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Human Technical Factors in FPSO-Shuttle Tanker interactions and their influence on the Collision Risk during Operations in the North Sea

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'Human technical factors in FPSO shuttle tanker interactions and their influence on the collision risk during operations in the North Sea'

Background

Floating production, storage and offloading (FPSO) units have long been employed in the North Sea, with the introduction of the first purpose built FPSO, Petrojarl 1, in 1986. Since then, the prevalence in the use of FPSO units in the North Sea has gradually been increasing.

Tandem configuration is the most common way of performing offloading operations from an FPSO. Such a configuration involves the tanker positioning itself at some distance behind the FPSO, and the two vessels connect by a mooring hawser and a cargo hose used for offloading (Chen and Moan, 2004). The shuttle tanker maintains its position using dynamic positioning (DP), keeping the mooring hawser free of tension, or by applying a small thrust astern, keeping the mooring hawser is tensioned.(Chen and Moan, 2005).

Historically there have been several collisions and near misses involving shuttle tankers and FPSOs in tandem offloading operations. Due to the large masses of the FPSO and shuttle tanker, and thus large potential impact energy, any collision involves a high risk. As it is found that offshore risk analyses traditionally have been focused on technical factors, often neglecting human factors, this thesis will focus on risks related to human and organisational factors (HOF) and their interaction with technical factors

Master thesis – objective and tasks

The overall objective of this master thesis is to investigate the current situation for risks relating to collisions between shuttle tankers and FPSOs during tandem offloading in the North Sea. More specifically, it investigates the HOF and technical risk factors considering a drive-off scenario where the shuttle tanker has a powered forward motion. It is intended to provide an overview of the previous research that has been done in the field and investigate what has been done in the decade following the conclusion of the first research projects in the early 2000's. Further, it is the students's intention to present updated frequencies for incidents and collisions involving DP shuttle tankers performing tandem offloading from FPSO, as well as to try identifying possible measures for significantly reducing the collision risk.

In the work, the student will perform extensive literature research as well as data collection from available sources. This includes obtaining feedback from people involved in the previously performed research as well as obtaining feedback from people working in the industry. Overall, the thesis investigates four aspects of tandem offloading operations and seeks to answer the following questions:

1) Literature study of the research on collision risk between FPSO and shuttle tanker during tandem offloading in the North Sea (i.e. the entire UK and Norwegian continental shelves).
    a. Pre year 2003.
        i. What were the major studies performed?
        ii. What were their findings and conclusions?
    b. Post year 2003.
        i. What are the major studies performed?
        ii. What are their findings and conclusions?
2) What are the risks involved in FPSO and shuttle tanker tandem offloading operations in the North Sea?
    a. What are the main technical risks involved? Describe technical equipment employed.
    b. What are the main human and organisational risks involved? Describe procedures for performing operations and training of personnel.
3) Which barriers are employed to mitigate the collision risk on shuttle tankers and FPSOs?
    a. Technical
    b. Human and organisational
4) What is the current situation in relation to the collision risk anno mid 2014?
    a. Have the number of incidents/accidents been reduced?
    b. Present updated frequencies for DP shuttle tankers.
    c. Has there been technical progress in the equipment employed during offloading operations?
5) How can the collision risk be significantly reduced?
    a. Are there possible technical measures for reducing the risk that have not been employed?
    b. Are there unresolved human and/or organisational risks that still need to be addressed?

Deadline: 10.06.2014

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PREFACE

This master thesis was written in the spring of 2014 at the Norwegian University of Science and Technology, NTNU, Department of Marine Technology. The work corresponds to 30 credits at NTNU.

The objective of this master thesis was to investigate the current situation for risks relating to collisions between DP shuttle tankers and FPSOs during tandem offloading operations in the North Sea, investigating human and organisational factors, and their interaction with technical factors.

The work involved an extensive literature research as well as data collection from available resources. The workload on the master thesis was evenly distributed throughout the semester, following a project plan that was made in February.

As I had to change the topic of my thesis in late February, to a topic in which I had no previous experience, the initial work process was challenging. However, the process proved rewarding and I am very grateful for the support I received.

First and foremost, I wish to thank Professor Jan Erik Vinnem, who acted as my supervisor at the Department of Marine Technology, NTNU. His guidance and expertise on the subject of this thesis was invaluable for the result. I also wish to express my gratitude to the Ship Modelling & Simulation Centre in Trondheim for gladly receiving me and sharing their expertise.

Tyholt, Trondheim, June 9th 2013.

Magne Erik K. Lundborg

Magne Erik Kirkbakk Lundborg

EXECUTIVE SUMMARY

Following a series of collisions and near-misses, involving shuttle tanker and FPSO performing tandem offloading operations in the North Sea, extensive effort was put to address the issue in the early 2000's. The aim of this thesis is to investigate the current situation for risks relating to collisions between DP shuttle tanker and FPSO during tandem offloading operations in the North Sea. The main research question was 'what major research has been performed on the collision risk between DP shuttle tanker and FPSO during tandem offloading in the North Sea, and what is the current situation of the collision risk, anno mid 2014?'

An extensive literature study was performed, featuring background material concerning FPSOs, shuttle tankers, and tandem offloading operations. The collision risk was further investigated by using both qualitative and quantitative risk analysis methods. The qualitative risk analysis included an assessment of human, organisational, and technical factors' influence in tandem offloading operations. Based on the aforementioned, a simple analysis of barriers against collision in a drive-off scenario was performed using the bow-tie method. The quantitative risk analysis included a statistical data analysis of reported incidents involving DP shuttle tankers performing tandem offloading from FPSOs on the UK and Norwegian continental shelves (UKCS & NCS), covering the time period from 1995-2013. The results from the risk analysis were further applied to propose possible risk mitigation measures for tandem offloading operations between DP shuttle tanker and FPSO.

