single point failure.

DP Equipment Class 2: This class has a redundancy that means loss of position should not occur in case of single point failure in the active components or system. Although, loss of position may occur due to single failure of static components. This class can offer auto changeover in case of failure of an active component. Active components include switchboard, generator, thruster, remote controlled valves etc. While static components can be pipes, cables, and manual valves etc.

DP Equipment Class 3: This class has very high redundancy and loss of position should not occur in case of any single failure including all components in any one fire subdivision from fire or flood and all components in any watertight compartment from flood or fire. A single fault also includes a single unintentional act by the DP operator or any person on board the vessel. This class offers an additional element of safety along with 2003 voting.

Class 3 DP vessels are in higher demand in oil and gas sector, this is to ensure higher safety of equipment, personnel on job and to adhere the in-place rules and regulations of the business. Beside the class definitions, IMO provides further requirements for each of the subsystem of the DP system. Rokseth et. Al (3) highlighted in their research that societies that provides DP classifications like DNV-GL, ABS and other postulate supplementary requirements for DP system. The aim of these requirements is to ensure the international standards for DP system are satisfied (2, 12).

Following table demonstrates the classification of the IMO based DP classification relates to DP system components by different societies in the DP business (27, 28).

Table 1: DP System Classification (39)

		Classification Societies		
Sr. No	**International Marine Organization (IMO)**	**Det Norske Veritas (DNV-GL)**	**American Bureau of Shipping (ABS)**	**Lloyds Register of Shipping (LR)**
1	Class 1	DPS 1/ DYNPOS-AUT	DPS-1	DP (AM)
2	Class 2	DPS 2/ DYNPOS-AUTR	DPS-2	DP (2A)
3	Class 3	DPS 3/ DYNPOS-AUTRO	DPS-3	DP (3A)

There exists a class 0 in DP system as well, but it will not be discussed in this thesis because the scope of Class 0 is stationary and manual positioning is required therefore it has very limited or no application in oil and gas sector. Minimum DP class requirements as per IMO (2) guidelines is given in appendix 1.

2.4 Basic Principles and Elements of DP System

Since the following two have been established through literature in the aforementioned text

(i) *Fundamental objective of the DP system is to automatically control the position and heading of the seagoing vessels*

(ii) *Vessels out in the sea are subject to different forces from weather (wind or storm), waves, and current alongside forces produced by the propulsion system.*

There are different internal and external forces action on the seagoing DP vessel. These forces produce six autonomies movements, namely yaw, sway, surge, pitch, heave, and roll. Figure 5 present the pictorial view of internal and external forces acting on DP vessel along with varied free motions caused as a result of these forces (29).

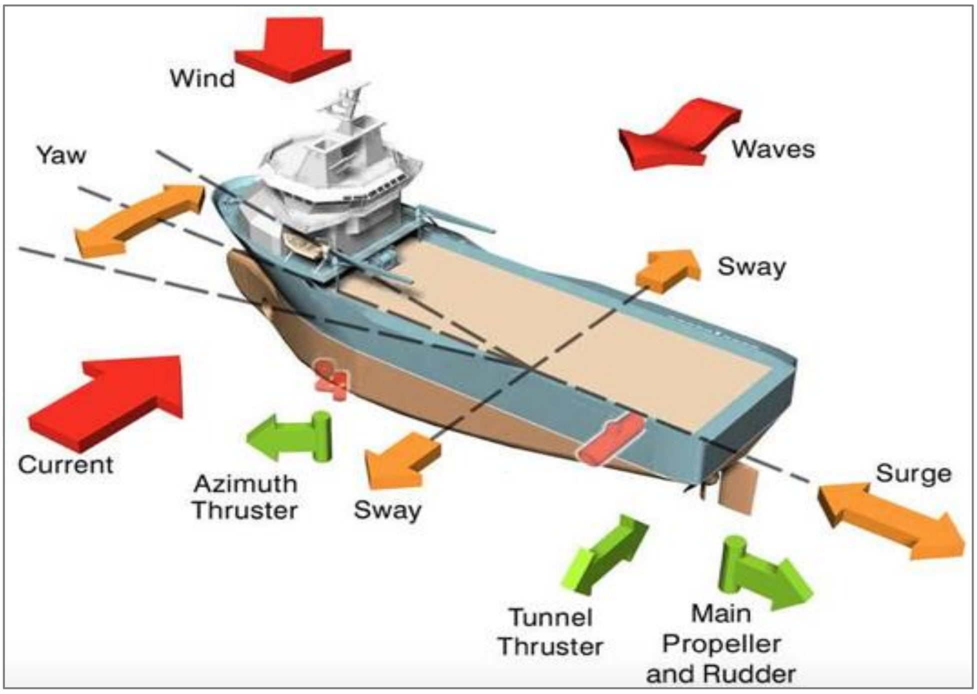


Figure 5: Forces acting on DP vessel (29)

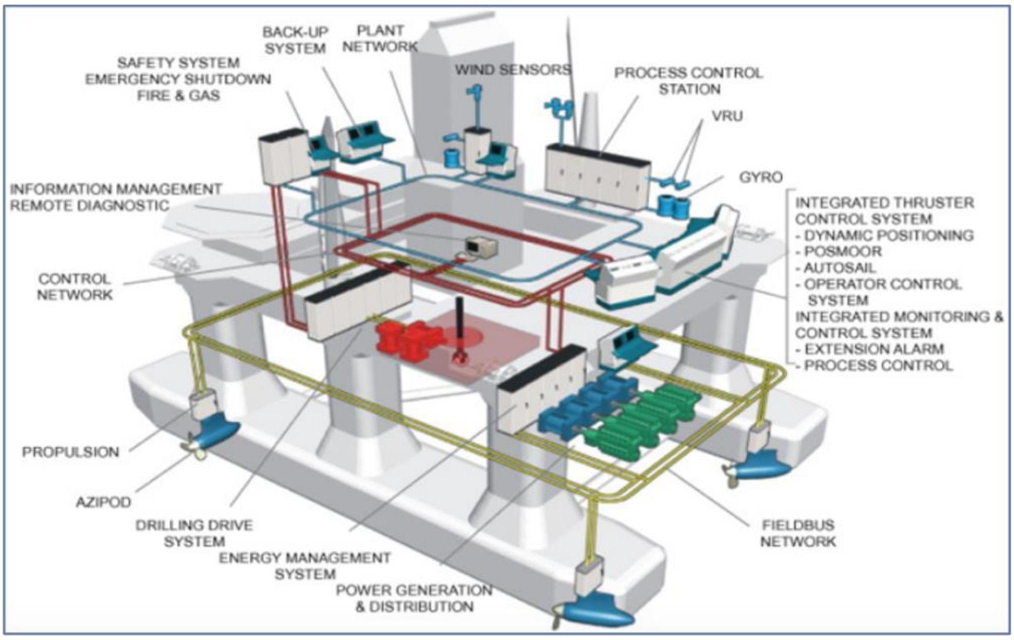


Figure 6: Components of DP System (30)

The orange arrows in the figure 5 shows the desired degree of freedom in which DP vessel position itself while counter acting the internal and external forces, presented in red arrows, using thrusters presented in green arrows. According to Chas and Ferreiro (31), yaw, sway and surge are degree of freedom in the horizontal plane while pitch, heave and roll are degree of freedom on vertical plane. DP system controls the degree of freedom on horizontal plane but not on vertical plane, nevertheless, for position-reference system to correct these motions the system must have the information about vertical degree of freedom. Position of the DP vessel is associated with sway and surge whereas heading of DP vessel is associated with yaw. It is important to mention that DP system is focused on automatic control of horizontal degree of freedom only (31).

2.5 Structure and Main Components of DP System

DP system comprises of mainly five sub-systems, that are listed below. Figure 6 illustrate different system on a DP rig.

- *(i)* *DP control sub-system*
- *(ii)* *Position and heading reference*
- (iii) *Power generation sub-system*
- *(iv)* *Thruster and propulsion sub-system*
- *(v)* *Environmental reference sub-system*

2.5.1 DP Control System

The DP control system consist of computer, joystick system and console or so-called operator station. The mainframes enabling the DP control system through software is termed as DP computer. The installation of single (simplex), two (dual) or triple (triplex) computer system entirely dependent on the notation of DP classes. For example, triplex computer system will be installed for vessel equipped with class 3 DP system.

The console is an interface with all the control input, switches, button, screen etc. for the operator to receive and send the data. Different parameters from important components like thruster system, power generation, control system etc., are displayed on the console screen. Console provides great exposure to the DP operator for the safely operation of the DP vessel operation.

2.5.2 Position and Heading Reference System

This is one of the most important system for the success of the DP system operation because DP system require reliable, accurate and continuous feed of data from position reference system. The accuracy of DP vessel depends on the accuracy of position reference system input. Position reference system consists of five different sub-system namely (i) Hydro acoustic, (ii) DGPS, (iii) Taut wire, (iv) Laser based and (v) Artemis. For the purpose of increased data validation for calculation of accurate position, Taut wire with hydro acoustic position reference system can be used with the GPS system (31).

2.5.3 Environmental Reference System

This system measures the different environmental forces action on the system. In the literature, mainly three environmental forces have been discussed that can cause the DP vessel to loss its position. These forces are created by wave, wind and current (31-33). Almost, all the DP system now equipped with sensors which collects environmental data, which is used to calculate induced forces action on hull and structure of the vessel. This allow the acting forces to be balanced before cause the damage in the form of loss of position or change in heading. Following are most commonly used environmental sensors in DP system (33).

Gyrocompass**:** The change in the heading of the DP vessel is detected by Gyro sensor and fed to the DP system controller.

Doppler Log**:** Speed of the DP vessel over the seabed is provided through Doppler log. It also records the speed signal from DGPS.

Vertical Reference Unit (VRU)**:** Pitch and roll are measured with the help of VRU. This sensor is often termed as motion reference unit (MRU). Although, it is not in the scope of DP system to control the movement in pitch, heave and roll axes, yet it is important that pitch and roll changes are measured to provide accurate compensation for other measuring equipment.

Wind Sensor*:* To measure the speed and direction of the win in the sea a sensor called anemometer is used.

2.5.4 Propulsion System

According to Boletis et al. (34) capabilities of DP vessels depends on the propulsion system installed on the vessel. Control system used for the system plays very vital role to achieve the optimum performance of overall propulsion system. Generally, there are three types of thrusters used for DP vessels.

- *i)* *Main propeller*
- *ii)* *Tunnel Thrusters*
- *iii)* *Azimuth Thrusters*

Propellers provide bi-directional thrust but due to the shapes of the blades and effect of the hull the thrust in the reverse direction is only 40-60% is available in forward direction.

Tunnel thrusters are always framed in the bow or stern of the vessel. These thrusters enable the DP vessels to move sideways and allow turning moment. The effectiveness of these thrusters is only realized at a low speed and when placed at as larger distance as possible under the waterline.

Azimuth thrusters are generally placed in pods and can rotate to any horizontal angle provide more control for the direction of the thrust inside 360o. These provides the DP vessel better maneuverability compared to fixed propeller and rudder system.

2.5.5 Power Generation System

Power generation system is the backbone of DP vessel. Many accidents happen in DP vessels due to failure of power system. Despite of the fact that power system in DP vessels has made great progress but still many accidents happen due to failure of this system. This is most important system for the operation of DP system because it provides power to the thrusters and all supplementary system along with DP control and reference systems as discussed above.

Thrusters are the highest power consuming components on the DP vessel. To avoid power failure many DP vessels are equipped with diesel-electric power plant. In case of power cut out from main AC supply, the back-up batteries will supply the power to the essential components to avoid any failure. Essential components can include computer systems, alarms, reference system, consoles and display (31). Figure 7 gives a better view of DP components.

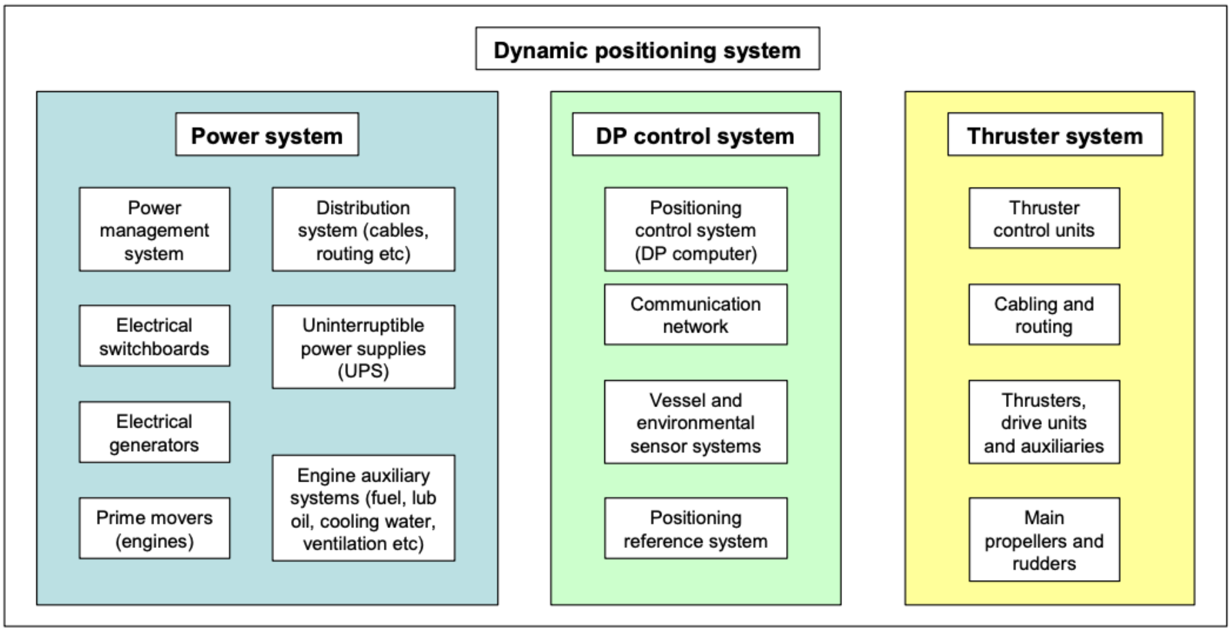


Figure 7: **Dynamic Positioning Components (30)**

Chapter 3

Aquaculture and DP System

Some basic concepts have been developed and application with background of DP system have been discussed in chapter 1 and chapter 2. DP system innovatively has been adopted in aquaculture, specifically on a fish farm out in the sea, for the first time. Havfarm 2 is a boat shape steel structure fish farm with its propulsion system (dynamic positioning system) that will function free of mooring installation. Since Havfarm 2 will be operating out in the sea with harsh weather conditions so DP system will be used for position keeping and transfer of fish during production lifecycle. The general idea of Havfarm 2 is to make use of highly exposed areas when the weather condition permits and more protected areas when there is a risk that environmental loads will exceed certain safety levels, and this is achieved with the help of DP system.

Since aquaculture is seeing an innovative application of DP system for first time so it is imperative to understand the basics of aquaculture before we can suggest some safety measures for aquaculture industry when it comes to DP system application. Following chapter will briefly discuss the concepts and development of aquaculture along with components of a fish farm.

3.1 Aquaculture Industry

Aquaculture, most known as fish farming industry, is flourishing worldwide to meet the dietary needs of the world’s rising population. Figure 8 shows the annual growth of the aquaculture industry since 1980s.

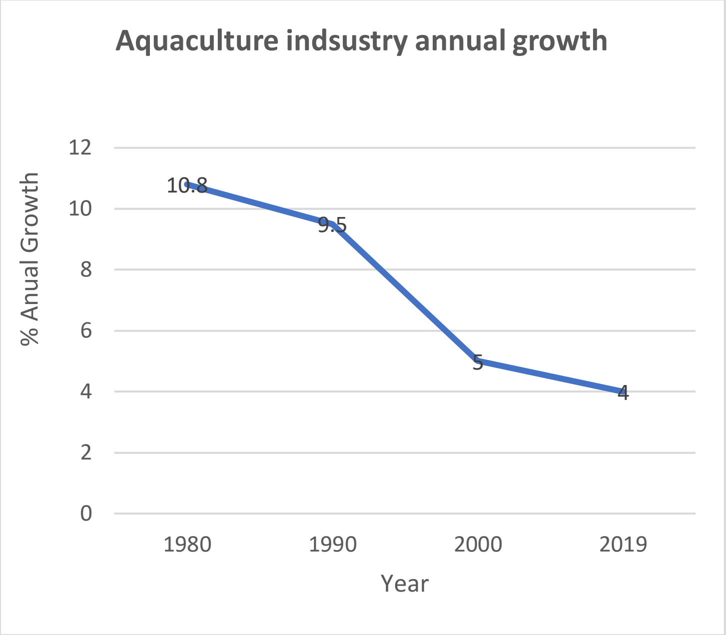


Figure 8: Annual growth in aquaculture industry (35)

It is very interesting trend that the world has seen an exponential growth in aquaculture in 1980s and 1990s later the industry started to mature and slowed a compound annual growth of about 4% in 2019 (35). Norway has started to witnessed growth of a commercial aquaculture from 1970s. Since then aquaculture has evolved as a main industry in Norway, after oil and gas, and becoming one of the biggest salmon exporter in the world (8).

There are certain parameters and regulations regarding design and shape that the industry must follow while setting up fish farms. The design and shape requirements vary as per desired volume of fish which is in accord with law and regulations. For example, as defined by Aquaculture operation regulation (36) the density of fish in one production unit shall not exceed 25 kg/ m^3. Furthermore, The Directorate of Fisheries (Norway) (37) declare very clearly how much fish can be produced, *"A standard permit for food fish production is 780 tons while in Troms and Finnmark, a permit is up to 945 tons."*

3.2 Types of Fish Farms

Floating fish farms are available in different shapes and designs, conceptually the selection is made according to volume of fish containment in the cage and environmental conditions of the location. Floating fish farms can be categorized in following three types based on structural properties in sea environmental conditions (38).

(i) *Flexible System Farms*
(ii) *Hinged Connected Bridges*
(iii) *Rigid Structures*

3.2.1 Flexible System Farms

These kind of fish farms are often called Circular Collars. A single unit of circular collar farm would be made of welded high-density polyethylene in a desired length to get the right diameter of the whole structure. Fences and different pathways may be attached to the structure in order to make the operational platform safer for workers operating it. Two rims can be connected to ensure sufficient buoyancy and serve as a working platform (38). Figure 9 illustrate the floating collar fish forms

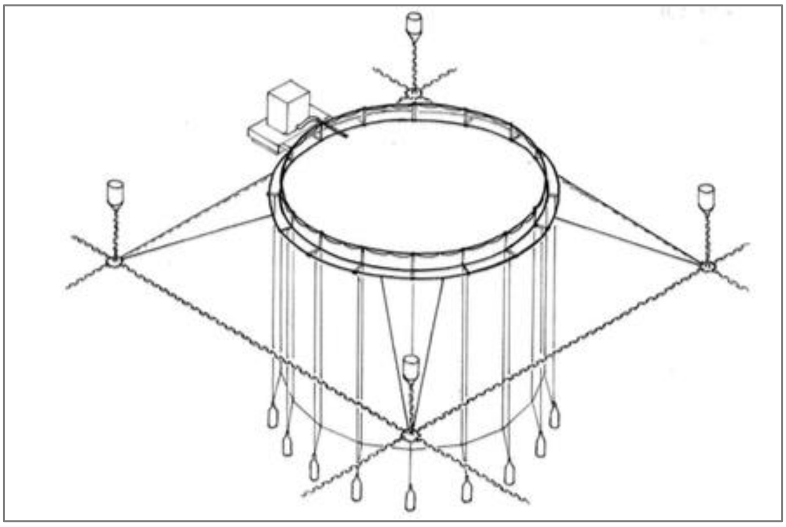


Figure 9: Floating Collar Fish Farm (Illustration of by SINTEF Fisheries and Aquaculture)

A classic floating collar fish farm will have a cage and mooring system to keep the cage in its desired position. The advantage of using such farms is that it ensures good water flow because of optimal distance between the collars (38).

3.2.2 Hinged Connected Bridges

This is a square type of cage which is connected by bridges of steel and floatation is connected with the structure which enables the cage to float better than floating collar cage. The downside of this cage is that it only has a freedom of moving on x-axis it cannot move in vertical axis. Moreover, due to limited flexibility forces like current, and wave can cause undesired stress leading to fatigue. There is another fish farm based on the similar concept called Catamaran Steel Fish Farm both models are presented in figure 10 (Hinged connected bridge on right and catamaran on the left) (38).