Research relating to the collision risk in FPSO-shuttle tanker offloading operations, performed post the conclusion of the JIP project 'Operational Safety of FPSOs', is found to be mainly concerned with further work regarding the risk elements that were identified in the JIP project and the PhD thesis of Dr. Ing. Haibo Chen, as well as providing updated statistics on incidents and risk levels.

Results from this thesis' risk analysis revealed a decrease in the frequency (both absolute and per offloading) of incidents and collisions, during FPSO-shuttle tanker offloading operations on the UKCS & NCS, when comparing 1995-2003 versus 2004-2013. For the UKCS & NCS aggregated, per mid-2014, the collision frequency estimated to lie in the range of 4.5E-04 to 8.0E-04 per offloading, and the drive-off frequency is estimated to lie in the range of 9.0E-04 to 2.3E-03 per offloading.

Several measures for reducing the collision frequency have been proposed and discussed in this thesis. The measures addresses DPO competence level, time available for initiating recovery action, cooperation between shuttle tanker and FPSO, and alternative field configurations. The collision frequency can be significantly reduced by applying direct offloading configuration instead of tandem offloading configuration. However, there are technical and operational issues that have to be resolved, before applying such a configuration to ship-shaped FPSOs

SAMMENDRAG

Etter en rekke kollisjoner og nesten-kollisjoner under tandem losseoperasjoner mellom bøyelaster og FPSO i Nordsjøen, ble det på begynnelsen av 2000-tallet lagt ned stor innsats for å adressere problemet. Formålet med denne avhandlingen er å undersøke den nåværende situasjonen i forhold til risiko relatert til kollisjoner mellom DP bøyelaster og FPSO under tandem losseoperasjoner i Nordsjøen. Hovedproblemstillingen var 'hvilke større forskningsprosjekter har blitt gjennomført i forhold til kollisjonsrisikoen mellom DP bøyelaster og FPSO under tandem losseoperasjoner i Nordsjøen, og hva er den nåværende situasjonen for kollisjonsrisikoen, anno midten av 2014?'

Det ble gjennomført et omfattende litteraturstudie, som inkluderte bakgrunnsmateriale om FPSO, bøyelaster og tandem losseoperasjoner. Kollisjonsrisikoen ble videre undersøkt ved bruk av både kvalitative og kvantitative risikoanalytiske metoder. Den kvalitative risikoanalysen omfattet en vurdering av menneskelige, tekniske og organisatoriske faktorers innflytelse på tandem losseoperasjoner. På grunnlag av det overnevnte, ble det utført en enkel analyse av barrierer mot kollisjon i «drive-off» scenarier ved hjelp av bow-tie metoden. Den kvantitative risikoanalysen inkluderte en statistisk analyse av rapporterte hendelser med DP bøyelastere som utfører tandem lossing fra FPSO på britisk og norsk sokkel (UKCS & NCS). Analysen dekker perioden 1995-2013. Resultatene fra risikoanalysen ble videre brukt til å foreslå mulige risikoreduserende tiltak for tandem losseoperasjoner mellom DP bøyelaster og FPSO.

Det viser seg at forskningen som har blitt gjennomført på kollisjonsrisikoen under FPSO-bøyelaster losseoperasjoner, i etterkant av det felles industriprosjektet 'Operational Safety of FPSOs', hovedsakelig omhandler videre arbeid med risikoelementene som ble identifisert i industriprosjektet og doktorgradsavhandlingen til Dr. Ing. Haibo Chen, samt oppdatering av statistikk om hendelser og risikonivåer.

Resultater fra denne avhandlingens analyser avdekket en nedgang i frekvensen (absolutt og per losseoperasjon) av hendelser og kollisjoner under FPSO-bøyelaster losseoperasjoner på norsk og britisk sokkel, for perioden 2004-2013, sammenlignet med perioden 1995-2003. Kollisjonsfrekvensen for norsk og britisk sokkel samlet, anno midten av 2014, estimeres å ligge i området 4.5E-04 til 8.0E-04 per losseoperasjon, og «drive-off» -frekvensen estimeres å ligge i området 9.0E-04 to 2.3E-03 per losseoperasjon.

Flere tiltak for å redusere kollisjonsfrekvensen har blitt foreslått og diskutert i denne avhandlingen. Tiltakene adresserer DP operatørs kompetansenivå, tilgjengelig tid for å iverksette handling for å unngå kollisjon, samarbeid mellom bøyelaster og FPSO, samt alternative feltkonfigurasjoner. Kollisjonsfrekvensen kan reduseres betydelig ved å bruke «direct offloading» konfigurasjon i stedet for tandem konfigurasjon. Det er imidlertid tekniske og operasjonelle problemer som må løses før man kan bruke en slik konfigurasjon på en skipsformet FPSO.