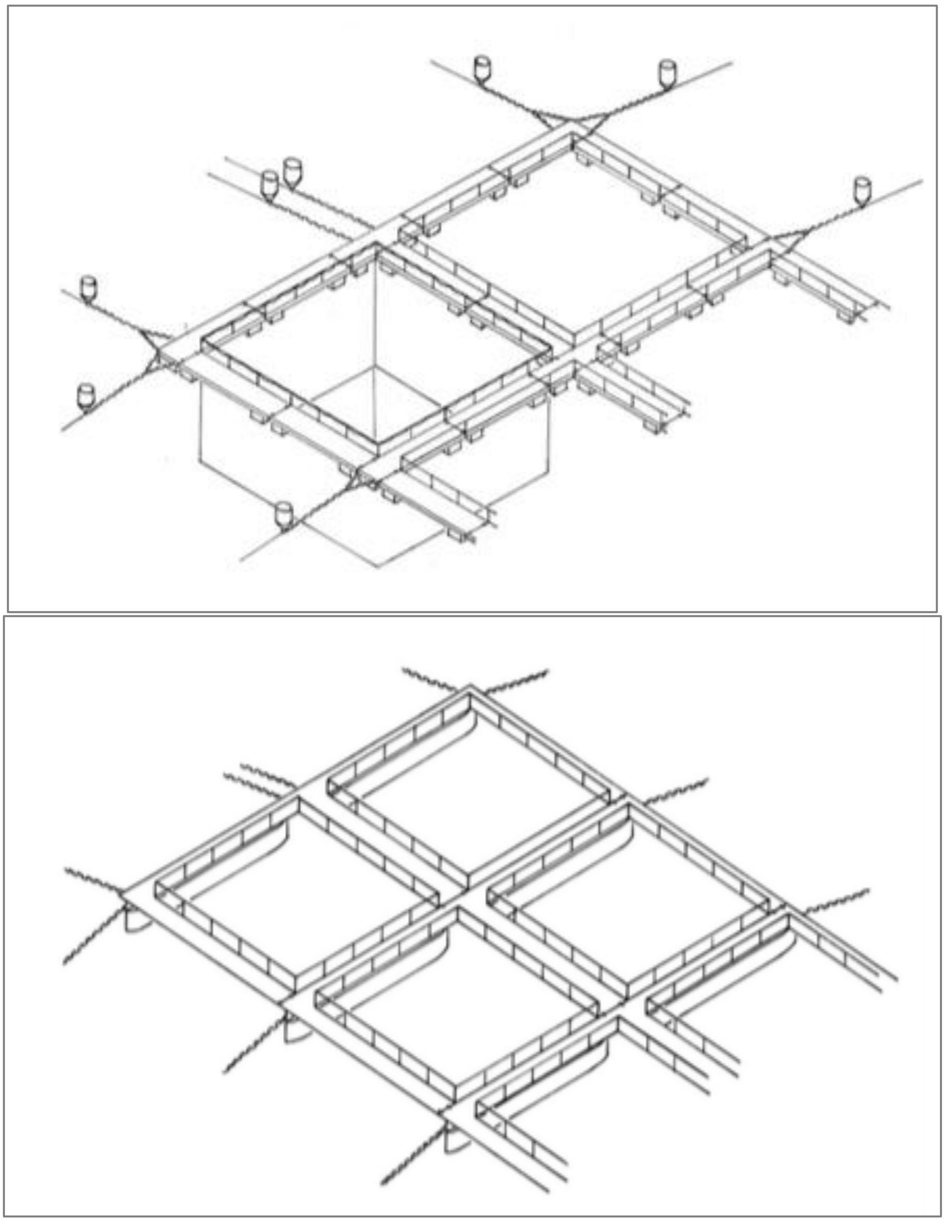


Figure 10: Hinged Connected Bridge and Catamaran Steel Fish Farm (Illustration of by SINTEF Fisheries and Aquaculture)

3.2.3 Rigid Structures

This type has many variations within itself, but most widely used model consist mainly of steel pipes welded together to form square collars. Due to limited flexibility and rigid structure these forms are more exposed to environmental stresses and lead to fatigue. Therefore, they are not suitable for exposed locations (38).

3.3 Fish Farms Components

A fish farm typically consists of several cages most often ranging from 6-12 different cages. The number of cages varies depending upon the dimensions of the cage and size of the location. According to NS9415, following are the main components of the fish farm (39)

1. *Floating Collar*
2. *Net Cage*

3. *Feed barge*
4. *Mooring System*

Floating collar integrate all parts of the fish farm by serving attachment point for the net. While net cage is aimed to keep the fishes in the containment reducing risk of fish escape, net cage is connected with floating collar. Different functions are linked to feed barge e.g., feed storage, feeding management system, control room, maintenance inventory store etc. Mooring system is used to ensure the fish farm is kept to its desired position. It consist of ropes, floats and bottom attachments (38).

3.4 Contemporary Fish Farm

As discussed earlier, Norwegian aquaculture industry has seen rapid growth and serious efforts have been made for further expansion and to deal with the industry challenges. Aquaculture industry in collaboration with researchers started looking for innovative solutions to keep up with the growth and expectations from this industry.

With the development of the industry, government regulated and introduced the policy how this business will work under strict guidelines e.g., each fish form is allowed to have only allowed density/volume as mentioned in section 3.3. Aquaculture industry in Norway is regulated by licenses, each site is bound to adhere to in place rules and regulations of the aquaculture sector. Norwegian Government made a innovate breakthrough by allowing the fish producer to get innovation licenses. The idea behind innovation licenses was to address the concerns in the aquaculture related to environment and industry challenges. Under these licenses' companies can be allowed to produce more fishes than mentioned regulated. Following three concepts in the form of state of the art fish forms have been approve to meet the abovementioned requirements (37).

- *(i) Ocean Farm 1*
- *(ii) Havfarm*
- *(iii) The Egg*

Ocean Farm 1 was the first of its kind to be operated in the extreme harsh weather conditions. The project is partially fund by Innovation Norway in the development phase and implemented partner was SalMar. The statics of the Ocean Farm 1 was somewhat like this, capacity of 6240 tons with volume o 250000 m^3, height 68m and diameter is 110m. Fish handling is being carried out internally meaning no external vessels are required to perform the job. Farm 1 is furnished with three bulkheads that allow the possibility of isolating the plant into three sections enabling fish handling rather easy. The fish producer has planned to run the operation on Farm1 with 3 to 4 workers on each day to ensure systematic monitoring of the operations (40).

Another concept proposed by Nordlaks is Hvafarm, this is even bigger, and the farm is a ship shape with capacity of 10,000 tons of salmon that is about 2 million fishes. The design is so that it can withstand the as high as 10 meters high waves. The farm has six cages with surface area of 2500 square meter and depth is 60 meters. Hvafarm is intended to lay at one position throughout its lifetime of 25 years. NSK ship design is also working towards Hvafarm 2 and another concept called FjordMax (41).

Figure 11: Ocean Farm 1 pictorial view (40)

Figure 12: Hvafarm 1 by NordLaks (41)

Hauge Aqua proposed a concept of egg-shaped closed fish farm and Marine Harvest developed and designed the Egg. The egg was given permission of total volume of 22000 cubic meter that can contain 3120 tons of fish.

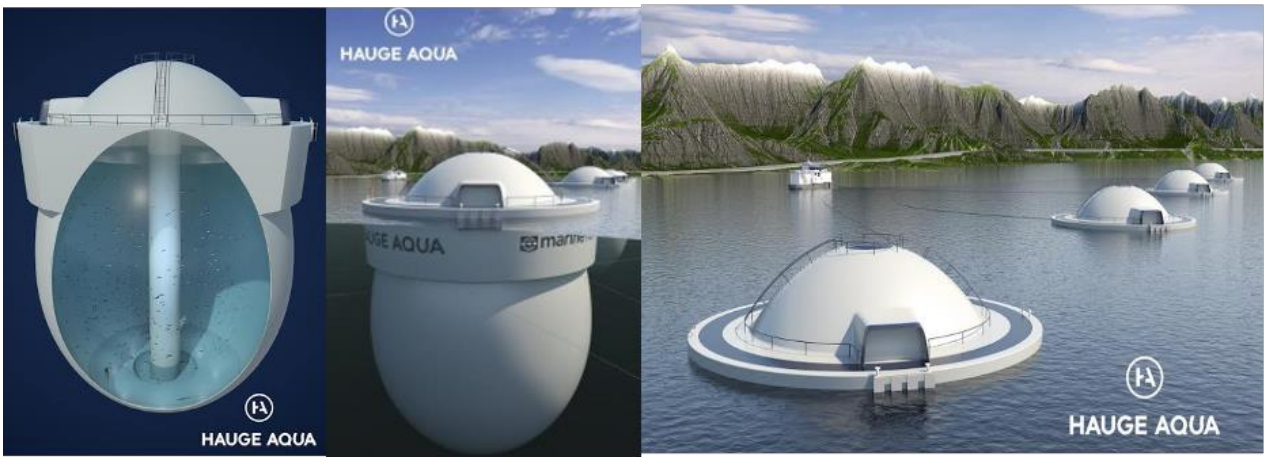


Figure 13: Egget Fish farm (42)

3.5 Aquaculture and Oil & Gas

Although, in Norway both oil & gas and fishery are for export but still it is interesting to note that in 1970s Norwegian market has witnessed growth in hydrocarbon exploration and development of commercial aquaculture. Although, both sectors started their commercial growth at the same time but due to the fact that oil & gas provides more wealth has seen major technological development since its early days in Norwegian market. Historically, aquaculture and fish farming is commonly known as experienced based trade where fish farms at established closer to the coast. Due to number of reasons including environmental challenges, limited coastal-line areas and others, the need of more offshore fish farming in the future was realised. Nevertheless, aquaculture activities in the ocean with harsh weather conditions brought new challenges that aqua culture industry has not seen yet. For example, farm and fish cage design or structure, operations and maintenance activities in harsh weather conditions. Forecasting of weather conditions and significant operations factors become most important information for aquaculture on offshore sites (43).

According to Norwegian Ministry of Trade Industry and Fisheries 2017, aquaculture industry in Norway has huge potential and can stand out as the leading ocean industry in the future (44). This is indeed a very ambitious thinking, but the Government has taken some serious steps in this determination. In this connection, Norwegian government in 2015 has introduced free development licenses to incentive advanced technological conception to achieve the desired potential in aquaculture industry (41). Although, aquaculture operations and hydrocarbon exploration activities both are carried out in the ocean, but both differ greatly due their nature and water depth both sectors operate. Typically, hydrocarbon exploration is carried out almost at 1800meters depth while ocean farming is done at 100-300 meters' depth. Having said that, offshore aquaculture activities present some nice favourable features including opportunities for future expansion (large space), minimal conflict with other user groups, minimal exposure to human sources of pollution, optimal environmental conditions and reduce negative environmental impacts of costal fish farming (45-48).

Offshore oil exploration activities go back almost 125 years with petroleum exploration activities started in 1896 in California. Since many countries around the globe have fair share of oil and gas resources and its most in demand wealth, therefore this sector has seen rapid growth in technological development. On the contrary, aquaculture industry has developed very slowly throughout the world. There can be number of reasons but the few of main reasons can be overall profit margins in livestock (fish etc.) compare to oil and gas were very low (49). However, aquaculture industry can gain great benefits from the development or maturity of oil and gas industry by intelligently applying standards, regulations and technological advancement from oil and gas to aquaculture industry. For example, use of sensors, Internet of Things (IoT), risk assessment methods, use of DP system, that is widely used in oil and gas sector for position keeping requirements can be used in aquaculture activities, etc. Next section will elaborate bit more on use of dynamic positioning system in aquaculture industry.

3.6 Technological Qualification in Aquaculture Industry

Norway has seen a great demand of its seafood product around the globe and is the second largest exporter of seafood after Vietnam (50). As mentioned earlier, seeing great demand of Norwegian salmon and to offer bigger fish facilities to the fish farmers government decided give licenses for ocean farming in rough water and harsh weather conditions. This was also decided to focus on environment in the calm fjord of Norway and ensuring the fish health.

The decision to move Norwegian aquaculture in the deeper water was a great shift for the industry that provide huge opportunities for the growth of the sector. However, this transition of the industry give birth to significant technological and operational challenges. From the safety and reliability point of view, exposed aquaculture activities demands new technical solutions syndicated with farming operational concepts (51). Figure 14 shows six different identified research areas for safe and reliable aquaculture operations and sustainable production (52). The identified areas are proposed by the Exposed Aquaculture Centre, SINTEF Ocean which was developed in 2015 to enhance the capability of business sector to innovate by concentrating on longstanding research (51).

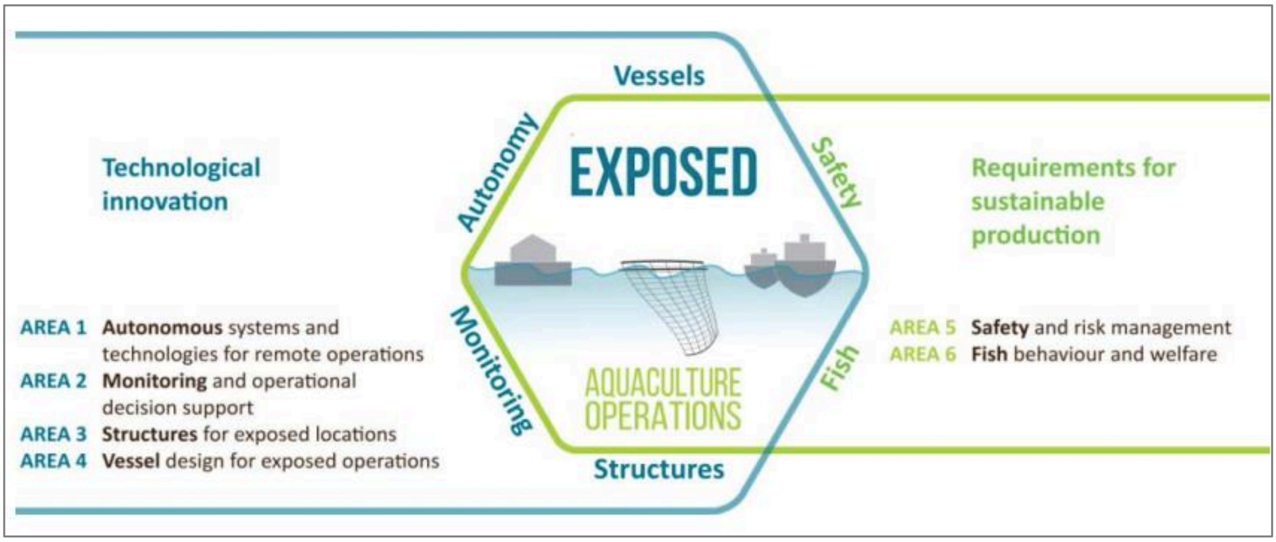


Figure 14:Six areas for safe and reliable aquaculture operations and production (52)

First four areas highlighted in blue are meant to focus on technological innovation for safe and reliable aquaculture operations in exposed conditions. While last two areas highlighted in green represent the core requirements for sustainable productions (52). Area1will enable the industry to be less depend on clos human involvement for day to day and periodic operations. Area 2 will provide ways for robust monitoring of environment, structure, system and fish welfare and support operational decision. Area 3 addresses the needs of aquaculture structure required for the operations in exposed conditions while ensuring personnel safety and fish welfare. Are 4 will research mainly on the design component of vessels, supporting equipment, and logistic solution to ensure safe and efficient operations in exposed aquaculture. Area 5 will research and proposed improved risk management strategies and system for operations in exposed conditions. Area 6 will focus on technologies and new operational solutions in order to ensure fish welfare (51).

For many years technology has been making significant improvements in all the industries. Technological advancement has revolutionized the traditional industrial operations with the use of sensors, IoT, computer aids etc. Aquaculture industry in the past ten years has gain significant attentions, as a result technology is inventing new ways of doing aquaculture activities for this industry. Aquaculture industry has witness a rapid growth in recent years, the consumption worldwide has gone from 6% in 1980 to 46% in 2018 (50).

Nevertheless, the aquaculture has seen a rapid growth but at the same time industry is facing some real challenges for example, environmental issues, high operating costs, increasingly deteriorating environmental conditions. There has been discussion of extending industry 4.0 into aquaculture 4.0 to address some of the biggest challenges. These changes and innovation not only involve the construction of structure but also other components. Atmospheric and natural resources monitoring system (fish, minerals, hydrocarbons etc.) have been incorporated into less regulated production system to forecast production and to manage food supplies in order to prevent waste (53)

Many aquaculture technology experts like DNV-GL, Kongsberg, Siemens and others are working intensively in effort to offer comprehensive technological solution for the rapidly growing aquaculture industry. The aim is to provide a solution in combination of electrification, automation, and digitalization with cutting edge technologies for improved productivity and sustainability.

Nanotechnology, a relatively new technology, has contributed greatly in many industries. With the use of this technology one can measure, observe, manipulate and manufacture things at nanometres level. Nanotechnology has wide usage and potential aquaculture industry. Following are some of the applications of it in aquaculture industry by Can et al. (54)

- Improving bioavailability of functional compounds
- Nano filtration of water
- Production of effective and better fish feed
- Antifouling in fishing and aquaculture nets

Li and Chenhong (55) discussed that with ever increasing demand of aquaculture products and decreasing labour availability in the sector has called for an urgent need of new and intelligent ways of aquaculture. Further, it was argued that smart aquaculture has become very much possible with the emergence of technologies like IoT, artificial intelligence (AI), big data, cloud computing, and robotics.

Development of new technologies are fundamental requirements for the growth of any industry. When deployment of new technology happens, regardless of novel concept or standard concept of technology, safety and reliability of the technology is of great importance during its operations. It is of great importance to carry out the technology assessment of new technology to identify that it meets the specified requirements to be fit for the service in the industry. Although, DP system is not really a novel technology for offshore but its application in aquaculture is quite contemporary. Therefore, it is vital to identify if DP system fulfil the technology qualification of the aquaculture industry.

3.7 Dynamic Positioning System in Aquaculture

Application of dynamic positioning (DP) system in aquaculture industry is relatively new and yet to mature. Due to limited DP system application in aquaculture, there exists almost no or very limited literature on the topic. Fubin, a functional safety expert at DNV-GL, is of the view that from hardware perspective DP system in aquaculture consists of same components as in oil and gas or other sectors and components are like DP controller, thruster, power supply, reference system etc. The key difference is the operational limits specified in different industries for the DP system. For example, for service platform lying next to the host platform, drive off in 5 meters can cause accident. Although for the fish farmthis is not a concern because the fish farm will be out in the sea at far distance, 500 + meters, away from colliding any objects.

In order to understand the application and benefits of DP system in aquaculture industry, researcher from SINTEF and companies working/ed have been contacted. Responses from SINTEF researcher, NSK AS, DNV-GL, Navy Rørvik are shows in Appendix 2. All the respondent agreed that there exist little literature and application of DP system in aquaculture is not as critical as it is in oil and gas sector. Generally, DP-0 class is used in aquaculture. Havfarm2 for the first time using DP-2 class (56).

3.7.1 Havfarm 2 and DP System

According to Nordlask (56), Havfarm 2 is particularly designed as an offshore structure fish farm with propulsion as ship and farm has capacity of 10,000 tonnes fish. As planned after Havfarm 1 the Havfarm 2 version must be equipped with dynamic capabilities. In order to make the Havfarm 2 dynamic, it was equipped with DP system. By means of DP system fish farm can maintain its position by its prolusions. Havfarm 2 is designed and meant for the more exposed locations offshore and the idea behind the concept was that it should operate in exposed offshore location when weather permits and in case of extreme wave and current Havfarm 2 should seeks move to locations with feasible weather conditions. The migration from one location to another location is managed by means of propulsions thrusters. In order to make Havfarm 2 more energy efficient it is equipped with some anchors as well (56).

Havfarm 2 has revolutionized the aquaculture industry with new methods and approaches. As Havfarm 2 does not operate in a traditional manner, therefore regulatory clarification or consequence of developing new regulations to account for Havfarm 2 should be developed. The typical examples can include the following

1- Havfarm 2 should not be anchored to a specific site, instead it should be exposed to more location and have ability to operate in all weather conditions
2- The requirements for position keeping using DP system for Havfarm 2 should be different than the DP system in offshore drilling vessels. The reason for this is that the drilling vessels needs to maintain its position during failure to shut down the operation. While it is not necessary to maintain position of Havfarm 2 in case of failure.
3- Loss of position for Havfarm 2 does not pose severe consequences unlike drilling vessels.
4- It is also important that DP system must be able to account for the swim speed of the fish. That have to do with the health being of the fish. The relative speed of water inside the case should be below a given value (57).

Accounting for the health and safety of the fish is another feature of the DP system in Havfarm 2. A provided amount of dissolved oxygen in the water is required for the healthy fish (salmon). Since the salmon uses oxygen, the consistency of the water in the hindmost cage can become low. This needs to be countered by the DP system by either shifting or adjusting the vessel's heading, allowing more water of high quality to pass through the hindmost cage (57). Figure 15 explain the water quality problem with different colour shaded for good to bad quality.

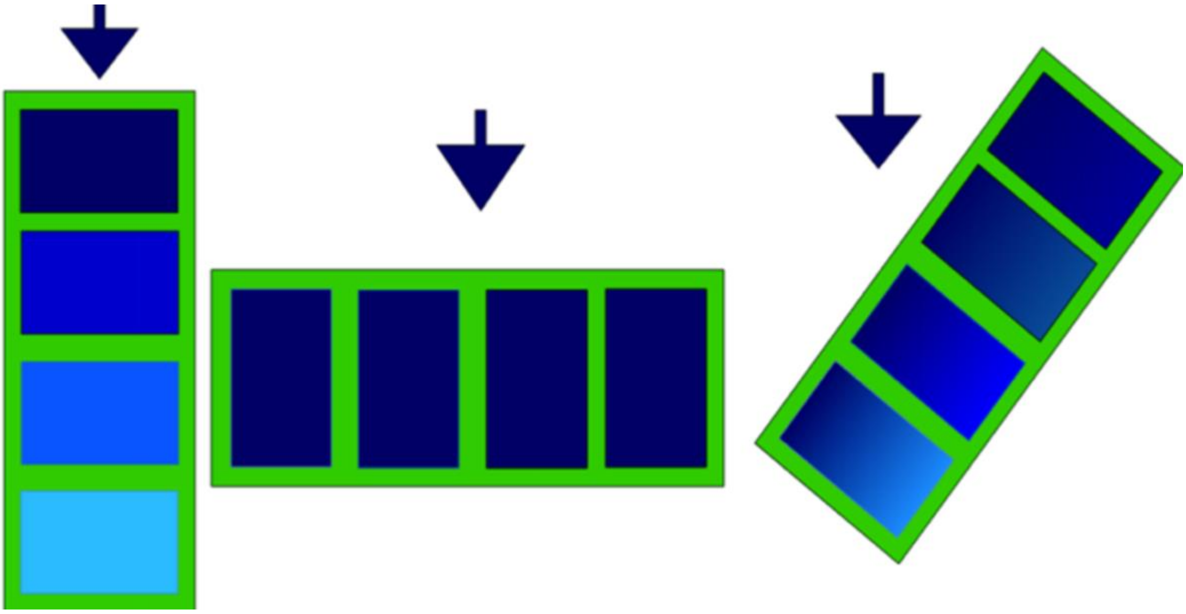


Figure 15: Water Quality reduction on Havfarm 2 (dark blue is of high quality and light blue is poor) (57)

The arrows in the above figure represent the flow of water i.e., from the top. In case vessel is static and heading along the flow of water, due to availability of many nets and salmon utilising all the oxygen make the water polluted consequently reducing the water quality. The dark blue water represents high quality while light blue is of bad quality. The figure 15 also shows that if vessel is stationary and headed orthogonal to the water flow then there will be high quality water for the salmon. The consequence of that is it would require a lot of energy to counter the drag forces. The position in the extreme right represent the most optimal condition where the water quality can remains high and forces acting on vessel are acceptable, this is achieved by changing the heading of the vessel (57).

Chapter 4

Risk Analysis Methods

This chapter after discussing some basic risk concept will explain the background of failure mode and effect analysis and risk prediction methods (linear regression, correlation, and logistic regression analysis) that will be used for qualitative and quantitative risk analysis in chapter5.

4.1 Relevant Risk Concepts

In the quest of extending operations horizons e.g., exploration of hydrocarbon in deeper water, the systems were prone to rapid technological advancement leading to increasingly more complex and compound systems. These multifaceted technological developments give rise to novel and supplementary convoluted failures that are difficult to identify and leading to jeopardising the safety and reliability of critical operations. In today´s technological empowered business era where tools and machines are more complex, businesses face different risks all the time. Risk can be expressed both qualitatively and quantitatively. Before we dive into risk analysis of DP system in different applications, it is important to briefly develop a conceptual understanding of risk and its relevant concepts, so the reader can develop a good understanding for the rest of the thesis.

4.1.1 Risk

The term risk has very broad meaning and can vary widely depending on the context it is used for. According to Rausand and Haugen (58) the term "risk" in some cases refers to chances, probability or likelihood while in another case "risk" may refer to hazard, threat and danger. Therefore, risk in its generality can be defined as "the probability or likelihood of something going wrong in a processor an operation". Moreover, Rausand and Haugen (58) further argued that risk can be clarified by the following questions

a) What possibly can go wrong?
b) What is the likelihood of that happening?
c) What are the consequences (if it goes wrong)?

While IMO defined the risk as "the combination of the frequency and severity of the consequence" (59). So, the risk can be expressed by the following mathematical expression.

$$Risk = Pr.\ of\ occurrence \times Consequence$$

4.1.2 Risk Analysis

In literature, there exist many definitions of risk analysis but according to Rausand and Haugen (58) risk analysis is "a systematic study to identify and describe what can go wrong and what the causes, the likelihood and the consequences might be". While Aven (60) defined risk analysis as "a way to describe risk i.e. to present an informative risk picture".

Risk analysis, according to Rausand and Haugen definition, aimed to answer the questions asked in the risk definition. According to National Research Council (61) there are three key elements of risk analysis and their interactions have been shown by the following Venn diagram (figure 16).

Figure 16 : Key elements of risk analysis by NRC (62)

4.1.3 Risk Assessment

Risk assessment is "a process of planning, preparing, performing and reporting a risk analysis, and evaluating the results against risk acceptance criteria" (58). According to Aven (60) following are the steps to identify the risk magnitude in risk assessment.

- Identification of threats, hazards, and opportunities
- Analysing causes and consequences
- Risk description

4.1.4 Risk Management

Risk management is defined as a "process for identifying, analysing, and communicating risk and accepting, avoiding, or controlling it to an acceptable level considering associated costs and benefits of any actions taken"(63). Figure 17 illustrate the risk management process proposed by ISO 31000

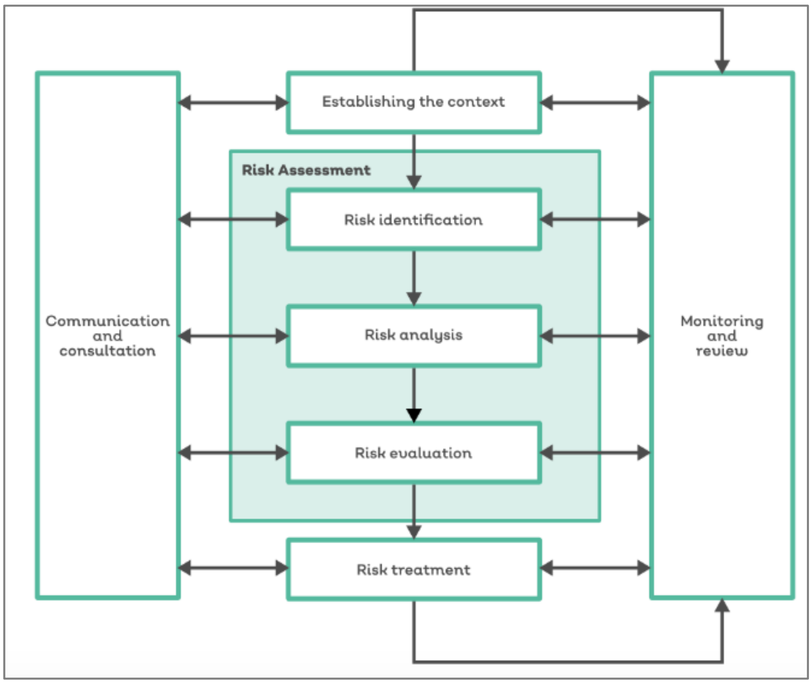


Figure 17: Risk management process [adopted from ISO 31000 (64)]

The risk management process by ISO 31000 shows that risk management is establish by following the steps from determining the context to risk assessment to risk treatment. Risk assessment is further divided into three steps including (i) risk identification (ii) risk analysis and (iii) risk evaluation. As shown in the figure 17, the interaction between the risk management steps (centre), communication and consultation (left), and monitoring and review (right), is very important for effective and successful implementation of risk management process.

Although, the models like one proposed by ISO 31000 give a good framework for managing risk but it is very important to introduce different layers of safety system to reduce risk of any major accident. It is argued that risk management models are disintegrated in a view that different risks are not subject to an overall assessment. Therefore, it is needed to establish more integrated risk management models. Moreover, identifying, taking measures and evaluating risk in design phase is of great significant to avoid rework, costly implementation, and wastage of resources (65).

4.1.5 Risk Communication

Assessing and identifying risk is not enough, it is rather more important to communicate the scope and consequences of the risk, and results of risk assessment with the key stakeholders including decision makers. Other than following the laws and regulations, the goal of risk communication is to assist all the key stakeholders that can be affected with the risk (60, 62).

4.2 Risk of DP System

Since the introduction of DP system, the safety and reliability of DP operations have been of great concerns. The bigger concerns about the reliability and safety of DP system operations were raised from the oil and gas industry following series of DP accident in UK North Sea.

After series of DP incidents UK's Health and Safety Executive (HSE) agency commissioned DNV to probe into the matter. The results of DNV study revealed that many of stakeholders were source of developing errors including design by shipyard, contractors, and suppliers. DNV also highlight in its finding that lack of effectively implementation of FMEA at all levels (managers, design, suppliers, etc.) was the major reason of DP failure (66).

The risk analysis and risk assessment approaches used for DP system ranges from qualitative, quantitative, and fuzzy. In recent years number of risk analysis methods have been employed to assess and analyse the risk in DP system like FMEA, FMECA, HAZOP, HAZID, Survey analysis, and other similar methods but risk analysis using machine learning or so-called quantification methods have been left out. Each of these approaches have its pros and cons, so in this thesis the risk in DP system has been analysed using both qualitative, FMEA, and quantitative statistical methods, linear regression, correlation, and logistic regression analysis. FMEA have been discussed before in the literature, therefore more emphasis was on statistical method in this thesis to quantify the risk. R studio have been used to perform statistical risk analysis.

As mentioned before, there are different methods available for risk analysis but the most critical is the quality of the result from the analysis, for the very reason that risk analysis is the most important tool to ensure the reliable and safe operations. There are different opinions about what risk implies and how it should be carried out. For a technologically equipped system like DP, IEC 60300-3-9 has given fundamental steps to consider while performing risk analysis (67). The steps are shown in the figure 18.

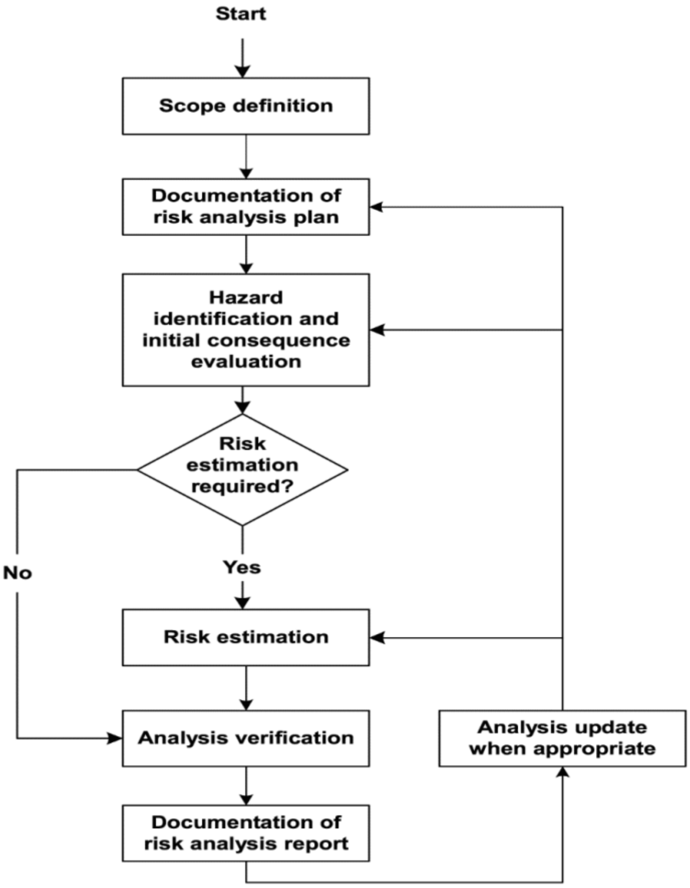


Figure 18: Risk analysis flowchart (67)

This risk analysis flowchart is a general representation and can be implemented in almost any system for analyzing risk. The same flowchart can be implemented very well to risk in DP system. In this thesis risk estimation is done with FMEA and verification is carried out with quantification of risk in DP system using statistical risk analysis methods.

4.3 Study Data

To achieve the objective of the thesis discussed in chapter 1, historical DP system incident data was required for the analysis. During the operations of DP system if any station keeping event or incidents occurs it's the responsibility of the DP system owner or operator to report the incident to the international trade association for the maritime contracting industry like IMCA or governing bodies. IMCA collect varied critical data about DP incident and both members and non-members of the organization can report the incident. IMCA collect data about DP incidents, DP undesired events and DP observation.

Since this thesis is completed in collaboration with DNV, so the DP incident annual data from IMCA for the period 2010 to 2018 was provided by DNV. Annually collected data throughout nine years lacks consistency in data regarding operational mode, DP class and other similar factors. Nine years incidents data was carefully analyzed and sorted in a manner that was required for the risk analysis and risk prediction. Although, IMCA collect three different kinds of data regarding DP as mentioned above but for in this thesis only DP incident data has been considered. IMCA defines DP incident as loss of capability of DP system to holds its position and heading in certain environmental conditions (27).

IMCA bifurcate incident data in two categories that are main causes and secondary causes. In this thesis, both main and secondary causes have been considered with key focus on main causes. Secondary causes data was used for correlation analysis and to create some assumptions which were tested using risk analysis. Total incidents reported during nine years period were 712 out of which 458 were main causes and 254 were reported as main causes combined with secondary causes of DP failure. The sorted data is presented in appendix 6 in tabular form.

Overall percentages of different factors contributing to the DP incidents are presented in the pie chart (Figure 19) generated using the nine years IMCA data. The pie chart was generated using the overall incident picture without differentiating between main and secondary causes. The distribution of main and secondary data is discussed in section 4.4.1 distribution of data. It is evident from the pie chart that the top three sub-systems that contributed to the DP system failure are thruster and propulsion 29%, computer 17% and power system with 13% share.

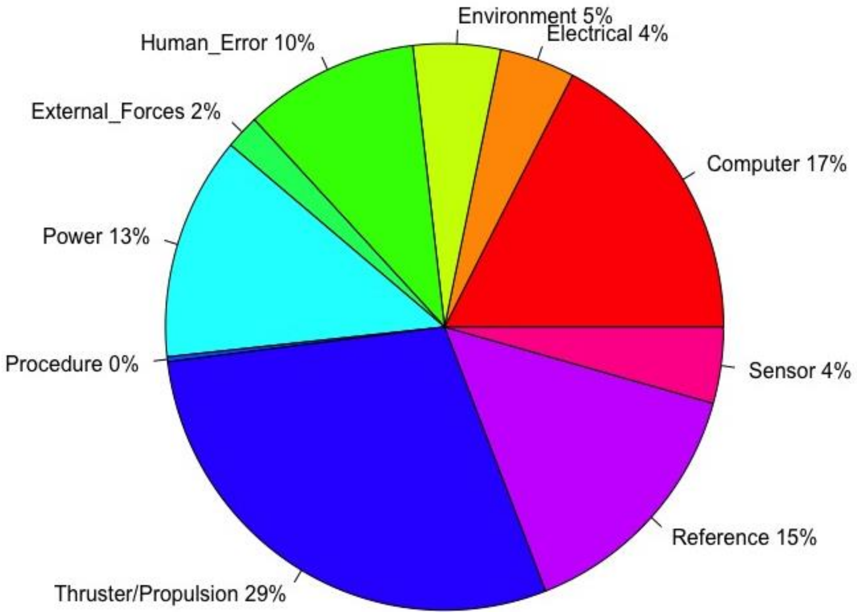


Figure 19: Pie-chart results of DP incident based on IMCA nine years data

4.4 Qualitative Analysis: Failure Mode and Effects Analysis (FMEA)

Failure mode and effects analysis (FMEA) is a prevailing tool to design and maintain reliable system, exploring their potential failure modes from the view of severity, occurrence, and detection. DP FMEA has its origin in IMO guidelines for vessels with DP system and is regarded as the most important technical document in the required documents for DP operated vessels. By the guidelines, FMEA is required for DP vessel with class 2 and 3. DP FMEA determine the safety, reliability and redundancy system for DP vessels (2).

According to IMCA (27) FMEA is defined as "a systemic process to identify potential design and process failure before they occur with the intent to eliminate these failures or minimize the risk associated with them". The core objective of FMEA is to detect a single point failure in any system (software, power, thruster etc.) in DP vessel which would trigger loss of position keeping ability of the vessel.

Typically, FMEA is performed in collaboration with cross functional and multidisciplinary team including engineers and technicians from design, reliability, maintenance, safety and other departments. FMEA is always should always lead and coordinated by a manager or team lead in different activities. While working in cross functional team, conflict is inevitable, therefore most of the tasks in FMEA must be performed together by experts to mitigate conflict (68). Figure 20 shows the flowchart of the FMEA analysis.

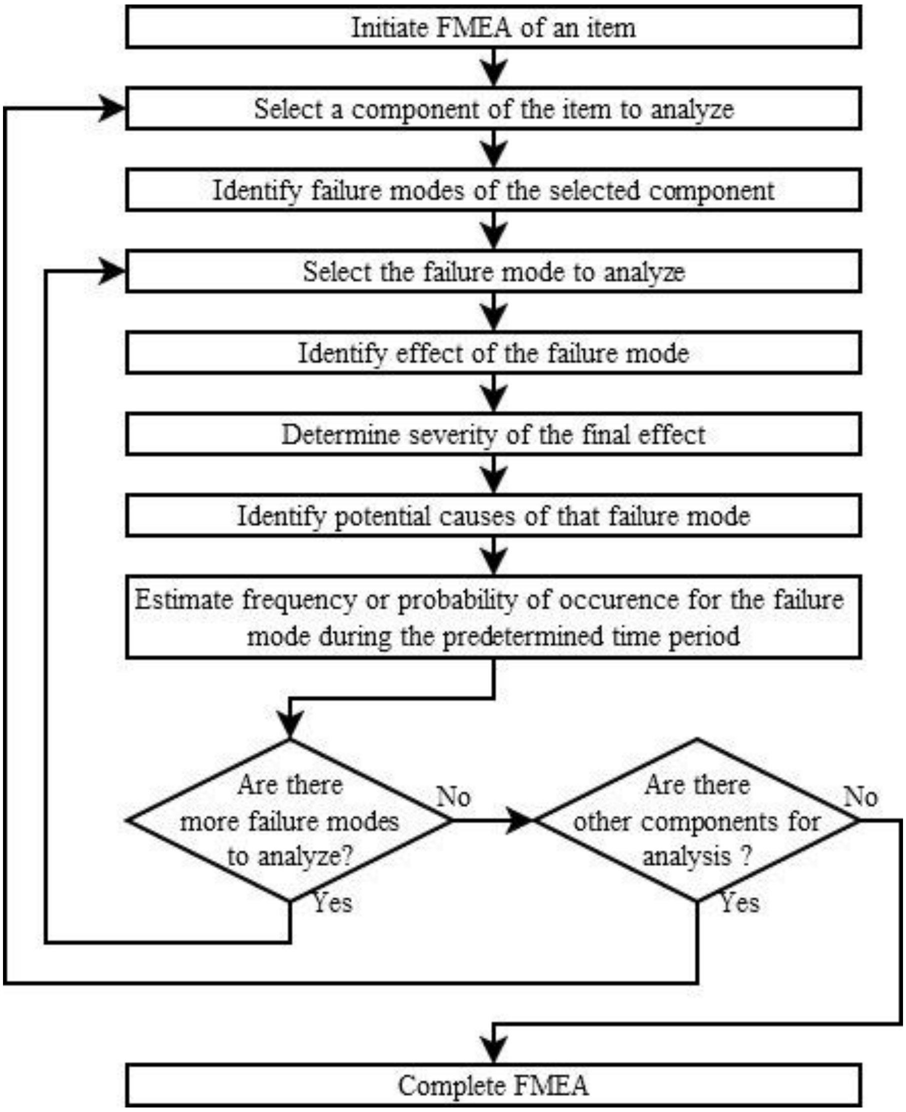


Figure 20: FMEA Flowchart (68)

In reliability analysis of DP vessel, the probability of failure of all DP systems like power system, thruster, controller or computer system, sensor and human error must be taken into consideration. FMEA consists of a standard worksheet to identify and eradicate failure modes during design phase or outline processes to avoid dangerous consequences of failure that might happen in operation phase. Following is a simple example of FMEA worksheet for a DP system (69).

Table 2: FMEA Worksheet of DP Vessel [adopted from (86)]

Sub-System	Cause of failure		Failure Mode	Effect of failure	Severity
Controller	Computer	Hardware	No Thrust	LoP	High
Generator	Power Generation	Generator	Overspeed/ Reverse Power/ Blackout	Drift off	High
Sensor	References	DGPS	Measurement Error	LoP	High
Thrusters	Thruster	Rudder	Incorrect or low Thrust	LoP	High

Thrusters	DP Computer	Software	Incorrect or low Thrust	LoP	High
Thrusters	Thruster	Cooling	Incorrect or low Thrust	Misalignment ahead	Low

Different classification societies and regulatory agency like IMO, DNV-GL, Lloyd's (2, 12, 69, 70) and other has made FMEA as mandatory requirement document for DP vessels. For consequences of failures study different approached have been suggested in literature like statistical and probabilities analysis, block diagram analysis and monitoring of system status during operation (65, 71). The limitation of these methods is that they do not address the risks of failure in design phase. Therefore, FMEA is the preferred choice for risk analysis of DP system.

Spouge (72) in his report for DNV-GL has pointed out concerns like if redundancy is adequate method for risk management in DP system and DP FMEA is superior choice over other simpler methods like Fault Tree Analysis (FTA). While, Rokseth et al. (3) argued that redundancy is indispensable for DP vessels but that might not be enough for risk management and DP FMEA is an effective tool if implemented with set framed objective and careful guidance. On the other hand, Moratelli et al. (73), claimed that FTA should be used with FMEA for effective risk analysis because standalone these methods cannot cover all aspects of the reliability analysis of DP system. Rokseth et al. (3) in their research also mentioned that failures may occur due to different layers of abstraction that are not cover or protected by redundancy e.g. physical processes. Such failures are not covered in DP FMEA.

Chen and Nygård (6) based on the historical incident rates, proposed a new way of quantifying risks associated with DP operations near offshore installation, whereas consequences are based on impact energy, installation structural capacity etc. The approach takes into account a very important factor of human innervation actions.