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ABBREVIATIONS

ABS – American Bureau of Shipping

BBD – Barrier block diagram

CODAM – COrrosion and DAMage (PSA database)

CPP – Controllable pitch propeller

DECC – UK Department of Energy & Climate change

DNV – Det Norske Veritas

DP – Dynamic Positioning

DP1 – Dynamic positioning class 1

DP2 – Dynamic positioning class 2

DPO – Dynamic position (system) operator

FPSO – Floating, production, storage, offloading

FSU – Floating storage unit

FTA – Fault tree analysis

GBA – Gravity-based structures

HOF – Human Organisational Factor

HSE FOD – UK Health and Safety Executive Field Operations Division

HSE OSD – UK Health and Safety Executive Offshore Safety Division

HSE$_1$ – UK Health and Safety Executive

HSE$_2$ – Health, Safety and Environment

IE – Initiating event

IMCA – International Marine Contractors Association

IMO – International Maritime Organisation

ISO – International Organization for Standardization

JIP – Joint Industry Project

MAIB – Marine Accident Investigation Branch

MMI$_1$ – Man-Machine Interface

MMI$_2$ – Man-Machine Interaction

NCS – Norwegian continental shelf

NMA – Norwegian Maritime Authority

NMD – Norwegian Maritime Directorate

NORSOK – Norwegian standards for petroleum related activities on the NCS.

NPD – Norwegian Petroleum Directorate

OGUK – Oil & Gas UK (former UKOOA)

PD – Proportional derivative

PMS – Positioning Monitoring System

PRS – Positioning reference system

PSA – Norwegian Petroleum Safety Authority, *Norwegian*: Petroleumstilsynet (PTIL)

RIF – Risk Influencing Factor

SPM – Ship Resource Management system

STP – Submerged Turret Production system

UKCS – UK continental shelf

1. INTRODUCTION

Floating production, storage and offloading (FPSO) units have been used in the North Sea since 1980`s, with the introduction of the first purpose built FPSO, Petrojarl 1, in 1986. Since then, the prevalence in the use of FPSO units in the North Sea has gradually increased. In total, there are currently (per May 2014) 29 FPSOs operating in the North Sea.

In literature, *floating, production, storage and offloading unit* is a common term used to describe a marine vessel designed to permit direct production, storage, and offloading of process fluids from subsea installations. The term floating structure implies that that the full weight of the structure is supported by buoyancy, which includes weight of the mooring system, riser system, operational equipment and lightship weight (Paik and Thayamballi, 2007). It further implies that the unit can be relocated, although it is normally stationed at a location for extended periods of time. FPSOs are commonly ship-shaped units having a submerged, internal or external turret mooring system (NTS, 2013). The operational principle of a FPSO turret mooring system is that the hull of the FPSO rotates around the turret, positioning the hull according to the dominant weather conditions. The rotation can be either active or passive.

Unless stated otherwise in this thesis, the term FPSO is used to describe *ship-shaped* FPSO units. Further, since the offloading operations for a ship-shaped FPSO are similar to a ship-shaped *floating storage unit (*FSU), the term FPSO is applied to cover both FPSO and FSU units, in order to enhance the thesis' readability. FSU units are generally ship-shaped marine vessels designed for storage of crude oil or condensate (NTS, 2013), i.e. FSU units do not have capabilities for oil processing.

FPSOs in the North Sea mostly rely on the use of shuttle tankers for offloading of their cargo oil. The term *shuttle tanker* is used to describe a trading tanker traveling back and forth between a shore terminal and a FPSO or FSU, transporting oil ashore. Furthermore, tandem configuration is the most common way of performing offloading operations from an FPSO. Such a configuration involves the tanker positioning itself at some distance behind the FPSO, and the two vessels connect by a mooring hawser and a cargo hose used for offloading (Chen and Moan, 2004). The shuttle tanker maintains its position using dynamic positioning (DP), keeping the mooring hawser free of tension, or by applying a small thrust astern, keeping the mooring hawser tensioned (Chen and Moan, 2005).

1.1 PROBLEM DESCRIPTION AND RELATION TO PREVIOUS STUDIES

Historically, there have been several collisions and near-miss incidents, involving shuttle tankers and FPSOs performing tandem offloading operations in the North Sea. Due to the large masses of the FPSO and shuttle tanker, and thus large potential impact energy, any collision involves a high risk. As it was found that offshore risk analyses traditionally had been focused on technical factors, often neglecting human factors, effort was put address this research gap in the early 2000's.

From 1996 to 2002, the research project 'Operational Safety of FPSOs' was performed by NTNU and SINTEF, on the behalf of two major oil companies and the Health and Safety Executive UK (HSE). The overall objective of the project was to develop risk assessment methodologies for FPSOs. In the second part of the project (2000-2002), the risk assessments methodologies developed in the project's first phase (1996-2000) were used to analyse the collision risk between FPSOs and shuttle tankers during off-loading operations, mainly focusing on contributions from human and organisational factors (HOFs). Two summarizing reports were issued, (Vinnem, 2000) and (Vinnem et al., 2003b).

In parallel with the aforementioned research project, Dr. Ing. Haibo Chen performed his PhD study 'Probabilistic evaluation of FPSO-tanker collision in tandem offloading operation'. (Chen, 2003) addresses the collision risk by separately investigating the initiating stage and the recovery stage of potential collision scenarios.

This thesis will succeed the aforementioned studies, providing an up to date assessment of the risk in FPSO-shuttle tanker tandem offloading operations in the North Sea.

1.2 OBJECTIVES

The overall objective of this thesis is to investigate the current situation for risks relating to collisions between DP shuttle tankers and FPSOs during tandem offloading operations in the North Sea. More specifically, it investigates HOFs and technical risk factors considering a drive-off scenario where the shuttle tanker has a powered forward motion. This thesis uses the definition of (Chen, 2003, p.11) for DP shuttle tanker drive-off events, i.e. an event where the DP shuttle tanker "*is driven away from its targeted/wanted position by its own thrusters in offloading operation. This is not a planned or wanted event*".

This thesis is intended to provide an overview of the previous research that has been done in the field and investigate what has been done in the decade following the conclusion of the first research projects in the early 2000's. Further, it is the author's intention to present updated frequencies for incidents and collisions involving DP shuttle tankers performing tandem offloading from FPSO, as well as to try identifying possible measures for significantly reducing the collision risk. The main research question of this thesis is 'what major research has been performed on the collision risk between DP shuttle tanker and FPSO during tandem offloading in the North Sea, and what is the current situation of the collision risk anno mid 2014?' In order to answer this, the thesis investigates four aspects of tandem offloading operations and seeks to answer the following sub questions:

1) What are the major studies performed on the collision risk between FPSO and shuttle tanker during tandem offloading in the North Sea (i.e. the entire UK and Norwegian continental shelves)?
2) What are the main risks involved in FPSO – shuttle tanker tandem offloading operations in the North Sea?
3) Which barriers are employed to mitigate the collision risk on shuttle tankers and FPSOs?
4) What is the current situation in relation to the collision risk anno mid 2014?
5) How can the collision risk be significantly reduced?

1.3 LIMITATIONS

There are some limitations to the work performed worth mentioning. This focus of this thesis is limited to the main systems and on-board equipment, as well as the personnel, directly involved in FPSO – DP shuttle tanker tandem offloading operations. This includes both vessels' crew and operating organisations. Thus, it does not consider the impact of other systems that may be operated simultaneously aboard the vessel, nor does it consider other offloading methods e.g. parallel offloading. Moreover, only DP operated shuttle tankers are considered, thus other field configurations, e.g. 'taut hawser', are not considered. More specifically, it considers an offloading system comprising of the DP shuttle tanker and the FPSO during all offloading phases, and the offloading arrangements. However, as the offloading phase has been shown to be the most vulnerable phase in relation to collision risk, the thesis does not explicitly consider the other phases of tandem offloading operations.

This thesis's risk assessment is intended to be a coarse risk assessment, implying that field specific configurations and characteristics are not investigated in detail. Moreover, consequences of collisions are not considered, only the frequencies. Hence, the proposed measures are aimed at reducing the frequencies and not consequences. Further, this thesis does not address the acceptability of the present levels of collision risk between FPSO and shuttle tanker.

The statistical analysis of incidents presented in this thesis only includes operations from 01.01.1995 to 31.12.2013, and results do not refer to any specific shuttle tanker operator, nor to tandem offloading operations from any particular FPSO/FSU field. Moreover, the results are obtained by aggregating incidents from several shuttle tankers performing tandem offloading from multiple FPSO/FSU fields on the UKCS & NCS. Hence, the frequencies should be regarded as representative estimates for North Sea tandem offloading operations.

1.4 STRUCTURE

The report consists of five parts:

1. Background material on FPSO-shuttle tanker offloading operations.
2. Theory and methods.
3. Analysis of FPSO-shuttle tanker collision risk.
4. Results from statistical analysis.
5. Discussion and conclusions.

Chapter 2 presents background material concerning FPSO-shuttle tanker offloading operations, the vessels and technical equipment. This part focuses on issues specific for tandem offloading operations between DP shuttle tanker and FPSO, describing the vessels, equipment, and operational considerations.

Chapter 3 presents the theory and methods applied in this thesis. The main focus here is on risk assessment and HOFs.

Chapter 4 presents the main part of this thesis, the risk analysis of FPSO-DP shuttle tanker tandem offloading operations in the North Sea. It provides a description of the risks involved in such operations and research performed previously on the subject. Further, it describes the thesis’ qualitative and quantitative risk analysis, covering HOF aspects, barriers, and statistical data on incidents and collisions.

Chapter 5 presents the results from the risk analysis described in chapter 4. It consists of two main parts, one covering the overall incident frequencies, and one part covering the collision frequency.

Chapter 6 presents a discussion of this thesis’ results and methods, as well as possible measures for reducing the collision frequency.

Chapter 7 presents this thesis’ conclusions and recommendations for further work relating to this thesis’ research.

2. BACKGROUND

In order to facilitate a better understanding of the risks involved when performing tandem offloading operations in the North Sea, it is first necessary to introduce the basics of such operations, as well as the vessels involved. This chapter introduces FPSO units and shuttle tankers, before presenting the main concepts and issues related to performing tandem offloading between such vessels, i.e. configurations, station-keeping, DP system and training of personnel. Additional information is also presented in appendixes A2, A3, A4.

2.1 GENERAL INTRODUCTION TO FPSO UNITS

FPSOs offers the possibility to fulfil several functions using only one offshore unit, i.e. production, storage and offloading, alongside the possibility of exporting the product onshore using shuttle tankers. Thus, FPSOs remove the necessity of an export pipeline infrastructure, only requiring a riser and mooring system to bring the product to the surface. Consequently, FPSOs have become recognized as one of the most economical alternatives for deep- and ultradeep-sea field developments, as the building cost of fixed platforms outweigh the investment and operational cost for FPSOs on such depths. FPSOs have also become popular for marginal field developments due to the possibility of relocating the FPSO (Paik and Thayamballi, 2007). Figure 1 shows a FPSO and associated equipment used in operations at a subsea oil field development, as well as offloading to a shuttle tanker in tandem configuration.