DNV-GL has established and recommend practices for FMEA of redundant system where FMEA method have been customized to DP redundancy verification. To distinguish DP FMEA from redundancy we can call it DP FMEA. The primary purpose of DP FMEA is almost the same as FMEA's aim "to systematically conclude the feature design plan of DP vessel and verify that vessel is designed in a way that failure of single component does not lead to loss of position". Moreover, DP FMEA repeatedly produces input to authentication test by enclosing hypothesis and uncertain conclusion and test (3).

Though most of the standards present similar elements but there exists some difference in the standards, but among all the standards only IMCA guidelines precisely talk about DP system. Following table present key element of FMEAs according to different standards (72):

Table 3: Key components of FMEA in different standards (72)

Standard	Components of FMEA
BS 5760	A statement of the objectives of the study
(IMCA, BS 5760, IMO, DNV, ABS)	Describe the main functions of the system block to show interaction between different main building blocks of the system.
(IMCA, BS 5760, IMO, DNV)	Breakdown of the functional blocks into physically and functionally independent elements.

(IMCA, BS 5760, IMO, DNV, ABS)	Identification of all major failure modes for each element
(IMCA, BS 5760, IMO, DNV, ABS)	Indication of usual reasons for each failure mode
(IMCA, BS 5760, IMO, DNV, ABS)	Definition and categorization of the consequences of each loss on other objects, total DP scheme and vessel positioning
(IMCA, BS 5760, IMO, ABS)	Description of the process of identification of failure
(IMCA, BS 5760, IMO)	Description of the method of detecting if failure has occurred
(IMCA, BS 5760, ABS)	Consideration of potential general modes of failure
(IMCA, BS 5760, IMO)	Analysis specific FMEA worksheets
(IMCA, BS 5760)	Documents and drawings on which the analysis was based
(IMCA, BS 5760, IMO)	FMEA's ties with the test software and site-specific risk analysis

In nutshell, the FMEA's original emphasis was placed on design of system with high reliability. To avoid total system failure, in design phase, FMEA seek out and eliminate any single point failures. Moreover, by mean of effective use of FMEA failures of components, that have serious effect on system performance, can be identified.

4.4.1 Criticality Analysis (CA)

Sometime using FMEA solely is not very insightful to understand the risk because it determines the risk in rather broader terms. To get better understanding of risk associated with the failure mode of each component FMEA is extended with the criticality analysis to form FMECA. FMECA can be steered either using top-down approach or bottom-up approach. The difference between two approaches is that, top-down method is used in design phase prior to structure finalization and it is mostly function oriented, while bottom-up approach is used when system concept has been finalized. For either approach criticality analysis can be carried out qualitatively and quantitatively. Usually, quantitative approach is used when data of the components is available, alternately qualitative approach is used. Quantitatively CA can be calculated with the following equation resulting in a number (58)

$$Cm = \beta \times \alpha \times \lambda \times t$$

Cm is Criticality mode

β is failure effect probability

α is failure mode ratio

λ is failure rate

t is operating time

When using qualitative approach, the result can be classified with the severity level which can be defined with numbers, very unlikely to frequently, high to low, critical to minor etc.

Qualitative results can also be presented as a matrix so called a risk matrix. The simple layout of a risk matrix can be following

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

Figure 21: Risk Matrix (69)

The green area represent only ALARP (as low as reasonably practice) actions are required, yellow area represent consideration of more investigation with ALARP, and red area resent risk reducing measure are necessary. According to IEC 60812 standard, the possible classification used in risk matrix can be given in the following table.

Table 4: Failure likelihood as per IEC 60812 (74)

1	**Very Unlikely**	**Once every 1000 years or more seldom**
2	**Remote**	Once every 100 years
3	**Occasional**	Once every 10 years
4	**Probale**	Once every year
5	Frequent	Once ever month or more frequent

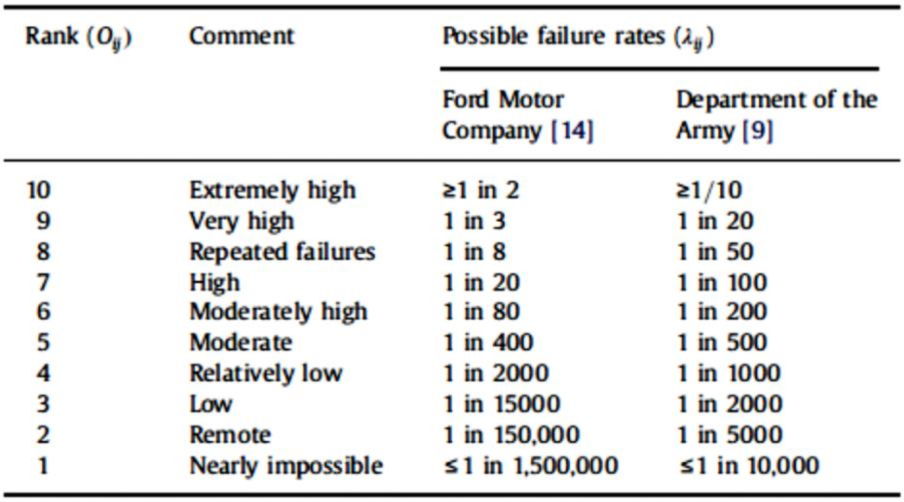
4.4.2 Risk Priority Number (PRN)

With the help of PRN method risks of potential failure modes can be ranked. PRN is a product of ranking factors like potential failure mode severity (S), probability of failure occurrence (O), and likelihood detection (D) (75).

$$PRN = S \times O \times D$$

The value of these ranking factors can vary in the range of 1 to 10 and resultant PRN can vary in the range of 1 to 1000. The higher the PRN value the higher the risk. It can be a key decision-making indicator to prioritize the failure modes with similar PRN value leading to corrective action. Corrective action can lead to reducing one of the ranking factors but the values for all the ranking factors S, O, and D are different. Tables in appendix 3 shows the example of severity, occurrence and likelihood detection ranking (75).

If failure rate data of components is available, it can be used to get the ranking factor. Figure 22 represent the ranking factors and the corresponding quantitative failure rates as per different industry standards (76).



Rank (O_{ij})	Comment	Possible failure rates (λ_{ij})	
		Ford Motor Company [14]	Department of the Army [9]
10	Extremely high	≥1 in 2	≥1/10
9	Very high	1 in 3	1 in 20
8	Repeated failures	1 in 8	1 in 50
7	High	1 in 20	1 in 100
6	Moderately high	1 in 80	1 in 200
5	Moderate	1 in 400	1 in 500
4	Relatively low	1 in 2000	1 in 1000
3	Low	1 in 15000	1 in 2000
2	Remote	1 in 150,000	1 in 5000
1	Nearly impossible	≤1 in 1,500,000	≤1 in 10,000

Figure 22: Ranking occurrence against failure rate in different industry standards(76)

4.5 Statistical Analysis for Quantification of Risk

Regression analysis is a method for investigating functional relationship among two or more variables. The relationship is generally expressed in the form of a model or equation connecting response or predictor variables. This thesis has used linear regression and logistic regression for the prediction of risk in DP system failure.

4.5.1 Linear Regression Analysis

This analysis endeavor to model a relationship between two variable factors by fitting a linear equation to observe data. In this analysis one variable is dependent and other is independent variable. For example, number of failures due to main or secondary causes is dependent variable and time (years) is independent variable. Typically, linear regression analysis is given by the following equation.

$Y = a + bX,$ where Y is dependent variable and X is independent variable.

In this thesis, the analysis was performed with an aim to quantify the failure rate contributed by different main causes and to identify the significant main causes contributing to the failure of DP system. To do so linear regression models using number of failures as outcome for the model have been applied. The linear regression results were plotted using “forestplot” function in R.

4.5.2 Correlation Analysis:

There are two types of correlation analysis that are Pearson correlation and Spearman´s correlation analysis. In this thesis, Pearson correlation analysis have been used. Pearson correlation coefficient the analysis is also known with other names like Pearson´s r, bivariate correlation etc. Two set of data are correlated linearly by using this analysis. The result ranges from +1 to -1, where positive correlation represent that both variables are driving the results in same directions while -1 is representing otherwise.

To identify the contribution of secondary causes in overall failure rate, author did not use regression model due to insufficient statistical power issue. Instead, using this same data, computed Pearson correlations between 8 primary and secondary causes (computer, electrical, environmental and external forces, human and procedure errors, power, thruster and propulsion, reference system and sensors) using R. All correlation (between causes) values were plotted as heatmaps using "ggplot" function in R.

4.5.3 Logistic Regression Analysis:

Logistic regression analysis is a predictive modeling technique just like other regression but in this analysis the dependent variable is a binary variable. This analysis investigates the relationship between a dependent variable and independent variables. The dependent variables can only have two possible values i.e., 0 and 1 or Yes or No.

The heatmap from Pearson correlation analysis was used to identify the main cause(s) strongly correlated with one or multiple secondary causes. As the number of failures due to main causes itself or alone were predominantly higher than the failures caused by main cause combined with a secondary cause (458 vs 254 failures, respectively) so we assume that the failure due to main cause e.g., failure of computer or thruster system has significant impact on the failure of DP system compared to the failure of these system in secondary cause. Logistic regression model is used to predict that how high is the risk of failure for such main cause alone when compared with that main cause in combination of different secondary causes. For this regression model, failure due to combination of main cause with different secondary causes was made as reference group represented as zero group in the data file and the risk of failure was calculated in the main cause group alone represented as 1 in the data file. After sorting the data as per analysis requirements, the analysis was run in R studio using logistic regression model. So, the analysis gives odd ratio (OR) from this model quantifies the risk of failure associated with main cause alone if counter group has no risk (OR=1).

All analyses were performed using R version 4.0.3 and a p value of <0.05 was used to identify the statistically significant results.

Chapter 5

Risk Analysis of DP System

In this chapter risk analysis of DP system based on IMCA data from 2010 to 2018 will be carried out using FMEA and statistical risk prediction methods as explained in chapter 4.

5.1 Risks of DP System in Aquaculture Applications

Typically, DP system automatically enable vessels to keep its heading and position by means of its own thruster system. DP system has become an important part of vessel system in many industries. After the success of DP system in different industries, aquaculture for the first time is utilizing DP system for its operation in the sea with harsh weather conditions. According to Nordlaks (56) Havfarm2 will use a dynamic positioning system that will allows vessel to adjust their position and direction automatically using thrusters and propellers. In the case of a storm, the platform will be able to propel itself to a safe place based on anticipated weather conditions. Different risks associated with DP system has been discussed in this thesis, but loss of position is the most significant risk in DP operations. Since the objective of DP system in aquaculture is same as in other industries so in general the risk associated with DP system in aquaculture is also same as in other industries, but the consequences can be different.

One of the most highlighting aspect of DP system in aquaculture is the efforts to reduce the carbon emission by utilizing environmentally friendly LNG engines for power generation. As explained in section 3.7 different controls and simplified thrust on Havfarm2 can ensure the high quality of water for fish welfare while reducing the environmental impact. DP system also ensure good welfare of the salmon in the farm by providing dissolved oxygen in the water to the fish and this is done by slowly moving or changing the heading of vessel through DP system. So, the implications or consequences of failure of thruster or power or control system can be rather critical in aquaculture as DP system will be responsible of control of heading and position and welfare of salmon.

Resistance to loss of position and robustness of recovery to loss of position are two important aspects that define the safety of DP system operations in aquaculture. It is critical to assess both factors for safe DP operations in aquaculture. Basically, dynamic positioning system operations in aquaculture in harsh weather conditions is demanding and in case storm conditions DP system should take the farm to a safe and sheltered location. Since DP system is a human and machine interaction system so it is very important to consider both technical and human faults improvement for safe DP system operations. In oil and gas sector most of risk studies on DP system evolved around technical risk assessment in DP system, but it can be a good lesson learnt for aquaculture to focus on human and organization aspect during risk assessment of DP system.

5.2 Framework for Risk Analysis

As already established through literature in chapter 2 and IMCA DP system incident data from 2010 to 2018 that there have been accidents happening during operations of DP system in different applications. Although, DP system has made a great journey to ensure safe operations since its application in different field, but the accidents are still happening today. Industry has taken some serious steps to ensure high level of protection system to avoid catastrophic consequences in the DP operations. As a result of such measures the frequency of incidents reported are considerably low specially in oil & gas. The other main factor of the low incident data is reporting of incident from the owners and operator of DP system is still not 100%.

While FMEA, FMECA, FTA and other similar qualitative methods have been used more often for risk analysis of DP system, but statistical methods have been used very rarely to quantify and predict the risk in DP system. This thesis has used both qualitative (FMEA) and quantitative method (logistic regression model) for risk analysis of DP system. For this purpose, first FMEA is carried out and then logistic regression analysis is conducted using DP incident data (IMCA DP incident data 2010 – 2018) to quantify the risk. The results from both analyses are compared and discussed. Following steps presents the framework of risk analysis of DP system used in this thesis.

Step 1: Data Analysis

In this step the provided data, from IMCA, was analyzed, interpret, classify as per requirements of the analysis. Since the objective of the thesis is to carry out risk analysis of DP system, therefore main and secondary factors concerning failure of DP system and influencing factors data was prepared. The data related to sub-systems, Electrical and mechanical components, procedures, human error, software related error, and other were analyzed and prepared for further analysis.

To ensure some consistency and power in the data, some factors in the main and secondary cause of failures have been merged e.g., human error and procedures have been merged to form one category as there were only few incidents in procedures category. Some boundaries for the analysis are necessary and they are defined in section 5.2.2.

Step 2: Qualitative Risk Analysis

To understand the qualitative perspective of risk in DP system, FMEA was carried out. Since FMEA does not quantify the risk due to lack of relevant data, therefore in the next step quantification of failure is carried out based on available incident data.

Step 3: Quantification of Risk

In this step quantification of the failure contribution by various main causes contributing to the failure of DP system was carried out. This is done with the linear regression analysis and only main causes contribution to the failure of DP system is used for this purpose.

Step 4: Identification of Significant influencing factors

In this step the correlation between secondary causes and main causes will be developed using Pearson correlation. The aim of this step is to study and identify secondary causes combined with key main causes as factors that contribute the most in failure of DP system.

Step 5 Risk Prediction Analysis

In this step the risk prediction of failure of DP system have been carried out using logistic regression analysis. Failure of DP system due to main causes alone and due to main causes in combination with secondary causes data was used in risk prediction.

5.3 Results and Discussion

This section will establish the understanding of distribution of data used for the risk analysis leading to qualitative and quantitative analysis. The results from both analyses will be discussed and compared.

5.3.1 Distribution of Data

IMCA data specify total of ten sub-systems due to which DP incidents has occurred during nine years period. Figure 23 represents the distribution of failure for all 10 main causes reported in the data over a period of 9 years starting from 2010. Here thruster and propulsion errors caused more failures than the other factors with a total of 39 failures in year 2018 alone. Similarly, external forces and procedure errors did not cause as many failures as other causes, and thus have very low statistical power to perform a reliable regression analysis.

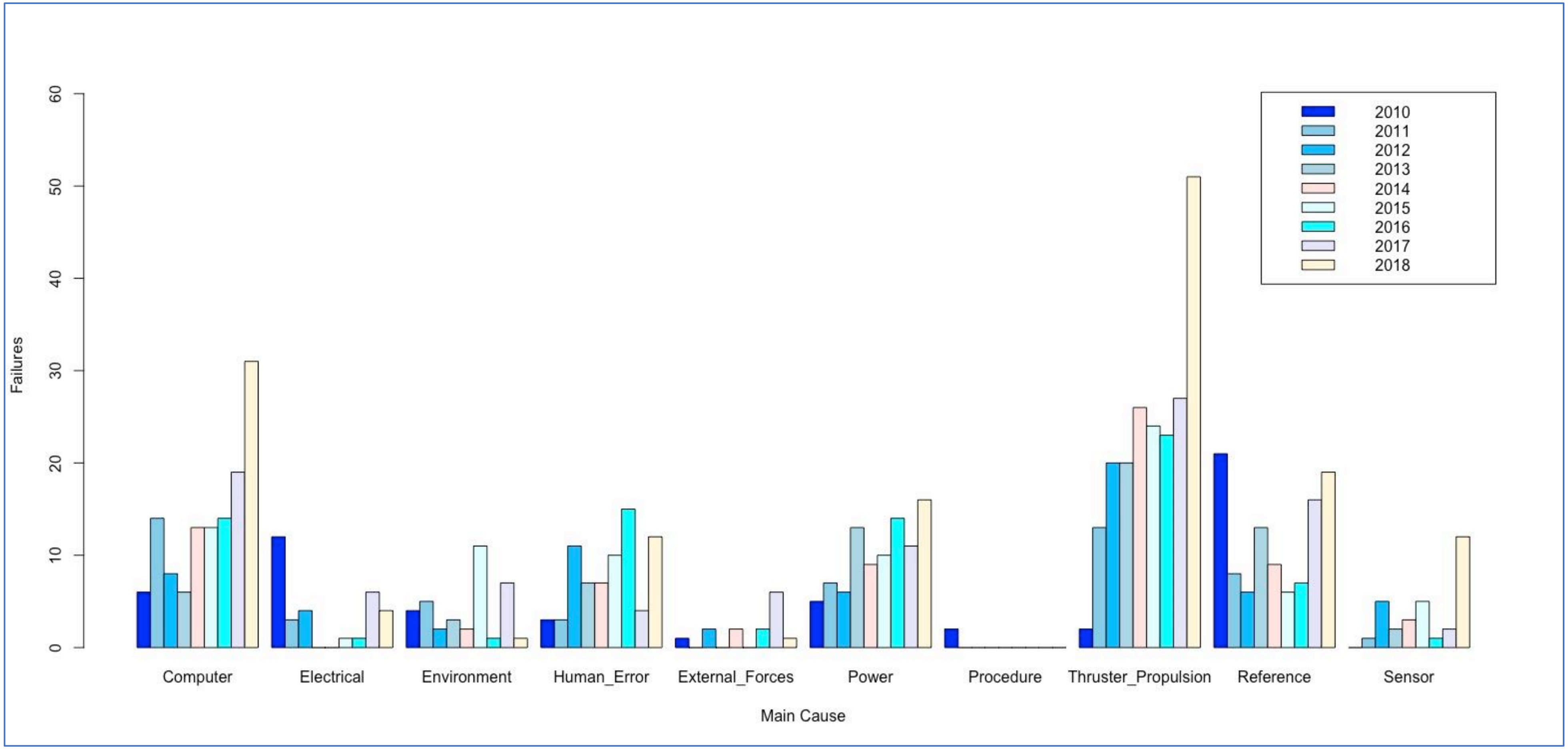


Figure 23: Distribution of failures for main causes over a period of nine years data

As mentioned earlier, the power of data used in this thesis is not very strong. Therefore, to improve the power of regression analysis we combined environmental failures with external forces failures and human error failures with procedure error failures for both primary (Figure 24) and secondary caused and electrical failures with the mechanical failures for secondary causes only (Figure 25). Figure 23 shows that overall main causes like thruster and propulsion, computer, power, and reference system have a major contribution in DP system failure incidents.

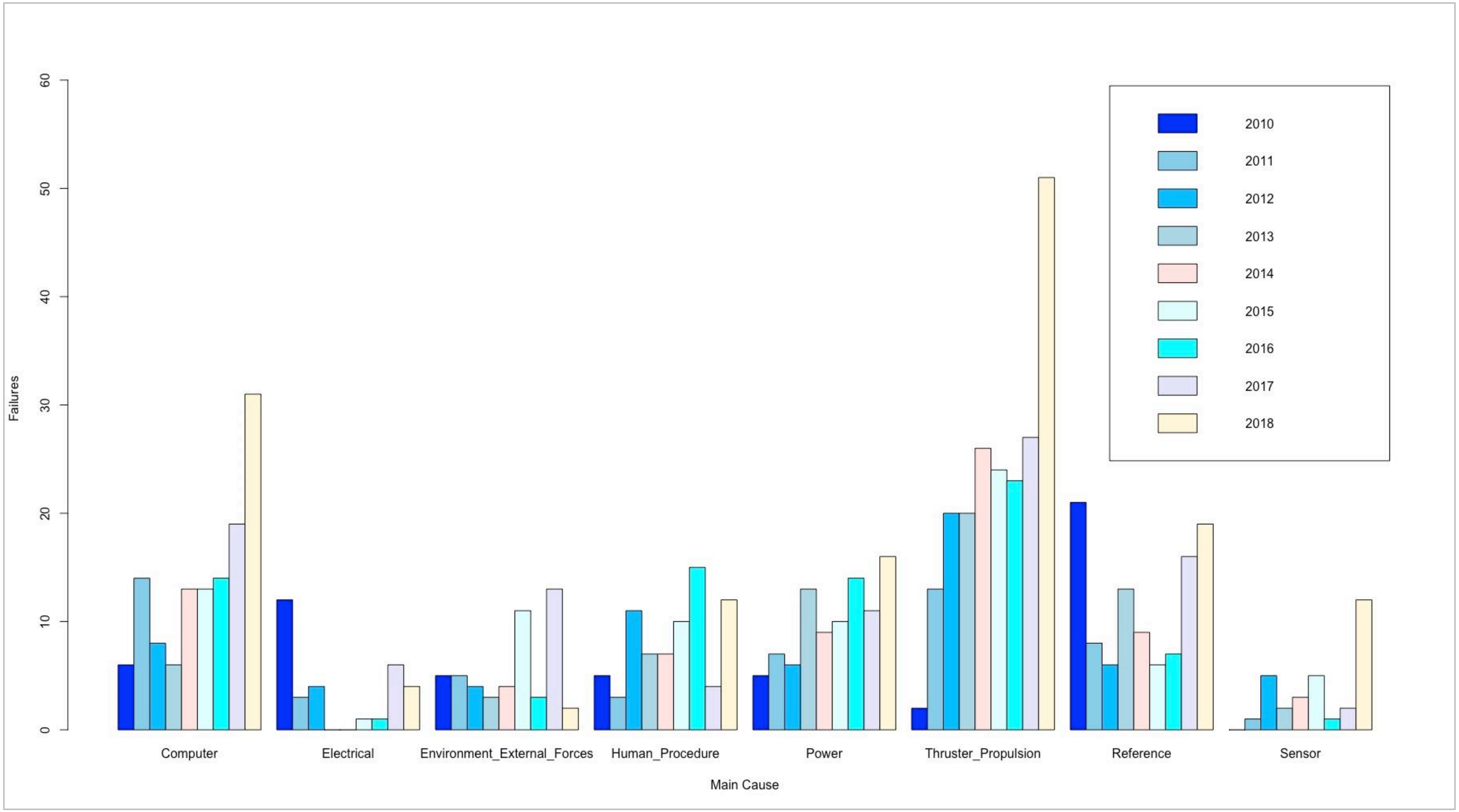


Figure 24: Distribution of failures for main causes after combining fewer representative causes over a period of nine years data

Collective summary of number of failures caused by all 8 main causes from 2010 to 2018 is presented in the following table. All these causes collectively caused 712 failures, either alone or in combination with a secondary cause, in 9 years. Among these causes, thruster and propulsion caused a total of 206 failures (29%) followed by 124 (17.4%) and 105 (14.7%) failures due to computer and reference system errors, respectively.

Table 5: Collective summary statistics for main causes of failures over a period of nine years (2010-2018)

Main Cause	Mean	SE	Median	SD	Minimum	Maximum
Computer	13.78	2.58	13.00	7.74	6.00	31.00
Electrical	3.44	1.27	3.00	3.81	0.00	12.00
Environment and External Forces	5.56	1.27	4.00	3.81	2.00	13.00
Human and Procedure Errors	8.22	1.34	7.00	4.02	3.00	15.00
Power	10.11	1.25	10.00	3.76	5.00	16.00
Thruster and Propulsion	22.89	4.36	23.00	13.08	2.00	51.00
Reference	11.67	1.93	9.00	5.79	6.00	21.00
Sensor	3.44	1.21	2.00	3.64	0.00	12.00

Distribution of failures stratified by main causes in combination with a secondary cause are shown in Figure 25 and Table 6. Out of 712, 254 (35.7%) failures were caused by main caused combined with one of the 8 listed secondary causes. Here, overall patterns can be distinguished graphically. Both figure and table showed that collectively electrical and mechanical errors were secondary reason of maximum number of failure (n=78; mean/year 8.67) followed by human and procedure errors (n=72; mean/year 6.00) over 9 years

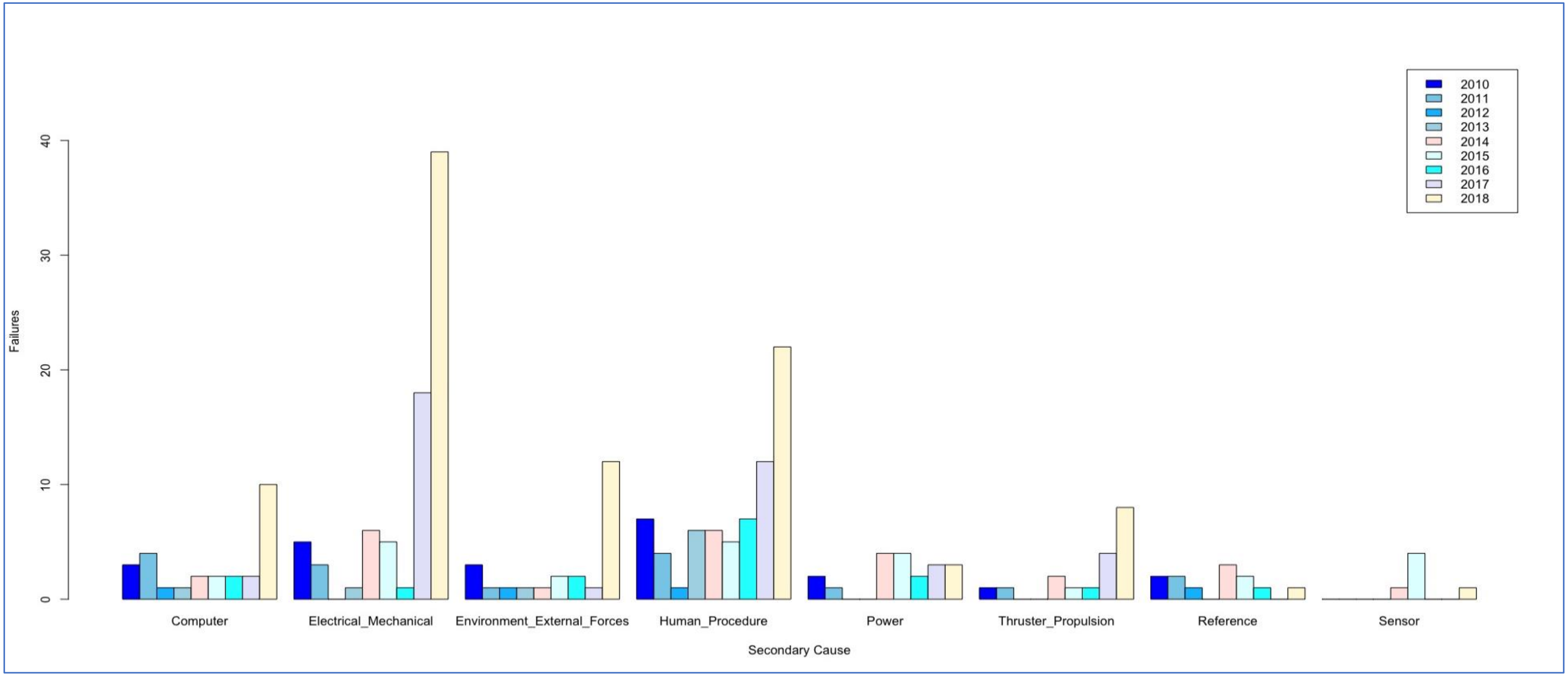


Figure 25: Distribution of failure rates for different secondary causes over a period of nine years data collection

Figure 25 shows distribution of different DP failure or incidents due secondary causes over period of nine years available in IMCA DP incident data from 2010 to 2018. It is evident that number of failures due to all secondary causes in 2018 year is more than rest of the years except secondary cause in power, reference system and sensors.

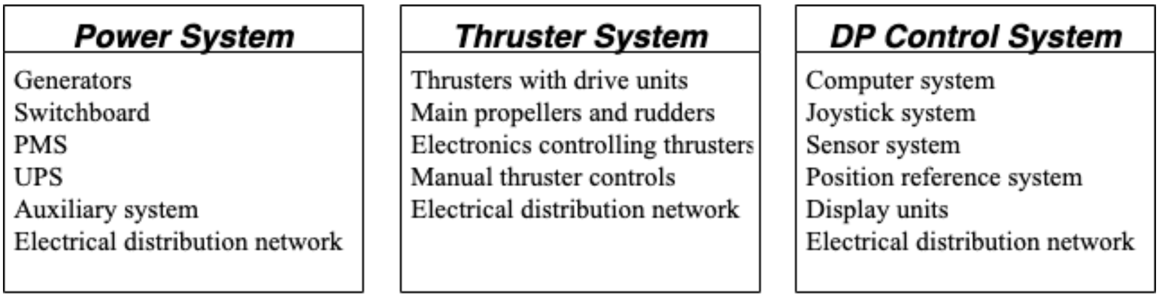
Table 6: Collective summary statistics for secondary causes of failures over a period of nine years

Secondary Cause	Mean	SE	Median	SD	Minimum	Maximum
Computer	3.00	0.93	2.00	2.78	1.00	10
Electrical	8.67	4.19	5.00	12.58	0.00	39
Environment and External Forces	2.67	1.19	1.00	3.57	1.00	12
Human and Procedure Errors	6.00	2.02	6.00	6.08	1.00	22
Power	2.11	0.51	2.00	1.54	0.00	4
Thruster_Propulsion	2.00	0.85	1.00	2.55	0.00	8
Reference System	1.33	0.33	1.00	1.00	0.00	3
Sensor	0.67	0.44	0.00	1.32	0.00	4

5.3.2 Failure Mode and Effects Analysis

A lot have been said about the FMEA in the earlier chapters. The core purpose of FMEA is to specify complete and systematic analysis by failure modes of all components to ascertain most significant failure modes with respects to station keeping of DP vessel. Through this technique, it has been tried to identify all possible failures that can cause failure to DP system to keep its position during operation.

Three sub-systems of the DP system and their components are studied in this thesis for risk analysis as shown in the following block.



Power System

Generators
Switchboard
PMS
UPS
Auxiliary system
Electrical distribution network

Thruster System

Thrusters with drive units
Main propellers and rudders
Electronics controlling thrusters
Manual thruster controls
Electrical distribution network

DP Control System

Computer system
Joystick system
Sensor system
Position reference system
Display units
Electrical distribution network

Appendix 4 shows a typical block diagram schematic of DP system. For the FMEA of DP system with notation DYNPOS AUTR under class DNV have been used. FMEA results can be very useful for prioritizing the individual sub-system or component depending on the failure mode and its impact on local and globally on the system. Furthermore, same result can lead to the improvement in the design and safe operations.

Possible Failure Modes and Analysis Conditions

For the selected notation of DYNPOS (AUTR) DP system, LoP should not happen as a result of failure of single component or sub-system. Followings are the some of the main considered failure modes among others that are presented in the FMEA for the analysis

i) Missing signals
ii) Malfunctioning equipment
iii) Complete power failure

iv) Failure of power fuse
v) Voltage fluctuation

Boundary conditions of the analysis

Following conditions are considered for the analysis

i) DP system is in operation
ii) Operator´s stations are in working condition
iii) Field process stations are working
iv) Switch board is working normally
v) DPO are present
vi) DP control system has redundancy with two or more computer controller implemented in parallel
vii) Generators have mechanical power input from diesel engines

System Arrangement

Under the appropriate section titles in the following table, specific requirements for each subsystem are described. Following table shows the system arrangement for the DNV notation DYNPOS (AUTR).

Table 7: System arrangement for DYNPOS (AUTR) as per DNV (77)

Sub-System or Component		DYNPOS(AUTR)	
Electrical PowerSystem	Electrical System	Redundancy in design	
	Main Switchboard	1	
	Bus-tie breaker	1	
	Distribution System	Redundancy	
	Power Management	Yes	
Thrusters	Arrangement of thrusters	Redundancy in design	
	Single levers for each thruster at main DP-control centre	Yes	
Positioning Control System	Automatic control, number of computer systems	2	
	Manual Control, independent joystrick system with automatic heading control	Yes	
Sensors	position reference systems	3	
	External Sensors	Wind	3
		Heading ref. system	3
		Vertical ref. sensor (VRS)	3
UPS		2	
Printer		Yes	
Back-up control centre for DP control back-up system		No	

To ensure redundancy, the power system divided into two or more sections. In the case that one system fails, the other will continue to function. During normal operation, single bus tie breakers may be closed, but they will automatically open if failure occur. Generators and prime movers are redundant for this DP class with redundant distribution system. Moreover, the number of generators for DYNPOS(AUTR) DP class should be according to the redundancy of this class and power management is done automatically through open and close busbar breakers. A failure in power management system should not affect the power generation but an alarm system should activate in the DP control center (1, 77).

Thruster control can be operated in three modes that are automatic, manually, and independent joystick by the DPO through DP control center. By DNV rules, for DYNPOS-AUTR the redundancy should not be violated in process of mode selection that means common switching may be carried out provided that each thruster system is electronically independent(12, 77).

In case of critical failure conditions are met, DP control system must execute a check and bring the system to safe stop or automatically shift to redundant system for safe operations. Automatic control includes control of heading and position while set point for both factors can be selected independent of each other and it is also possible to input position and heading values individually in automatic control mode. According to DVN, there is no specific acceptance criteria for vessel performance but in moderate weather conditions with DP operation the vessel should be able to keep position accuracy within 3m radius and ± 1° degree of heading (77).

Upon stoppage the thruster command should be zero regardless of manual or automatic means of stopping. While DYNPOS(AUTR) DP system is used, DPO can control the thrusters manually through a common joystick in the main DP control system. It is important to consider that reference system may be shared with other subsystems if failure in other system does not affect the DP system.

There are many guidelines and references for DP system FMEA and but IMCA proposes specific guidelines for the FMECA of DP system (27). To visualize and understand the different failures in DP system, nine years data from IMCA as presented in appendix 5 and 6 have been used. Most of the components causing failure of DP system have been incorporated in the FMEA worksheet presented in table 9, but factors like human error may not reflect directly. Indeed, such factors can have great influence on DP operations and have been incorporated in the next chapter for statistical regression analysis for risk prediction. In this chapter, all the incidents reported to IMCA during 2010 to 2018 have been analyzed in depth and converted into a useful FMEA worksheet.

The thesis has suggested some maintenance routines and measures to avoid or mitigate the risk of failure of components which can be replicate in any DP operations. Moreover, thesis will also present some lesson learnt and practices for safe operations of DP system in aquaculture as Havfarm2 will fully utilize the DP system for the first time in aquaculture. Although, DP system in aquaculture will be operating at lower water depth in comparison to its operations in oil & gas field, but the challenges can be similar as discussed in this thesis. The severity of failures and its consequences may or may not be same in both fields. Since, no historical data is available from aquaculture industry for DP system application, so it's hard to analyze if both sector shares same or varied risks from DP system. Technically DP system and its operating zones remains the same in all the application fields but how they are implemented, and risks of failure of DP system and consequences of failure can vary largely, figure 26 gives an overview of operating limits for DP system application in aquaculture (Havfarm2) and oil & gas drilling operations.

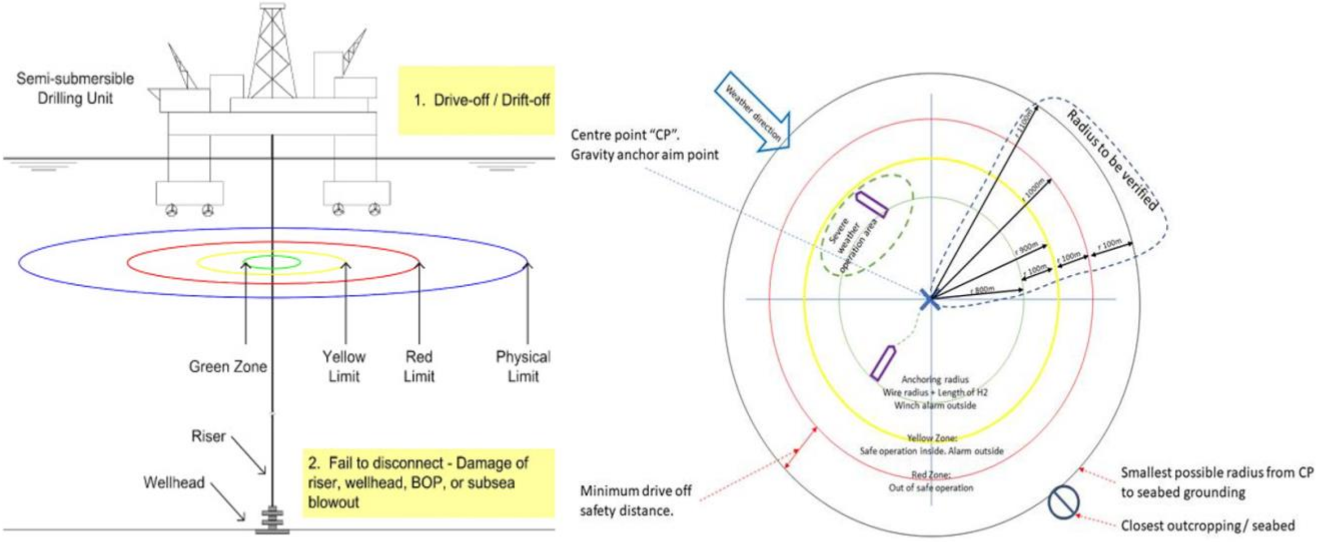


Figure 26: DP System operating zones for aquaculture, havfarm2, (right) and drilling rig (left) (15, 56)

DP system has following operational mode while in operation in Havfarm 2 for aquaculture.

Table 8: DP System Operational Mode for Havfarm 2 (56)

Operational Mode	Description
Happy fish mode	(Optional) Use anchors for station keeping. Use thrusters to ensure sufficient water quality for the fish
No wind mode	Use anchor for station keeping, no thrusters active. This can be used when the loads from wind and waves are low and predictable. Note that the loads from current could induce larger force then maximum force on anchor. This could lead to dragging of anchor, and must be investigated.
Heading control mode	Use anchor for station keeping, and thrusters for heading control. This is to make sure the vessel has the orientation with minimum subjected environmental loads
Trusted assisted position mooring mode	Use anchor and thrusters for station keeping. This includes both constant thruster assistance, heading control and damping of oscillations.
Operation mode	Use anchor and thrusters to maintain correct position and heading during operation. This includes, but not limited to: - Live fish carrier operations - Feed carrier operations - Ensilage operation - Other arriving vessels - Fish welfare

Storm mode	Only use thrusters, no anchor. The vessel shall be headed for minimum environmental loads, in addition to be located towards the environmental loads from the “DP centre point.” This can be seen as “Severe weather operation area” in the Figure 26.
Transit mode	Thrusters will be used for relocation.

Despite of number of improvements and strict redundancy requirements for the DP system, it is still not possible to rule out the probability of failure in DP system. While there are different methods available to reduce the likelihood failure of DP system but the only way to avoid single point failures in DP system is to perform an effective and through FME(C)A. It is equally or rather more important to perform tests to confirm the findings of FME(C)A for its effectiveness. As it has been established in earlier chapter that FME(C)A technique has been used frequently for risk analysis in DP system (71, 78, 79) , therefore in the following failure modes and effect analysis entries like components and functions of component in subsystems can be similar. Authors has contributed in the FMEA presented in this thesis with further study and more explicit view on failure modes, causes, effects, mitigation measures and implications of failure of components on DP application in aquaculture.

Table 9: Dynamic Positioning System Failure Modes and Effects Analysis

Sub-System	Component(s)	Function	Failure Mode	Failure Cause(s)	Local Effect	Global Effect	Severity Level	Risk reducing Measure	Remarks
Power System	Generator	Power generation	Breakdown of generator	Mechanical or electrical failure	Reduced or no power generation	Power load balancing or Blackout	Critical	Preventive maintenance and improve electrical redundancy. Should have emergency generator.	This can have operational and economic consequences
	Relay in Generator	Protect generator again overspeed	Generator is running at higher speed than desired	Failure of relay due to voltage spikes, hot switching capacitive and inductive load.	Protection system again overspeed is failed which may lead to generator tripping	Power generation capacity may significantly reduce	Moderate	Follow technological qualifications for electrical components and ensure maintenance routines are followed.	
	Busbars for 6kV	Main power supply, supplying 450V for industrial equipment and then 240V for non-industrial equipment	Short circuit in one of the two busbars.	Malfunction in circuit breaker of one of the two busbars.	Reduce capacity of auxiliary systems, bow and azimuth thrusters.	Less redundant system.	High	Ensure busbar protection schemes are strictly implemented.	Auxiliary system includes chilled water system, cooling pump, battery charging system for these busbars.
					Blackout	LoP occur due to loss of system function	Critical		

		Main power supply, supplying 450V for industrial equipment and then 240V for non-industrial equipment	Short circuit in common supply in both the busbars.	Failure of breaker Cable breakage	Thruster capacity is down to half	Thruster has reduced capacity may cause LoP	Critical	Ensure busbar protection schemes are strictly implemented. Improve maintenance routines and revisit test intervals.	This can have impact on life, assets and environment depending upon the application of DP vessel.
					Blackout	LoP due to loss of system function	Critical		
	Busbars for 440V	Supply power for industrial equipment	Short circuit in one of the two busbars.	Circuit breakers failure, cable breakage and mechanical components damages.	Blackout, Loss of azimuth propulsion, Loss of DP UPS1 or UPS2.	Reduced thrust capacity.	High	Ensure busbar protection schemes are strictly implemented. Improve maintenance routines and revisit test intervals.	Possible to investigate it at individual busbar level.
	Busbars for 240V	Supply power for non-industrial equipment	Short circuit in one of the two busbars.	Circuit breakers failure, cable breakage and mechanical components damages.	Loss of DP UPS1 or UPS2, loss of ship UPS1 or UPS2 and loss of power supply generator	Reduced thrust capacity	High	Ensure busbar protection schemes are strictly implemented. Improve maintenance routines and revisit test intervals.	Possible to investigate it at individual busbar level.