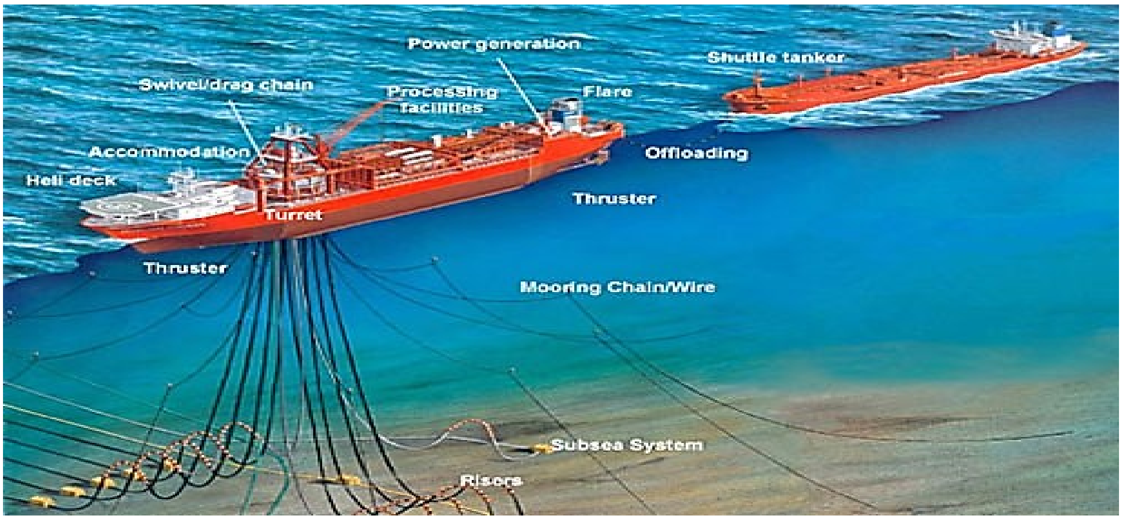

Figure 1: FPSO and shuttle tanker in tandem offloading (OET, 2014).

The FPSO is moored by several mooring chain wires, stretching from the turret, down to the seabed. The risers from the subsea production system are also connected to the turret, sending hydrocarbons up to the FPSO for topsides processing. The topsides have accommodation spaces and a heli deck for transporting personnel to/from the FPSO. Further, the topsides include processing facilities, a flare tower for burning off raw natural gas (gas flaring) that is unusable, and an offloading arrangement in the stern area. The processed hydrocarbon product is stored in large storage tanks in the hull of the FPSO, before being offloaded to a shuttle tanker at regular intervals. FPSOs in the North Sea typically have a length of 200-280 m, a width of 30-50 m, a moulded depth of 20-30 m, and a storage capacity of 600,000-900,000 bbl.

2.2 GENERAL INTRODUCTION TO SHUTTLE TANKERS

There are two applicable methods for exporting hydrocarbon products ashore from offshore installations: using shuttle tankers or using an export pipeline system. A shuttle tanker is a ship specifically designed for such transport purposes, often providing the more feasible export alternative in remote locations, deep waters and harsh environmental conditions. Shuttle tankers were first introduced in the North Sea during the 1970's, and have since become common in all parts of the world. DP shuttle tankers distinct themselves from regular crude oil tankers, being capable of operating independently in all environmental conditions. The vessels' outfitting includes a dynamic positioning (DP) system[1] for position keeping, and several thrusters located in the bow and stern. Low speed manoeuvrability is ensured by flap rudders and controllable pitch propellers (RIGZONE, 2014). Due to their superior seaworthiness, DP shuttle tankers are widely applied in the North Sea (Chen and Moan, 2002). Shuttle tankers performing tandem offloading are equipped with a loading system in the bow section of the vessel. A typical shuttle tanker on the NCS has a loading capacity of 900 000 bbl or approximately 120 000 tonnes oil (NOROG, 2011).

2.3 FPSO – SHUTTLE TANKER TANDEM OFFLOADING OPERATIONS

In tandem offloading operations from FPSO to shuttle tanker, the shuttle tanker is positioned at some distance behind the FPSO, with its bow facing the stern of the FPSO. An illustration of the tandem offloading concept is provided in Figure 2. Cargo is transferred from the FPSO via a flexible pipe, a transfer hose, stretching between the stern of the FPSO and the bow of the shuttle tanker. In order to protect the integrity hose, it is necessary to limit the relative movements of the two vessels. This is achieved using a flexible polyester cable, a hawser, which provides a passive mooring between the vessels (Wilkerson and Nagarajaiah, 2009).

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[1] The DP system is further outlined in Section 2.4.