	One of the two ship UPS system	240V uninterrupted power supply for ship essentials.	Uninterrupted power supply short circuit	Malfunction in UPS equipment which can be electrical or mechanical	IAS and PMS system may loss access. Loss of thrusters: bow tunnel thruster and 2 propulsion Azimuth thrusters.	Thruster capacity is reduced and impacted.	High	Carry out more intensive maintenance routines and refer to any available document from manufacturer.	
	Whole UPS System	240V uninterrupted power supply for ship essentials functions.	Uninterrupted power supply short circuit	Malfunction in UPS equipment which can be electrical or mechanical	Loss of alarm monitoring and controlling system, 1 of the CPU for integrated automation system, transformer, thruster system, bow tunnel thruster system	Thruster capacity is lost and may lead to LoP	Critical	Ensure good maintenance routines including maintain good temperature, maintain float voltages, perform routine visual inspections, and avoid over cycling.	This can have impact on life, assets and environment depending upon the application of DP vessel.
	DP system UPS for DP equipment	Provide 240V uninterrupted power supply for DP system equipment	Uninterrupted power supply short circuit	Malfunction in UPS equipment which can be electrical or mechanical	Alarm system and power supply for wind information display unit is lost	Loss of complete thrust capacity	High	Ensure good maintenance routines including maintain good temperature, maintain float voltages, perform	This can have impact on life, assets and environment depending upon the application of DP vessel.

								routine visual inspections, and avoid over cycling.	
	Expansion tank (Cooling System)	Diesel generator cooling	Not enough or zero supply of cooling water	A leak or a clog in the pipeline	Desired temperature is not maintained for generators	Generator may loss power generation capacity	Moderate	Ensure good maintenance routines including more visual inspection and ensure enough water supply.	It is worth using vibration testing to avoid leakage and likes failure.
		Cooling of prolusion motor	Not enough or zero supply of cooling water	A leak or a clog in the pipeline	Thruster motor temperature is not maintained as desired	May experience reduced thruster capacity	Moderate	Ensure good maintenance routines including more visual inspection and ensure enough water supply.	It is worth using vibration testing to avoid leakage and likes failure.
	Ball valves (Compressed Air system)	Air supply to Quick valve closing (QVC) system	Not able to provide desired air supply	Valve leakage, mechanical failures like spring failure, wear and tear and high cycle fatigue	Trouble starting air system	Will have little impact as all generators will be running in operational mode	Low	Ensure good maintenance routines including more visual inspection	Sometime valves make unusual noise if it’s waring out so this indicator can be used.
		For starting air receiver and air	Not able to provide	Valve leakage, mechanical failures like	Not enough air supply for generators		Low	Ensure good maintenance routines	Sometime valves make unusual noise

		supply to generators	desired air supply	spring failure, wear and tear and high cycle fatigue				including more visual inspection	if it’s waring out so this indicator can be used.
	F.O service tank (Oil Supply)	Fuel supply to generators	Not enough fuel is not provided to generators	Leakage of tank, brakeage of shut off valve for tank draining	Loss of FO supply	Generators may not start	High	Ensure good maintenance routines including more visual inspection	Sometime valves make unusual noise if it’s waring out so this indicator can be used.
	Power Management System (PMS)	To automatically control and monitor the power plant and ensure that power capacity is in line with vessel power demand at any time.	Power failure and distribution network wire damage	Fire in system or power failure	Loss of communication between PMS and programable logic solver	Power not provided as per needs of different systems	Critical	Maintain and ensure that main load is not overladed even if one of the generators become unavailable.	This can have high implications as the whole DP system is dependent on the power.
	Stop Switch	Fans in generator room	Short circuit of emergency loop or failure on demand	Malfunctioning of switch or short circuit in emergency busbar	Power supply to fans in engine room is disturbed that may lead to fire, damper for air supply to close	Temperature rises in engine room	Low	Regular maintenance and visual inspection	

		For switchboard room for cooling system	Short circuit of emergency loop or failure on demand	Malfunctioning of switch or short circuit in emergency busbar	Loss of switchboard cooling system	Reduced cooling for switchboard room may cause rise in temperature	Low	Regular maintenance and visual inspection	
Thruster System	Thruster: Bow tunnel thruster 1 and 2	To control thrust of bow tunnel thruster 1 and 2	In correct or low thrust	Mechanical or electrical components failure, Insulation Failure, Water ingress, winding fault	Bow tunnel thrusters 1 and 2 are lost	Reduced fwd thrust	Moderate	It is very important that DPO detect discrepancy is detected between command and feedback. If detected trip a thruster to avoid failure.	Along with automation DPO training is as important as full functioning of safety functions.
	Thruster: Forward azimuth thruster	To control forward azimuth thrusters	In correct or low thrust	Mechanical or electrical components failure, Insulation Failure, Water ingress, winding fault	Forward azimuth thruster lost	Reduced fwd or longitudinal thrust	Moderate	It is very important that DPO detect discrepancy is detected between command and feedback. If detected trip a thruster to avoid failure.	
	Thruster: PS propulsion	For thruster control of PS	In correct or low thrust	Mechanical or electrical	Loss of PS propulsion	Reduced fwd or	Moderate		

	azimuth thruster	propulsion azimuth thruster		components failure, Insulation Failure, Water ingress, winding fault	azimuth thruster	longitudinal thrust		
	Thruster: SB propulsion azimuth thruster	For thruster control of SB propulsion azimuth thruster	In correct or low thrust	Mechanical or electrical components failure, Insulation Failure, Water ingress, winding fault	Loss of SB propulsion azimuth thruster	Reduced fwd or longitudinal thrust	Moderate	
	K Thrust mounting plate for manual operation of thruster	Operating panel for manual control of thrusters	short circuit of 230V UPS2,3 and power supply unit 1,2 for mounting plate	Electrical failure	Manual control lost, tripping of power supplies	Reduced control	moderate	Regular maintenance
Control System	Computer System	To calculate the required steering angle and thruster output for each thruster	No output for thrusters	Hardware or software failure	Inefficient or unavailable system for command thrusters	As a result of no thrust or false input data to thruster loss of position may occur	Critical	Regular checking of DP computer for software errors. Ensure no external aids like USB etc are connected to DP computer which can

								cause external virus.	
	Display Unit	Display interface for operator	Not able to access the display unit	Power failure or hardware failure	Operator interface is not available	Due to redundant system may not have significant impact on system but reduce redundancy	Low	Ensure maintenance routine	If one display unit is unavailable the second system must be available to go on with DP operation
	IAS server 1 OR 2 on ECR and bridge for Alarm	To monitor and control handling of IAS with communication to input and output cabinets and operator station	Failure of Computer System	Malfunction in Computer System, power failure	Loss of Server 1 or 2	Reduced redundancy or loss of control or monitoring system	Low	Regular checking of DP computer for software errors. Ensure no external aids like USB etc are connected to DP computer which can cause external virus.	
	IAS server 1 AND 2 on ECR and bridge for Alarm	To monitor and control handling of IAS with communication to input and	Failure of Computer System	Malfunction in Computer System, power failure	Loss of Server 1 AND 2	Monitoring system control is lost	Critical	Both the system should not fail, intensive maintenance and interval	

		output cabinets and operator station						testing should carry out to avoid whole system failure.
	Ring Network of IAS and PMS	For operator station including input and output server, distributed input and ouput cabinets.	Breakage of wire in ring-network and short circuit of wire in ring-network	Malfunction in Computer System, power failure or fire case happening	Interrupted alarm system	Loss of control and monitoring system	High	Better maintenance routines and procedures should be enforced.
	Laser based position reference system Fanbeam	Position reference system for position input	Failure of sensor	Electrical failure or malfunction in sensor	Position reference data not available for DP system	Alternate position reference system DGPS 1 and 2 are activated	Low	Predictive maintenance can be adopted for such components to avoid failure. Moreover, technological qualification of these components important to avoid failure.
	Differential global positioning system (DGPS1)	To provide improved location accuracy, in the range of operations of each system	Power failure	Electrical or mechanical failure	Wrong or no signal from DGPS	DGPS can still be operative with other source	Moderate	Predictive maintenance approach can be very effective to understand and

								reduce failures here.
	Radio based reference system	Long wave radio frequency is used to send the correction to the DGPS receiver.	Loss of radio signal	Electrical or mechanical failure	Wrong or no signal from DGPS	DGPS can still be operative with other source	Moderate	Inspection and maintenance.
	Gyro Compass	For identifying heading references	Loss of gyro compass 1 or 2 or 3	Electrical or mechanical failure	Reduced available gyrocompass depending upon how many are failed	Reduced redundancy unless blackout	Moderate	Predictive maintenance
	Wind sensors (2)	For wind speed and direction identification	Sensor failure	Electrical or mechanical failure	Reduced or no availability of wind sensor	Reduced redundancy of wind sensor unless blackout	Moderate	Predictive maintenance
	Joystick Controller for manual control	To provide DPO with manual position control	Power failure	Electrical or mechanical failure	DP operator lost manual control	Loss of manual control	High	Preventive or corrective maintenance.

Since, FMEA tool is an analytical process so personal experience and expert judgement can be use in advantage to the effectiveness of the analysis results. Due to the current pandemic and limitation, author could conduct any planned visit to the operational sites and conversation with DPO and other relevant personnel. In the current analysis, redundancy and independency of the design have been given due respect.

Analyzing the incident data revealed that that thruster, computer, and reference system contribute to 61% in the 712 reported incidents during aforesaid period.

Thruster contribution is about 29% in those incidents. It can be argued that thruster as main cause of incident may not result in loss of position of DP system due to redundancy and usually the incident is concerned with one thruster. Nevertheless, the operation of the DP system had to be halted during maintenance on thruster.

DP system incidents due to computer system are over 17%. Again, IMCA reported data does bifurcate hardware or software related computer incidents leading to loss of position. Many studies reported that most of the incidents where computer system is a main cause of incident that involves a software related issues or operator error while operating the software. The magic trick of rebooting the system resolve the software issue sometime but other times software reliability or bug issue can be serious issues with computer control. In addition to software issues, other known computer related failures are virus in the computer system while using external aids on DP designated computer, network challenges.

Reference system has 15% contribution as main cause of DP system failure in analyzed data. In reference system the main contributor is DGNS system, reason being these sensors are vulnerable to atmospheric effect like flashing.

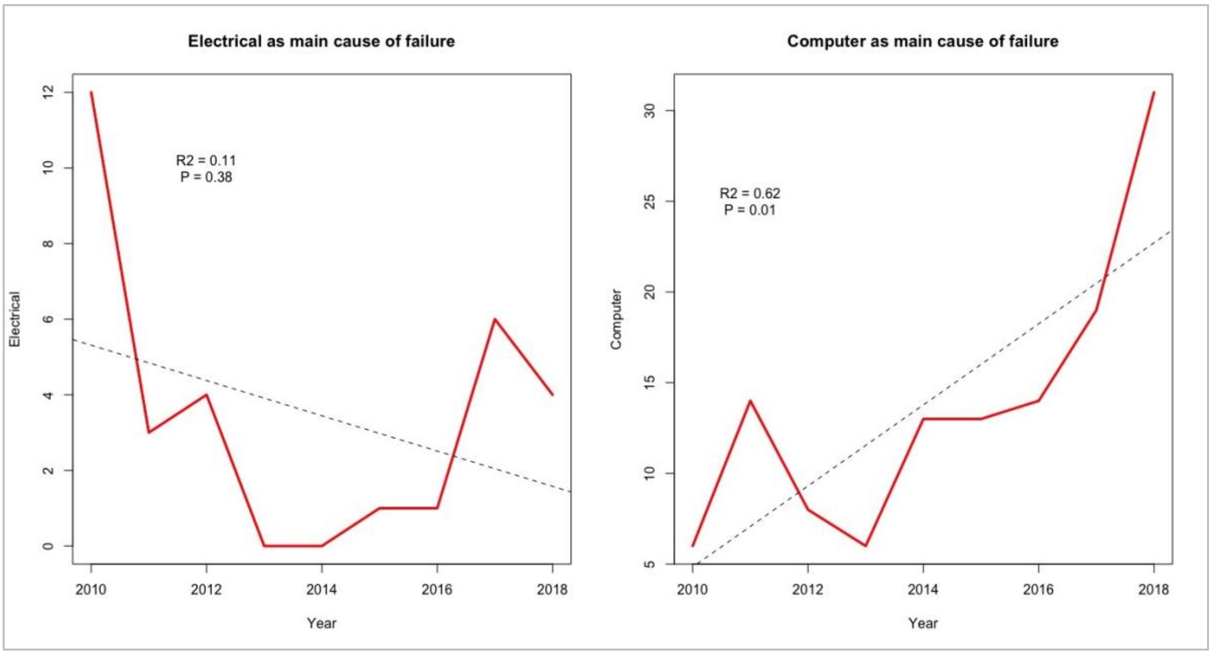
Power system as main cause of incident is also a concern to be given due attention. The reason for this thought is that the technology is evolving rapidly, and power system is becoming increasing complex and it can be rather challenging to identify the failures in a typically approach. This gives rise to utilization of techniques for hidden failures. Due to DPO or other relevant staff there are still quite significant incidents causing DP system failure.

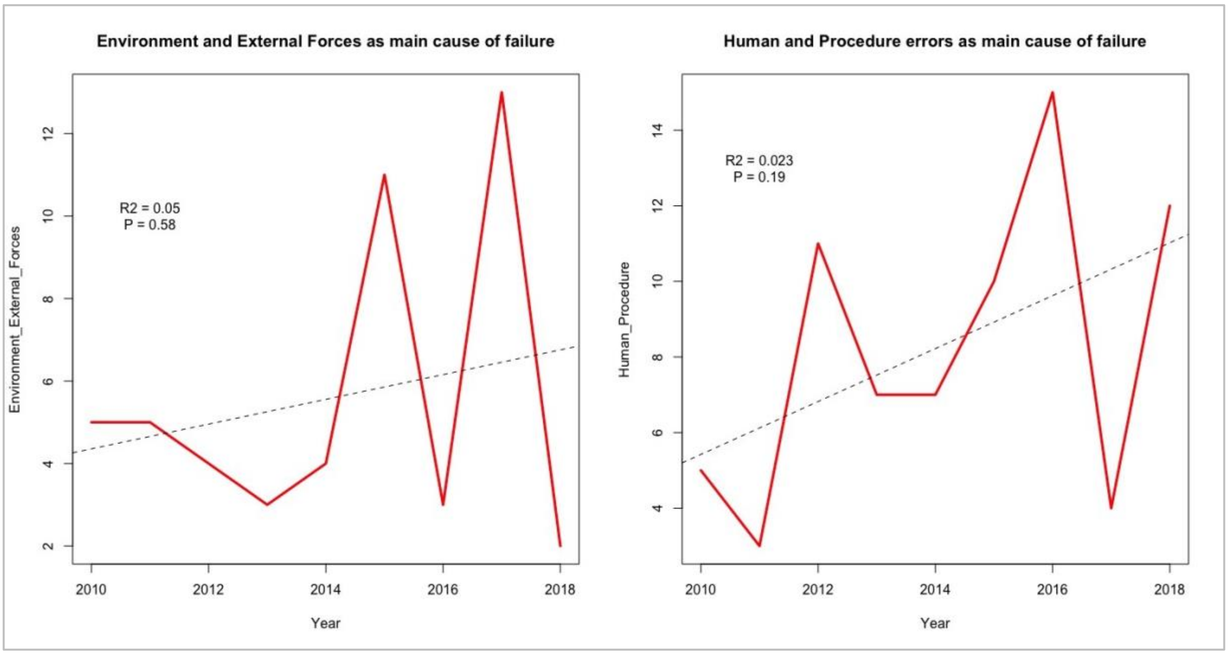
5.3.3 Linear Regression analysis

First, main causes were tested individually to quantify their contribution in the failure rates and to identify the main causes with statistically significant contribution over 9 years. Figure 27 present the graphical distribution of failure data over nine years for all 8 main causes used to perform the regression analysis. The red lines in each plot represents the yearly (on x-axis) distribution of number of incidents (on y-axis) contributed by each cause. The grey line in each plot represents the regression line and R^2 in each plot represents the percentage variation in the number of incidents explained by the change in independent variable (years in our case). P value for each plot is obtained from regression model and a p value <0.05 shows statistically significant trend.

Predominantly increasing trend for number of failures over year (red line) was observed for power, sensor, thruster and propulsion, and computer, while the failure rate trend for electrical errors was in reverse direction. Mixed trends were observed for all other causes (Figure 27).

The highest R^2 was observed for thruster and propulsion (75%) followed by power (R2=0.70) and computers (R^2=0.62).





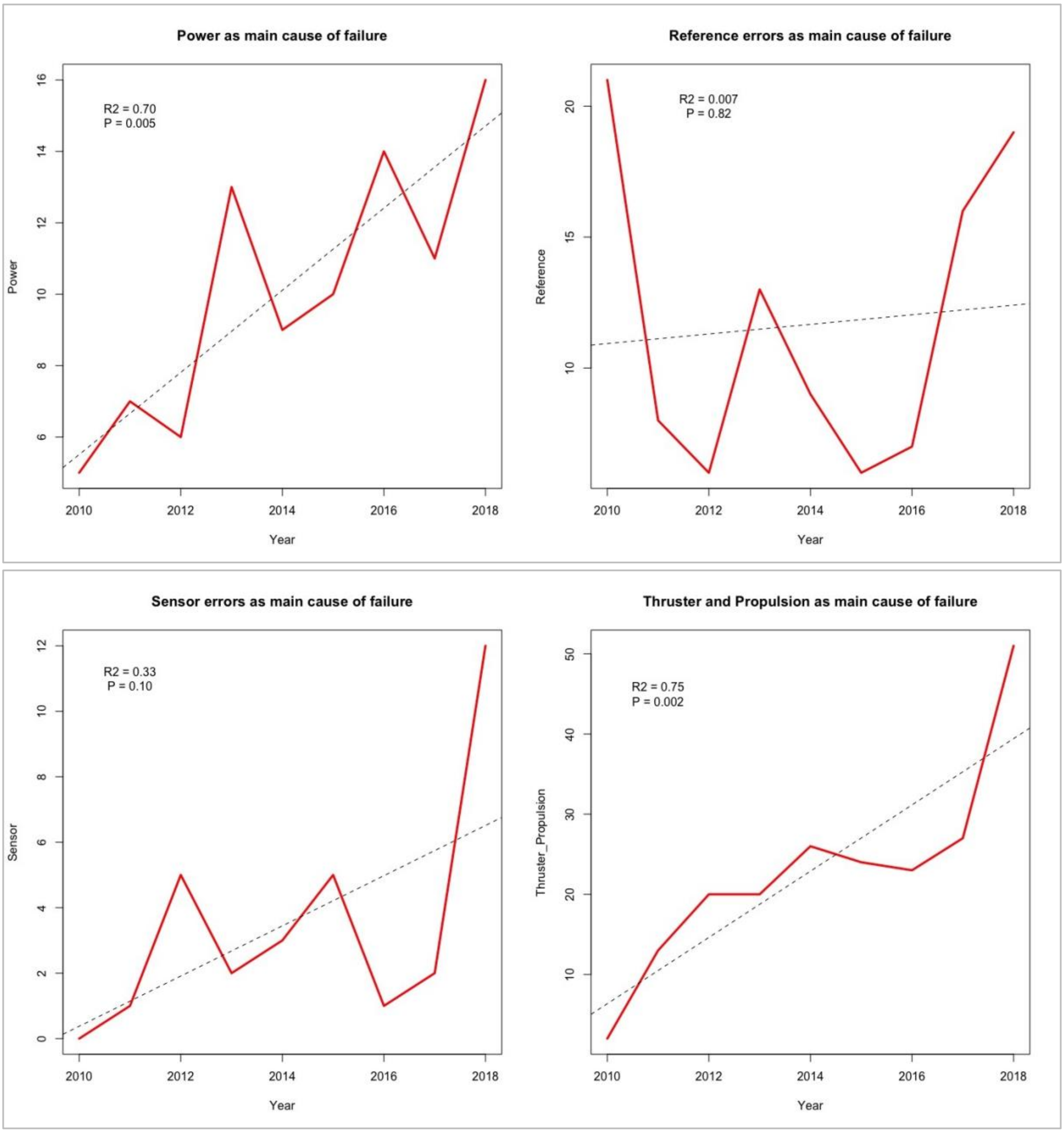


Figure 27: Regression plots graphically presenting the number of failures each year (red line) for 8 main causes

Regression results as presented as a forest plot in Figure 28. In forest plot, for each line the dot in the center represents the effect estimate (number of failures per year contributed by the tested cause) and error bars on both sides represent the 2.5% to 97.5% confidence intervals (CI). If the error bars do not cross the central vertical line at zero, then the regression results are statistically significant ($P<0.05$).

Consistent to the FMEA findings where computer system has critical impact on DP system failure, our linear regression analysis also supported the similar trend where computer system in increasing the number of failures per year by more than 2 (estimate = 2.23 failures/year, 97.5% CI = 0.68-3.78) with a statistically significant p-value ($P = 0.01$). Similarly, regression analysis further confirmed the high-moderate impact of power from FMEA with a significant regression estimate of 1.15 increased failures per year (97.5% CI = 0.48-1.82; $P = 0.005$). The

FMEA analysis identified that the thruster and propulsion system have moderate to high impact on DP system failure due to redundancy, while this impact was also in increasing direction in linear regression analysis where the calculated estimate was over 4 failures per year (estimate = 4.13; 97.5% CI = 1.99-6.28; P = 0.002) due to thruster and propulsion as main cause of incident. However, contradictory to the FMEA analysis, where electrical system was identified to have a high to critical impact on a DP system failure, regression analysis showed this system is decreasing the number of failures per year by 0.47 (97.5% CI = -1.63-0.70), though the results are not statistically significant (P = 0.38). All other causes increased the failure rate over time, though not significantly (Figure 28) which is consistent with FMEA analysis where these causes had moderate to low-moderate impact on a DP system failure. It is important to notice that FMEA does not address the human and procedure error directly while regression analysis quantify these errors by nearly 1 error increase per year.

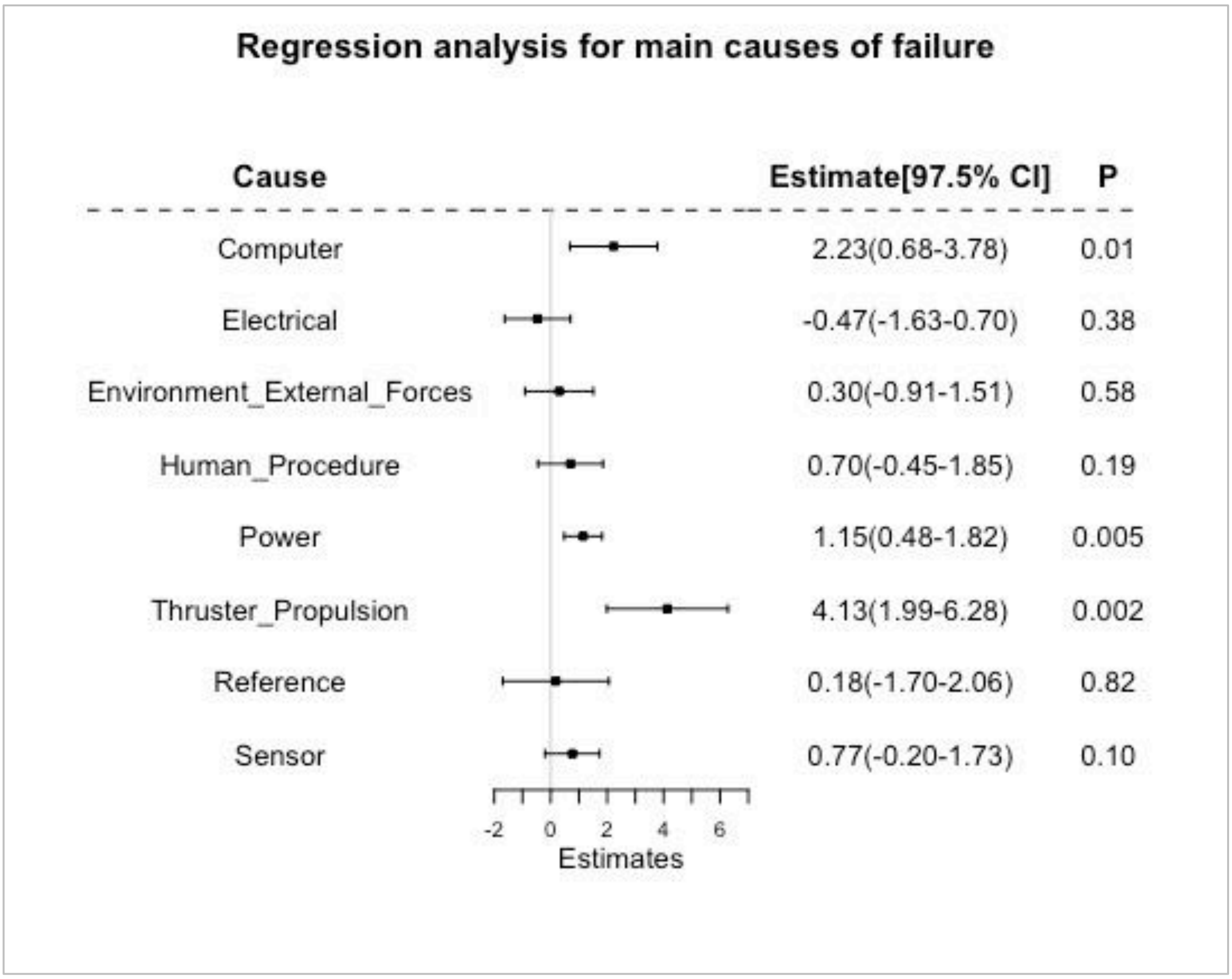


Figure 28:Forest plot to show the estimated number of failures per year contributed by each individual main cause calculated using linear regression model.

5.3.4 Correlation analysis

For 8 secondary causes, due to lack of sufficient statistical power for regression analysis, we were unable to apply the linear regression analysis as with such low power the confidence intervals will be wider to make a reliable conclusion. Instead, we performed the Pearson correlation analysis between the number of incidents contributed by all 8 main causes (computer, electrical, environmental and external forces combined, human and procedure errors combined, power, thruster and propulsion, reference system and sensor errors), and same causes as secondary reason of failure. This correlation was calculated to identify if any of these causes is strongly (and significantly) correlated as a main cause with any other cause as secondary reason of failure. In total 64 correlation values were calculated for with the correlation value, confidence intervals and p values are provided in index table 5. Then using the "ggplot" function in R, all 64 correlation values are plotted as heatmap (Figure 29). We used different shades of blue in this heatmap where lighter shades represent the stronger correlation between the main and secondary causes and darker shades represents vice versa. All causes when considered as main causes of failure, presented on y-axis and when considering those as secondary causes then plotted on x-axis. Out of 64, only 16 correlations were statistically significant ($P<0.05$) with correlation value ranging from 0.98 to 0.64. Stronger correlation values are interpreted as that the respective secondary causes contributed as an additional reason of the incidence along with the main cause. As one of the key facts about DP system is that to reduce the number of incidents, multiple failure dependencies were introduced. So, the stronger correlation in our heatmap might indicate the potential main and secondary causes combination(s) which can be helpful to reduce the future failure incidents in this system.

For example, among all 8 main causes, computer errors were significantly correlated with the highest number of secondary causes ($n = 5$) for failure including thruster and propulsion, electrical, human and procedure errors, computer and environmental errors combined with external forces (r from 0.94 to 0.78; P values from 0.0001 to 0.01). This finding further confirms that computer system might have a critical impact (as identified by FMEA and regression analysis) on DP system failure either alone or in combination with other strongly correlated secondary causes (heatmap Figure 29). Other three main causes showed significantly strong correlation with secondary causes include power, sensors, and combination thruster and propulsion with correlation values ranging from 0.83-0.68 (P ranges from 0.006 to 0.04). It is noteworthy that besides computer, power and combination thruster and propulsion are the other two main causes which were identified for their critical impact on DP system failure using both FMEA and linear regression analysis.

	Computer	Electrical	Environment_External_Forces	Human_Procedure	Power	Thruster_Propulsion	Reference	Sensor
Sensor	0.74	0.77	0.83	0.66	0.26	0.74	-0.08	0.37
Reference	0.5	0.6	0.53	0.67	0.1	0.56	-0.24	-0.29
Thruster_Propulsion	0.65	0.8	0.72	0.77	0.39	0.82	-0.24	0.26
Power	0.44	0.56	0.54	0.68	0.21	0.57	-0.48	0.11
Human_Procedure	0.17	0.11	0.38	0.17	0.06	0.13	-0.11	0.23
Environment_External_Forces	-0.31	0.01	-0.34	-0.06	0.44	0	-0.12	0.41
Electrical	0.18	0.18	0.17	0.18	-0.05	0.14	-0.01	-0.31
Computer	0.83	0.91	0.78	0.87	0.48	0.94	-0.12	0.16

Figure 29: Heatmap to show the Pearson correlation between main and secondary causes of failures. Here the dark blue shades represent weaker correlation between main and secondary causes while the lighter blue shades represent vice versa with a correlation value close to 1.

5.3.5 Logistic Regression Analysis

As identified from the heatmap, computer, sensors, combination of thruster and propulsion, and power were the main causes significantly correlated with different secondary causes in terms of number of failures. Collectively, these correlation analysis findings in combination with FMEA and linear regression analysis can be used to hypothesize that the failure rate for a DP system can be improved if the probability of failure can be bifurcated on a combination of multiple strongly correlated main and secondary causes of failure. Our data showed that the number of failures due to main causes alone are almost double than the combination of main causes with different secondary causes (458 versus 254) which can be used as a proof of concept that the rate of failure is reduced substantially if the failure risk is contributed by multiple reasons of failure. However, this assumption needs further testing using an appropriate statistical model for risk prediction like logistic regression analysis.

Here, we estimated that how high is the risk of failure for each of these 4 main causes (identified using FMEA, linear regression and correlation analysis), if the failure is cause by these causes alone (test group, labelled as 1 in the data file), compared to if the respective main cause is combined with different secondary causes (reference group, labelled as 0 in the data file), where the latter group was hypothesized to have lower risk of failure (Table 10). Thus, we applied binary (logistic) regression to calculate this risk of failure. The regression model provides odd ratio (OR) as an estimate of failure risk along with 97.5% confidence intervals. It is noteworthy that if an OR is greater than 1 then the tested cause is increasing the risk of failure, while an OR < 1 indicates that the tested cause is decreasing the risk of failure.

Our analysis showed (Table 10) that the risk of failure was significantly higher for all 4 main causes compared to their respective reference groups (main cause combined with secondary causes). The risk of failure was more than 3-folds higher (OR= 3.28; P = 0.01) for computer system as a sole cause of failure compared to the computer system combined with different secondary causes of failure. Here the confidence interval (1.76-16.04) was very wide and generally wider confidence interval represents that the data lacks sufficient statistical power to make a reliable conclusion. However, in our case the p value was less than 0.05 so finding can be used to predict the risk reliably due to its statistical significance (P = 0.01). The finding can also be interpreted in vice versa way where we can say that the risk of DP system failure can be reduced by 70% (as the OR for computer combined with secondary cause group will be 1/3.28 = 0.30 with the same P of 0.01) if failure dependency can be distributed to the computer system combined with other secondary causes than the computer alone. Please note that if an OR is less than one then the risk of failure is always in decreasing direction by 1-OR, for example in our case it was 1-0.30 = 0.70, so the risk was decreased by 70%.

Similarly, the failure risk associated with sensor as a sole cause of failure was 63% with a border line statistical significance (P = 0.05) but very narrow confidence interval (CI = 1.03-2.87). Thus, it can also be assumed that the risk of failure for this cause can be reduce by 39% (OR = 0.61; P=0.05) if the failure dependency is distributed between sensor and any other potential secondary cause (may be the ones strongly correlated from heatmap).

Similarly, the respective risk of failure associated with the thruster and propulsion and power as sole causes of failure was 86% and 35% higher (P = 0.002 and 0.0002) compared to the reference groups, respectively. Thus, our results showed that bifurcating the failure risk for multiple dependencies can reduce the DP system failure risk by 46% for thruster and propulsion and 26% for power.

Table 10: Risk analysis for 4 main causes which showed significant correlation with secondary causes of failure

Main Cause	OR (97.5% CI)	P
Computer	3.28(1.76-16.04)	0.01
Sensor	1.63(1.03-2.87)	0.05
Thruster and propulsion	1.86(1.33-2.97)	0.002
Power	1.35(1.19-1.66)	0.0002

OR is an odd ratio and CI is a confidence interval in the above table. The data used in the risk analysis of DP system in this thesis does not talk about the industries this data belong to but in general the results from the analysis can be implement in almost all the industries using DP system.

5.4 Recommendations for Safe Operations for DP System in Aquaculture

As mentioned in section 5.1 that DP system involves human-machine system. For safe and reliable DP operation in aquaculture and other industries, it is essential to consider all the main components of DP system including technical system failures and human operational failures in risk analysis or safety analysis. Risk analysis of DP system application in other industries has mainly focused on technical system failures but human interaction has not given much weightage. Incident data shows that 10% of incidents happen due to human error and it is also possible that some incidents due to computer failure also due to human error. To improve the safety and reduce the risk of loss of position of DP system in aquaculture the industry should focus on improving environmental conditions overall DP system and key personnel on DP system.

Environmental conditions like wind speed, waves height and sea current have direct impact on DP vessel´s performance. Harsh and sever weather with sudden change in wind speed, current direction can impact performance of relevant sensor to give input to the computer system to counter the environmental effects. DP control system and position reference system have major impact on safe and reliable DP operation. Other important subsystem under DP system for safe operation are Computer software, hardware and data network used along with vessel sensor which is normally termed as position reference system. Computer system is one of the main components of control system and it has contributed 17% of total incidents in DP incident data analyzed in this thesis, so author recommend the following best practices to avoid failure due to computer system

- No external aids should be allowed to use on DP computer system
- Internal and external audit of the software before DP operation
- Close contact with software provider and plan updates and test trials
- Software should be design in a way to detect and protect against virus
- Consistency with interface to avoid DPO error
- Ensure computer system hardware compatibility with software

- Ensure regular service and maintenance of computer system to avoid hardware failure
- Computer system should not be overclocked for higher speed as it will use more energy and produce more heat causing system to crash
- Hard drive should be changed after recommended cycles or time
- Aging and wear of computer system components should be checked and replaced as per manufacturer guide

Actions of DP operator or other personnel working on DP system can have a direct impact on the safe and reliable function of DP system. Aquaculture or any other industry should respect the following recommended practices to avoid any incident due to key personnel on DP system.

- Competency of the DPS staff
- Training of DPO
- DPO must have complete knowledge of the system
- Conduct regular refresher program of DP system (Reviewing basics can save catastrophic DP failures)
- Train and prepare DPO on simulator to respond to emergency scenario in shorted time window to avoid LoP
- Improve display design for DPO station with high visibility display
- DPO should be focused and not distracted throughout the DP system operation
- Ensure effective communication and teamwork between DP key personnel (this should be done at organizational level)

With the introduction of dynamic positioning system and automation in aquaculture fish farming, risk to human lives having been reduced immensely but the risk to the environment and asset has increased exponentially if failure happen. It is vital that the industry focused on researching and developing innovative solutions to protect the environment and asset while utilizing technology in offshore fish farming. Fishing industry in Norway have huge potential to outperform with safe and reliable DP system operations by adopting best practices and lesson learnt from DP system application in oil & gas and other industries.

Other than above recommendations following are some general recommendations for aquaculture, fishing, industry to perform safely.

- Worst case failure of DPS equipped vessel should be identified
- Power load calculations should be done and managed through PMS to avoid blackout incidents
- Battery backup system should have clear representation and distribution system
- Understand and ensure correct cooling system for thrusters.
- Auxiliary systems of all the subsystem should be give due respect

Finally, DP FMEA is important but there is a need to develop and research methods that look at the risk associated with DP system beyond technical systems only.

Chapter 6

Discussion and Scope for Further Work

6.1 Conclusion

The main objective of this thesis was to carry out risk analysis of DP system in different innovative applications. To be able to do this, qualitative method and statistical methods have been used on nine years DP incident data from IMCA. Qualitative risk analysis methods like FMEA have been used very often in different studies but risk have not been quantified that often. In this thesis, along with qualifying the risk, efforts have been made for the quantification of risk in DP system. One can argue that the power of the DP incident data was not very strong to drive results, but these results can give some starting point indication to mature the analysis with more powerful data in future.

The result of the analysis shows that certain sub-systems have more failure implications on DP system upon failure of those sub-systems. This thesis has used nine years incidents data from IMCA, where in total 712 loss of position incidence of DP system were reported. All the incidents were reportedly triggered by 8 different causes (both as main and secondary cause), including computer, electrical, power, human and procedure errors, reference system, environmental and external forces, thruster and propulsion, and sensor. Here, 65% of the incidents were caused by the main causes of failure while rest of 35% DP incidents were occurred due to combination of secondary and main causes or secondary causes alone.

Using this data, a series of analysis was performed to identify the failure risk associated with each of these causes along with predicting as if the risk of DP system failure can be changed by bifurcating the failure risk to multiple causes of failures. Using FMEA (a qualitative approach for risk analysis) it was identified that both electrical and computer system have critical impact on DP system failure while the critical to high risk is associated with thruster/propulsion, sensor, and power system. Application of linear regression (to quantify the risk of failure) confirmed that except electrical system, each of the other 7 causes were associated with increased failure rate, though the estimates were statistically significant ($P<0.05$) for thruster and propulsion, computer system and power only.

The correlation analysis showed that out of all causes, thruster and propulsion, computer system, power, and sensor were the only 4 main causes which were significantly correlated with the secondary cause of DP system failure. Using logistic regression analysis, we further confirmed that risk of failure was 3-fold to 35% higher if failure risk solely dependent on any of these 4 causes alone and this risk can be reduced up to 70% if the probability of failure can be bifurcated to the multiple causes of DP system failure.

6.2 Scope of Further Work

This thesis can be considered as a first attempt to investigate the risk analysis of DP system with statistical methods approach. The study was quite extensive with various analysis to see how risk can be analyzed. Still there is a lot of work need to be done to use statistical methods more effectively for the quantification of risk in DP system. The thesis highlights that there are different directions for further work and following are some of the recommendations.

Access to accurate data on component failure rates and conduct a reliability study of the DP system to aid in the identification of susceptible components and sub-systems. According to the results of the reliability study, improved maintenance plans can be draw for more reliable and safe DP operations.

IMCA should collect more detailed data of DP incidents when it happened e.g., water depth, wind speed, current, waves heigh, number of thrusters online etc. These parameters can help quantify risk with more power which can help to improve in the design and operations of the DP system.

More powerful data in terms of number of years and number of factors should be analyzed both qualitatively and quantitatively to predict the risk. Methods like survival analysis can also be considered to predict the risk and find out the safe and reliable operating limits of DP system.

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Appendices

Appendix 1

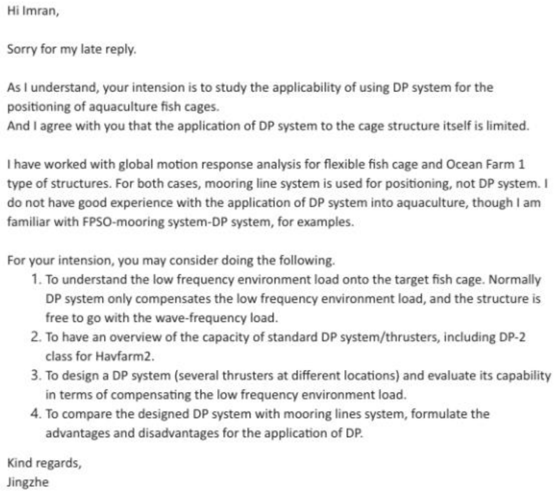
According to IMO (2) recommendation DP vessels with their application in specific industry usage much adhere to the class notation as given in the following table

Table 11: Recommended minimum DP class for different application industrial on DP (adopted from (2))

Application on DP	Minimum Recommended DP Equipment class	Remarks
Drilling	2	
Diving	2	
Pipelay	2	
Lifting	2	
Shuttle Offtake	2	
ROV Support (Open water)	1	
ROV Support (Closed surface/ Subsea)	2	
Logistics Operations	2*	Vessels of lesser Class may be used with appropriate structured risk identification and mitigation measures in place

Appendix 2

Email responses from different researchers and companies about application of DP system in aquaculture industry.



Hi Imran,

Sorry for my late reply.

As I understand, your intension is to study the applicability of using DP system for the positioning of aquaculture fish cages.
And I agree with you that the application of DP system to the cage structure itself is limited.

I have worked with global motion response analysis for flexible fish cage and Ocean Farm 1 type of structures. For both cases, mooring line system is used for positioning, not DP system. I do not have good experience with the application of DP system into aquaculture, though I am familiar with FPSO-mooring system-DP system, for examples.

For your intension, you may consider doing the following.

1. To understand the low frequency environment load onto the target fish cage. Normally DP system only compensates the low frequency environment load, and the structure is free to go with the wave-frequency load.
2. To have an overview of the capacity of standard DP system/thrusters, including DP-2 class for Havfarm2.
3. To design a DP system (several thrusters at different locations) and evaluate its capability in terms of compensating the low frequency environment load.
4. To compare the designed DP system with mooring lines system, formulate the advantages and disadvantages for the application of DP.

Kind regards,
Jingzhe

Dear Imran
Nordlaks asked me to give some comments.

The Havfarm 2 project is completely dependent on DP-technology, but also very novel, and outside all other normal aquaculture operations.

DP systems are normally used on feed transport vessels during offloading of feed into feed barges. Some of the newer live fish carriers, including Nordlaks' two newbuilding designed b NSK Ship Design are equipped with thrusters and DP capacity. This is becoming more and m normal, and more and more needed as locations are becoming more exposed. Common for most DP-equipped vessels within aquaculture is that the area normally not DP-classed, and have limited redundancy in the DP systems.

Just some initial thoughts and observations. Hope this helps.

Best regards / Mvh
Håkon Ådnanes

Mob: +47 95 92 08 36
email: hakon.adnanes@nsk.as
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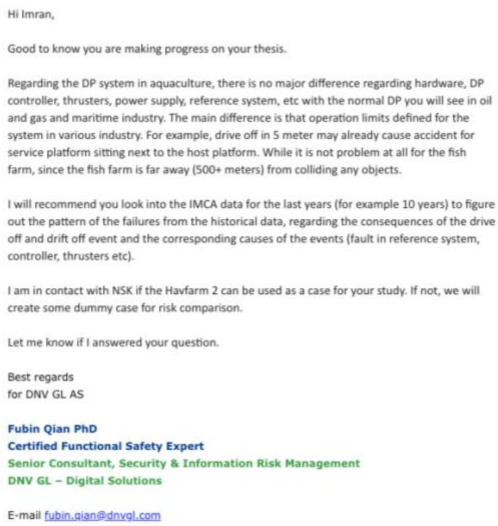
NSK SHIP DESIGN



Hi Imran,

Good to know you are making progress on your thesis.