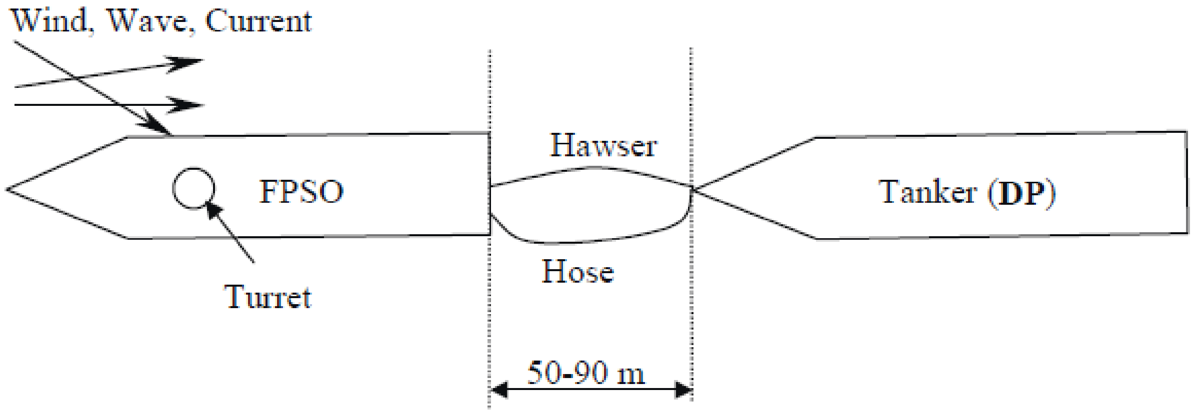

Figure 2: Tandem offloading operation, FPSO and DP shuttle tanker (Chen, 2003).

A tandem offloading operation can be divided into three main operation phases (Chen, 2003, Vinnem et al., 2003b, Chen and Moan, 2002):

1) *Approach and connection*: The shuttle tanker approaches the stern of the FPSO/FSU, stops at a predetermined distance, before connecting the messenger line, loading hose and hawser.
2) *Offloading*: The hydrocarbon product is transferred from the FPSO/FSU to the shuttle tanker.
3) *Disconnection and departure*: Upon completion of the offloading, before disconnection of the loading hose and hawser, the manifold is flushed. The hawser and loading hose is then sent back to the FPSO/FSU, whilst the shuttle tanker backs up, away from the FPSO/FSU stern.

The frequency of offloading operations is dependent on the production rate, the FPSO/FSU storage capacity, and the shuttle tanker size. Typically, it lies in the range of once every 3 to 5 days, the offloading operation having a duration of approximately 20 hours (Chen and Moan, 2002). An example of the process for a tandem offloading operation in the North Sea is included in appendix A3.

2.3.1 Field configurations

Tandem offloading systems comprise a combination of customised and off-the-shelf systems. As shown in Table 1, which contains some of the key characteristics for avoiding collisions between shuttle tanker and FPSO/FSU, the variety of characteristics in FPSO/FSU field configurations are multiple.

A FPSO is commonly custom-made for operating on a specific field, i.e. the FPSO's design and equipment is custom-made to suit the particular operational requirements and needs of that particular field. In areas where the environmental conditions are not very demanding, yielding less challenging conditions for offloading, the FPSOs tend to be converted commercial tankers. In the North Sea, the challenging environmental conditions have however made custom-made FPSOs the more common type of FPSO. There are also considerable variations between system configurations for offloading (Vinnem et al., 2003b). Shuttle tankers are normally not purpose built for operations on specific fields, however their outfitting largely determines which type of services they are appropriate for (Vinnem, 2013a).

Table 1: FPSO/FSU field configuration variations (Vinnem, 2013a).

Characteristic	**Variations**
FPSO station-keeping capabilities	Internal turret with 8-12 point mooring system
FPSO heading-keeping capabilities	Without heading control
	With heading control
ST heading and station-keeping capabilities	No propulsion
	Main propulsion (single or twin screw)
	No DP system
	DP1, DP2 or DP3 systems
Offloading mode	DP operated
	Taut hawser operated
Interface systems	With hawser connection
	Without hawser connection
Distance FPSO – ST	50-100 [m]
	80 [m]
	150 [m] (currently not in use)

The distance between FPSO and shuttle tanker during offloading operations in the North Sea varies from 50-110 m, the more common distance being in the range of 70-80 m. According to (Vinnem et al., 2003b), the distance lies in the range of 50 m up to 75-80 m for fields on the UKCS. On the NCS, the distance is stated to be in the range from 75-80 m up to 100-110m.

(Paik and Thayamballi, 2007) states that the use of DP systems in FPSO shuttle tanker operations can help fulfilling station-keeping requirements, disconnection limits, and contribute to maintaining production uptime in bad weather. However, (Helgøy, 2003) states that from a DP point of view, tandem offloading configuration is the most demanding offloading system, due to surge and fishtailing movements of the FPSO/FSU being especially challenging in tandem offloading operations. Still, it has become the most popular solution for offshore offloading in the North Sea. Tandem offloading from FPSO/FSU to DP shuttle tanker is in use at several fields on the NCS, i.e. from the Alvheim FPSO, Balder FPSO, Jotun A FPSO, Navigon Saga FSU, Njord B FSU, Norne FPSO, Petrojarl Varg, Skarv FPSO, Åsgard A FPSO and Åsgard C FSU. It is further planned to apply tandem offloading from FPSOs on Goliat and Knarr. (Kvitrud et al., 2012, Clarkson, 2013, ABF, 2014). On the UKCS, tandem offloading from FPSO/FSU to DP shuttle tanker is in use at Alba FSU, Anasuria, Aoka Mizu, Bleo Holm, BW Athena, Captain FPSO, Emerald FSU, Global Produser III, Gryphon A, Haewene Brim, Maersk Curlew, North Sea Producer, Petrojarl Banff, Petrojarl Foinaven, Schiehallion FPSO, and Triton FPSO (Clarkson, 2013, ABF, 2014). There are also a substantial number of fields that uses taut hawser based offloading (Vinnem, 2013a).