Regarding the DP system in aquaculture, there is no major difference regarding hardware, DP controller, thrusters, power supply, reference system, etc with the normal DP you will see in oil and gas and maritime industry. The main difference is that operation limits defined for the system in various industry. For example, drive off in 5 meter may already cause accident for service platform sitting next to the host platform. While it is not problem at all for the fish farm, since the fish farm is far away (500+ meters) from colliding any objects.

I will recommend you look into the IMCA data for the last years (for example 10 years) to figure out the pattern of the failures from the historical data, regarding the consequences of the drive off and drift off event and the corresponding causes of the events (fault in reference system, controller, thrusters etc).

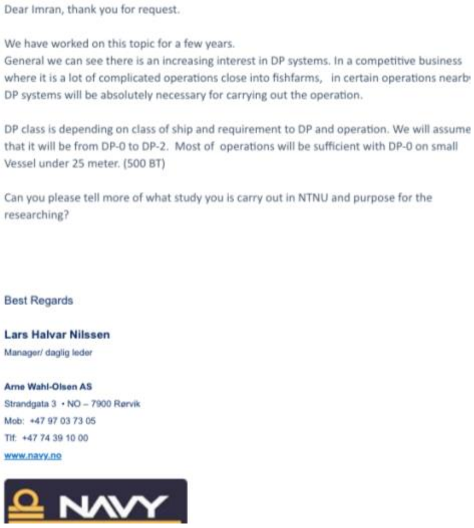
I am in contact with NSK if the Havfarm 2 can be used as a case for your study. If not, we will create some dummy case for risk comparison.

Let me know if I answered your question.

Best regards
for DNV GL AS

Fubin Qian PhD
Certified Functional Safety Expert
Senior Consultant, Security & Information Risk Management
DNV GL – Digital Solutions

E-mail fubin.qian@dnvgl.com



Dear Imran, thank you for request.

We have worked on this topic for a few years.
General we can see there is an increasing interest in DP systems. In a competitive business where it is a lot of complicated operations close into fishfarms, in certain operations nearb DP systems will be absolutely necessary for carrying out the operation.

DP class is depending on class of ship and requirement to DP and operation. We will assume that it will be from DP-0 to DP-2. Most of operations will be sufficient with DP-0 on small Vessel under 25 meter. (500 BT)

Can you please tell more of what study you is carry out in NTNU and purpose for the researching?

Best Regards

Lars Halvar Nilssen
Manager/ daglig leder

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Appendix 3

Table 12: Severity ranking criteria (75)

Rank	Description
1-2	Minor failure that the customer (internal or external) will probably not detect the failure.
3-5	Failure will result in slight customer annoyance and/or slight deterioration of part or system performance
6-7	Failure will result in customer dissatisfaction and annoyance and/or deterioration of part or system performance.
8-9	Failure will result in high degree of customer dissatisfaction and cause nonfunctionality of system.
10	Failure will result in major customer dissatisfaction and cause non- system operation or non-compliance with government regulations.

Table 13: Likelihood of Occurrence ranking criteria (75)

Ranking	Failure Effect	Description
1-2	Very High	$p \leq 1$ week
3-5	High	1 week $<p \leq$ 1month
6-7	Medium	1 month $<p \leq$ 1 year
8-9	Low	1 year $<p \leq$ 5 years
10	Very Low	> 15 years

Table 14: Detection Ranking(75)

Rank	Description
1-2	Probability is very high that the defect will be detected. Available controls and detection methods will most certainly detect the defect.
3-5	Probability is high that the defect will be detected. Available controls and detection methods will have good chances to detect the defect.
6-7	Probability is moderate that the defect will be detected. Available controls and detection methods will likely detect the defect.
8-9	Probability is low that the defect will be detected. Available controls and detection methods likely will not detect the defect.
10	Probability is very low that the defect will be detected. Available controls and detection methods will most certainly not detect the defect.

Appendix 4

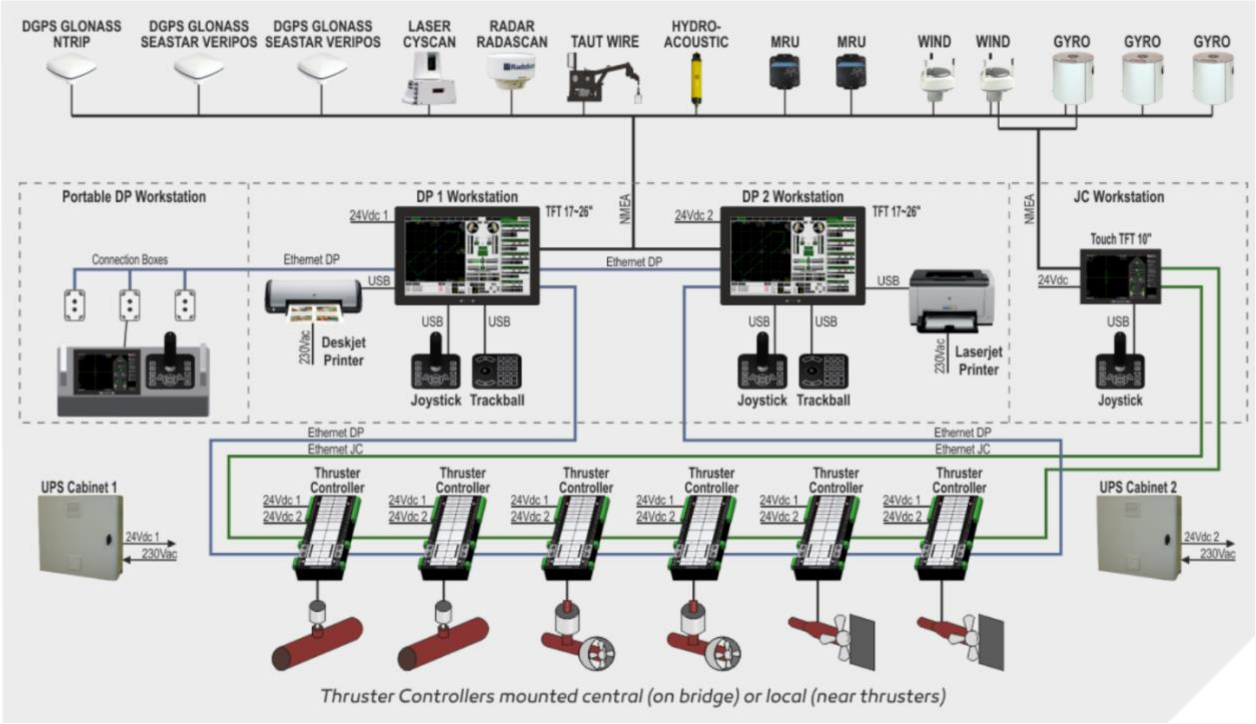

Figure 30: DP System Block Diagram (80)

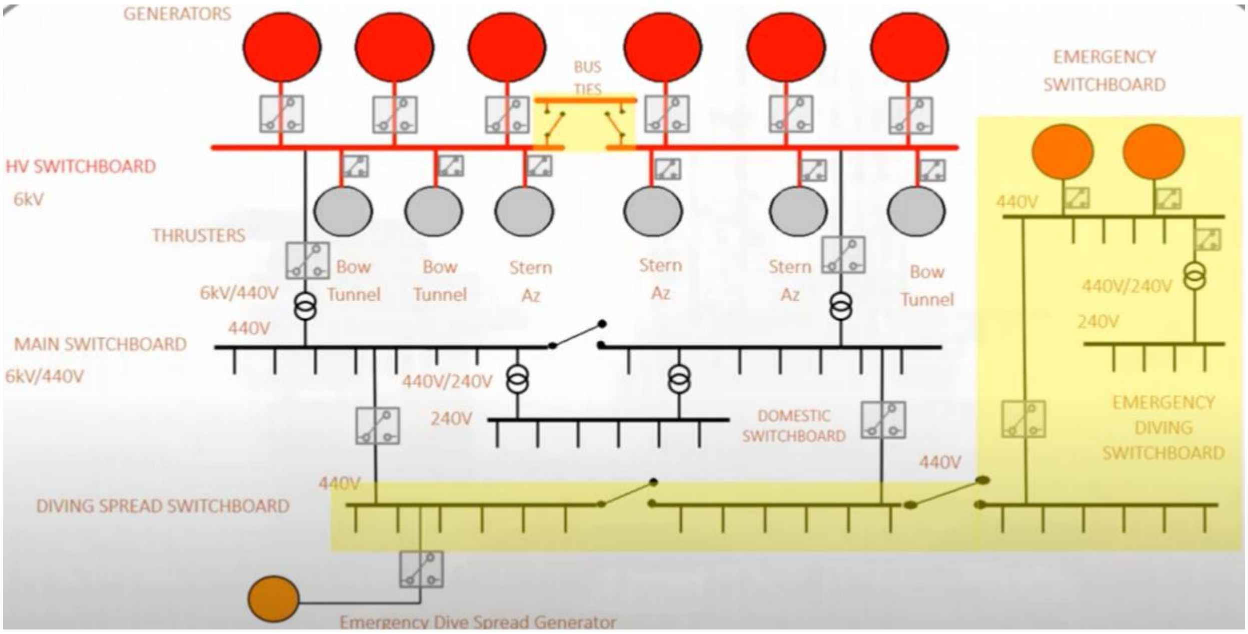

Figure 31: Power distribution for offshore vessel with DP system (81)

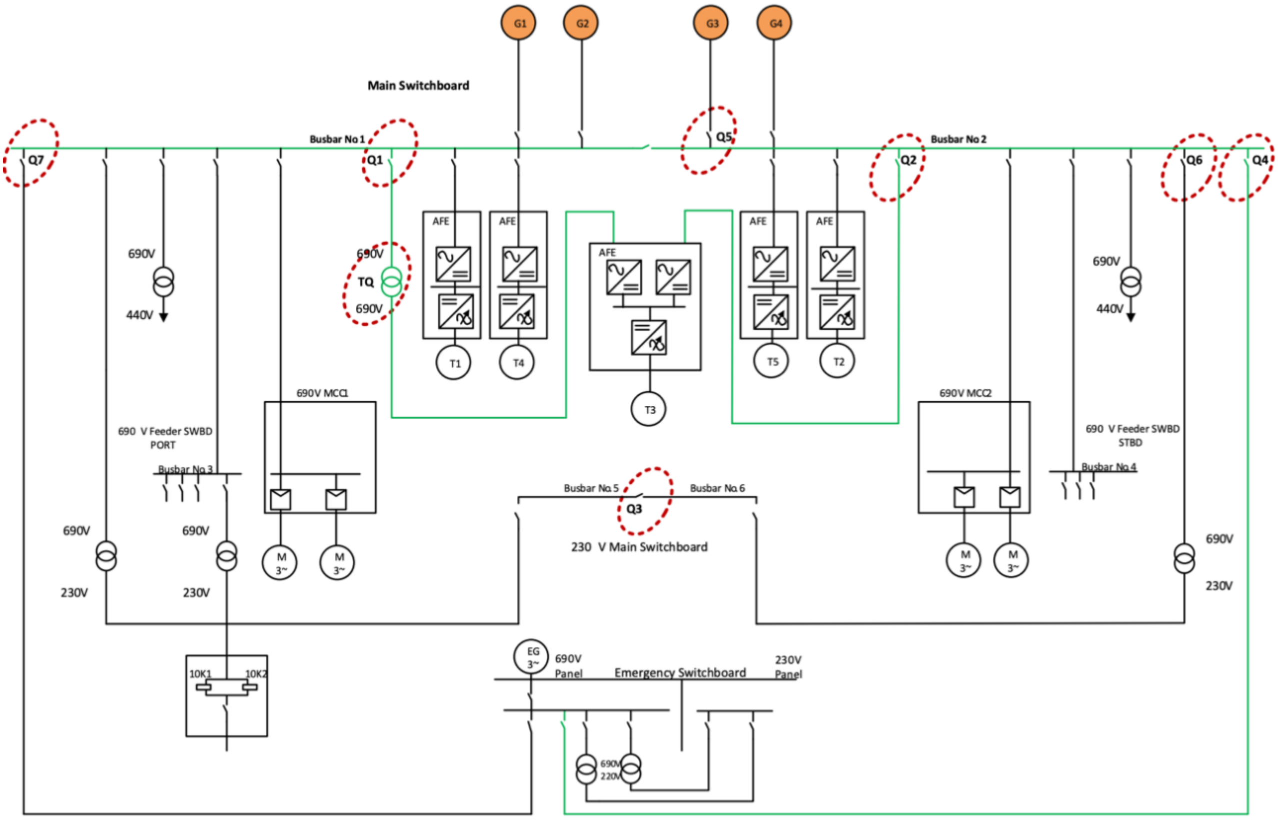

Figure 32: Power distribution for offshore vessel with DP system (79)

Appendix 5

Table 15: Correlation between main and secondary causes

Main Causes	Secondary Causes	r	95% CI	p
Computer	Thruster_Propulsion	0.94	(0.75-0.99)	0.0001
Computer	Electrical	0.91	(0.63-0.98)	0.0006
Computer	Human_Procedure	0.87	(0.50-0.97)	0.002
Computer	Computer	0.83	(0.38-0.96)	0.005
Sensor	Environment_External_Forces	0.83	(0.37-0.96)	0.006
Thruster_Propulsion	Thruster_Propulsion	0.82	(0.33-0.96)	0.007
Thruster_Propulsion	Electrical	0.80	(0.30-0.96)	0.009
Computer	Environment_External_Forces	0.78	(0.25-0.95)	0.01
Sensor	Electrical	0.77	(0.23-0.95)	0.01
Thruster_Propulsion	Human_Procedure	0.77	(0.21-0.95)	0.02
Sensor	Computer	0.74	(0.15-0.94)	0.02
Sensor	Thruster_Propulsion	0.74	(0.15-0.94)	0.02
Thruster_Propulsion	Environment_External_Forces	0.72	(0.10-0.94)	0.03
Power	Human_Procedure	0.68	(0.04-0.93)	0.04
Reference	Human_Procedure	0.67	(0.01-0.92)	0.05
Sensor	Human_Procedure	0.66	(0.002-0.92)	0.05
Thruster_Propulsion	Computer	0.65	(-0.02-0.92)	0.06
Reference	Electrical	0.60	(-0.10-0.90)	0.08
Power	Thruster_Propulsion	0.57	(0.14-0.90)	0.11
Power	Electrical	0.56	(-0.17-0.89)	0.12
Reference	Thruster_Propulsion	0.56	(-0.17-0.89)	0.12
Power	Environment_External_Forces	0.54	(-0.19-0.89)	0.13
Reference	Environment_External_Forces	0.53	(-0.19-0.89)	0.13
Reference	Computer	0.50	(-0.24-0.87)	0.17
Computer	Power	0.48	(-0.26-0.87)	0.18
Environment_External_Forces	Power	0.44	(-0.32-0.85)	0.24
Power	Computer	0.44	(-0.31-0.85)	0.23
Environment_External_Forces	Sensor	0.41	(-0.34-0.84)	0.27
Thruster_Propulsion	Power	0.39	(-0.37-0.84)	0.30
Human_Procedure	Environment_External_Forces	0.38	(-0.38-0.83)	0.31
Sensor	Sensor	0.37	(-0.39-0.83)	0.32
Sensor	Power	0.26	(-0.49-0.79)	0.50
Thruster_Propulsion	Sensor	0.26	(-0.49-0.79)	0.50
Human_Procedure	Sensor	0.23	(-0.51-0.77)	0.56
Power	Power	0.21	(-0.52-0.77)	0.58
Electrical	Computer	0.18	(-0.55-0.75)	0.65

Electrical	Electrical	0.18	(-0.55-0.75)	0.64
Electrical	Human_Procedure	0.18	(-0.56-0.75)	0.67
Electrical	Environment_External_Forces	0.17	(-0.56-0.75)	0.66
Human_Procedure	Computer	0.17	(-0.56-0.75)	0.67
Human_Procedure	Human_Procedure	0.17	(-0.56-0.75)	0.66
Computer	Sensor	0.16	(-0.56-0.75)	0.67
Electrical	Thruster_Propulsion	0.14	(-0.58-0.74)	0.72
Human_Procedure	Thruster_Propulsion	0.13	(-0.58-0.73)	0.73
Human_Procedure	Electrical	0.11	(-0.59-0.72)	0.77
Power	Sensor	0.11	(-0.60-0.72)	0.78
Reference	Power	0.10	(-0.60-0.72)	0.79
Human_Procedure	Power	0.06	(-0.63-0.69)	0.88
Environment_External_Forces	Electrical	0.01	(-0.66-0.67)	0.98
Environment_External_Forces	Thruster_Propulsion	0.00	(-0.66-0.66)	1.00
Power	Reference	-0.48	(-0.87-0.27)	0.19
Environment_External_Forces	Environment_External_Forces	-0.34	(-0.82-0.41)	0.37
Electrical	Sensor	-0.31	(-0.81-0.44)	0.41
Environment_External_Forces	Computer	-0.31	(-0.81-0.45)	0.42
Reference	Sensor	-0.29	(-0.80-0.46)	0.44
Reference	Reference	-0.24	(-0.78-0.51)	0.54
Thruster_Propulsion	Reference	-0.24	(-0.78-0.51)	0.54
Computer	Reference	-0.12	(-0.72-0.59)	0.76
Environment_External_Forces	Reference	-0.12	(-0.73-0.59)	0.76
Human_Procedure	Reference	-0.11	(-0.72-0.59)	0.77
Sensor	Reference	-0.08	(-0.71-0.62)	0.84
Environment_External_Forces	Human_Procedure	-0.06	(-0.70-0.63)	0.87
Electrical	Power	-0.05	(-0.69-0.63)	0.89
Electrical	Reference	-0.01	(-0.67-0.66)	0.98

Appendix 6

Table 16: IMCA DP System Incident Data (2010-2018)

Main Causes	Secondary Causes	Failures (2010)	Failures (2011)	Failures (2012)	Failures (2013)	Failures (2014)	Failures (2015)	Failures (2016)	Failures (2017)	Failures (2018)
Computer	NA	4	10	8	6	8	11	15	13	18
Computer	Human	2	1	0	0	2	0	0	4	6
Computer	Computer	0	3	0	0	1	2	0	0	5
Computer	Sensors	0	0	0	0	1	0	0	0	1
Computer	Electrical	0	0	0	0	1	0	0	1	0
Computer	Thruster/propulsion	0	0	0	0	0	0	0	1	0
Computer	Power	0	0	0	0	0	0	0	0	1
Reference System	NA	15	6	6	11	7	1	5	11	2
Reference System	Human	3	1	0	1	2	3	2	1	10
Reference System	Computer	2	1	0	1	0	0	0	1	3
Reference System	Electrical	1	0	0	0	0	0	0	3	2
Reference System	Reference	1	0	0	0	0	2	0	0	0
Electrical	NA	7	3	4	0	0	0	0	2	3
Electrical	Human and Mics. Error	1	0	0	0	0	1	0	1	0
Electrical	Power	0	0	0	0	0	0	0	1	0

Electrical	Electrical	3	0	0	0	0	0	0	1	1
Electrical	Thruster/propulsion	0	0	0	0	0	0	0	1	0
Environment	NA	2	3	2	2	2	6	0	7	1
Environment	Human	1	0	0	1	0	0	0	0	0
Environment	Reference	0	2	0	0	0	0	0	0	0
Environment	Power	0	0	0	0	0	1	0	0	0
Environment	Sensor	0	0	0	0	0	3	0	0	0
Power	NA	2	5	5	9	5	7	14	5	0
Power	Human	1	0	1	3	0	1	0	3	4
Power	Power	1	1	0	0	1	2	1	0	1
Power	Propulsion	1	0	0	0	1	0	0	0	0
Power	Electrical	0	1	0	1	2	0	0	3	10
Power	Thruster/propulsion	0	0	0	0	0	0	0	0	2
Human Error	NA	1	1	9	6	5	8	5		5
Human Error	Human and Mics. Error	1	2	1	1	0	1	6	0	3
Human Error	Computer	1	0	0	0	1	0	2	1	1
Human Error	Reference	0	0	1	0	1	0	1	0	1
Human Error	Thruster/propulsion	0	0	0	0	1	0	0	0	1
Human Error	Sensor	0	0	0	0	0	1	0	0	0
Human Error	Electrical	0	0	0	0	0	0	1	1	0
Human Error	Power	0	0	0	0	0	0	1	2	0
Thruster / Propulsion	NA	2	10	19	19	16	18	22	15	17

Thruster / Propulsion	Human	0	0	0	1	3	0	1	3	4
Thruster / Propulsion	Computer	0	0	1	0	0	0	0	0	1
Thruster / Propulsion	Electrical	0	0	0	0	3	5	0	9	23
Thruster / Propulsion	Power	0	0	0	0	3	0	0	0	1
Thruster / Propulsion	Thruster/propulsion	0	0	0	0	0	1	1	0	5
Procedure/External Factors	NA	0	0	2	0	1	0	1	4	2
Procedure/External Factors	Human	1	1	0	0	0	0	0	0	0
Procedure/External Factors	Mechanical	1	1	0	0	0	0	0	0	0
Procedure/External Factors	Thruster/propulsion	0	1	0	0	0	0	0	2	0
Procedure/External Factors	Power	0	0	0	0	0	1	0	0	0
Procedure/External Factors	Reference	0	0	0	0	1	0	0	0	0
Sensor	NA	0	0	5	2	3	4	0	1	2
Sensor	Human	0	0	0	0	0	1	0	1	7
Sensor	Mechanical	0	1	0	0	0	0	0	0	0
Sensor	Electrical	0	0	0	0	0	0	0	0	3