2.3.2 FPSO station-keeping

The North Sea offers some of the world`s toughest environmental conditions. The combination of large waves, strong ocean currents and strong winds, make marine operations in such areas are very demanding for both personnel and equipment. The complexity and size of the vessels have increased tremendously in the last decades and technical developments are continuously pushing the limits for what is technically possible, e.g. improvements to the DP systems are offering the possibility of expanding the vessels operational envelope. However, as one is positioned on utmost part of the technical frontier, it is necessary to be continuously considering the risks involved in order to ensure safe operations.

The ability of an FPSO to accommodate its positioning and motion control requirements is vital for both the functionality and operability of the unit. A FPSO must be capable of handling the environmental conditions and control its motions, in order to meet station-keeping requirements, e.g. from the riser system.

Floating offshore units are typically dependant on moorings as their principal means of station keeping. This applies to all normal design conditions as well as design storm conditions. Several types of mooring systems are applicable to FPSOs, e.g. turret moorings, articulated towers and soft yoke systems. Such systems allow the FPSO to weathervane[2]. Moorings are further often assisted by thrusters to keep the FPSO within its operational excursion limits, the thrusters providing improved heading control. However, the mooring system is designed to withstand the forces independently, in order to account for a sudden loss off thruster power.

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[2] Rotation of FPSO in compliance to the direction of external forces. (Paik and Thayamballi, 2007)

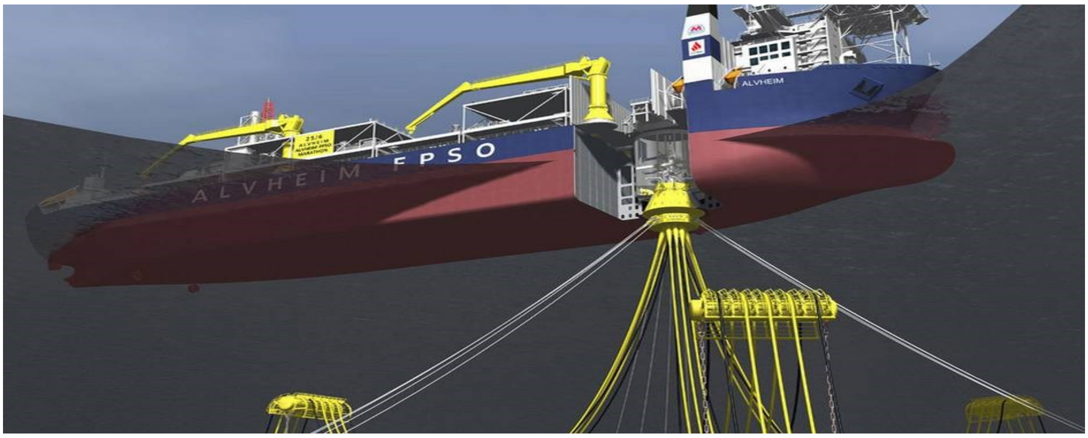

Figure 3: Alvheim FPSO with disconnectable STP system (APL, 2010).

Figure 3 shows the Alvheim FPSO with its disconnectable submerged turret production system (STP). The system comprises of the turret buoy, to which the mooring, risers and umbilical components are connected, and the FPSO`s shipboard system, consisting of all equipment needed for connection and operation of the STP system. The STP system allows the FPSO to shut down production and disconnect from the turret, e.g. in case of extreme weather conditions. The FPSO can later relatively quickly reconnect to the turret and resume operations (Aanesland et al., 2007).

(Paik and Thayamballi, 2007) describes the actions that are initiated in response to forces of nature on board a FPSO to be different from those on a trading tanker, which can be explained by their different operational patterns. Waves are commonly considered the primary force acting on a trading tanker for design purposes, and a trading tanker can simply adjust its sailing pattern to accommodate bad weather situations. Whereas on a stationary FPSO, the high requirements for operational uptimes requires the FPSO to be designed for less frequent bad weather situations, involving combinations of strong currents, high velocity winds and large waves.

2.3.3 Shuttle tanker station-keeping

As this thesis only considers shuttle tankers using DP for station-keeping during offloading operations, non-DP shuttle tankers are excluded from the discussion. However, one should be aware that such shuttle tankers are applied in tandem offloading operations at some oil fields.

The complexity of tandem offloading operations, especially in terms of strict demands for relative station keeping, inflicts high demands for the shuttle tankers positioning capabilities. Hence, most shuttle tankers tend to be equipped with an advanced DP system as well as tremendous propulsion capabilities. (Helgøy, 2003) describes a state of the art DP shuttle tanker in year 2003. It is equipped with twin propulsion engines, each capable of delivering up to 15000 [HP], two bow thrusters of 2400 [HP] each, as well as two tunnel thrusters aft of 1400 HP each.

The shuttle tankers DP system is completely automated; receiving input typically from two or three positioning reference systems (PRS), thrust measurements from each propeller/thruster, as well as speed measurements. Thus, the DP operator's (DPO`s) role is generally passive, consisting of monitoring the DP system and making small adjustments if necessary. However, due to the possibility of the DP system failing, the DPO must at all times be ready to take manual control over the vessel (Skogdalen and Vinnem, 2011).

It is a regulatory requirement for all shuttle tankers performing tandem offloading, from fields on the NCS having a post 2002 production consent, to be of DP2 class. Although it did not become mandatory until 1 January 2002, it has long been industry practice in Norway to require DP2 shuttle tankers for FPSO offloading operations from all fields north of the 62nd parallel. On the UKCS however, the Oil & Gas UK (OGUK) FPSO Guidelines only requires the use of DP2 shuttle tankers in environmentally sensitive areas or the Atlantic frontier. Thus, there is no specific requirement for the use of DP2 shuttle tankers in tandem offloading operations on the UKCS. (Vinnem, 2013a), estimates that 90% of operations on the NCS, and 20% of operations on the UKCS, have been performed with DP2 shuttle tankers.

2.4 DP SYSTEM

A dynamic positioning (DP) system is defined as a set of components employed to keep a floating vessel`s position stationary, or following a predefined route, by the use of propellers (Tannuri et al., 2006). (IMCA, 2007) further defines a fully operational DP system as a system that is capable of maintaining the vessel`s motions and control system accuracy within half the critical excursion limit for the task performed.

Generally, a DP system consists of three main areas: power, control and references (IMCA, 2007). Figure 4 provides an illustration of the various parts of the system and their interactions.

References denote the instruments providing information concerning position, environmental forces and vessel behaviour. Power denotes systems generating, distributing and consuming power. Control denotes the position control system and the power management system. (IMCA, 2007) states that regardless the degree of redundancy provided in the DP system, some control elements will be common. Thus, the most crucial constituents of the DP system are the constituents that connect multiple key pieces of equipment together.

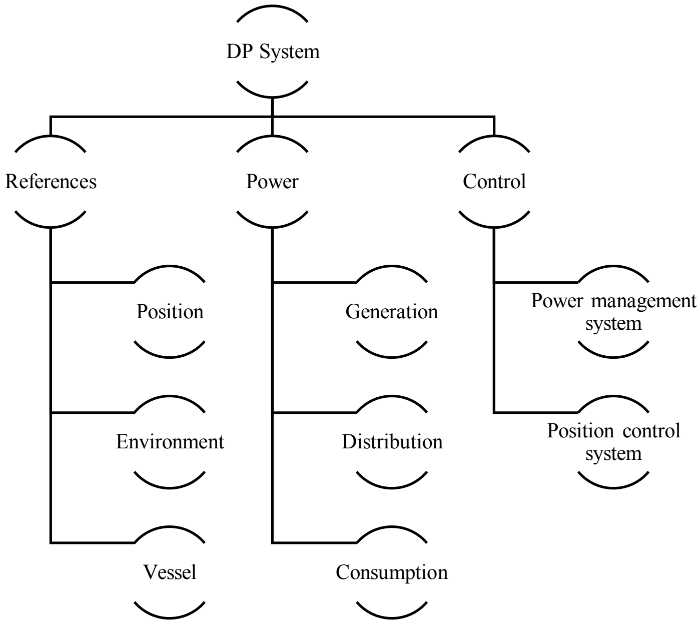

Figure 4: DP system`s main parts (IMCA, 2007).

Floating vessels are affected by complex environmental forces, which initiate minimum two separate vessel motions. The vessels are induced with large first-order wave-frequency forces and moments by wind generated waves, as well as low-frequency oscillations and steady motions due to wind, current and wave drift forces. The DP system must be able to suppress or counteract these motions in order to keep the vessel`s mean positions as close as possible to the predefined point or route. As it would be very demanding (and energy consuming) for the system to have the DP control system handling actual wave frequency motions, sophisticated filtering algorithms are applied on the input signals in order to separate the wave induced motion from the motion caused by slowly varying disturbances. It is common for commercial DP systems to use observer-based techniques, e.g. Kalman filtering which uses available information about the induced motions' dynamical behaviour alongside a predictor, to create an optimum state estimator (Tannuri et al., 2006).

The shuttle tanker`s displacement can increase by a factor of four during loading operations, thus changing its dynamic properties. Consequently, a constant gain controller in the DP system is undesirable, as it would imply the DPO constantly staying alert and correcting the shuttle tanker`s position manually, in order to safeguard against the approximations by the DP system (Tannuri et al., 2006). Therefore, the shuttle tanker`s DP system features special DP modes for maintaining a constant relative position to the FPSO during tandem offloading: a function accounting for surge/sway motions of the FPSO, and a function accounting for sway/heading motions of the FPSO. Together, these functions ensure that the shuttle tanker maintains its relative heading and distance to the FPSO, whilst avoiding excessive position adjustments from the shuttle tanker`s DP system (Chen, 2003).

2.4.1 Surge/Sway function

The DP system views the FPSO`s stern as a stationary point on the earth`s surface in normal 'Approach' and 'Weather Vane' modes. Since the position of the FPSO`s stern is in fact continually changing due to fishtail and surge movements, doing tandem offloading operations in such DP modes would lead to excessive position corrections from the shuttle tanker DP system, and its current estimates would also be incorrect. The Surge/Sway function accounts for this by defining a rectangle window that the FPSO stern can move within, without the shuttle tanker readjusting its relative position. If the FPSO moves outside current window, the window will be readjusted to the new position of the stern, and so on. The rectangle window's size can within a pre-set limit, be determined by the DPO. Further, relative and absolute reference systems are applied in combination to enable such position keeping, i.e. Artemis and DARPS in combination with DGPS (Chen, 2003).

2.4.2 Sway/Heading function

Maintaining a minimum mean relative heading difference between the shuttle tanker and FPSO in tandem offloading operations, i.e. maintaining the shuttle tanker pointing towards the FPSO`s stern hawser terminal point, is crucial due to the hawser and loading hose stretching between the vessels. Thus, swift heading changes of the FPSO impose problems, which is especially common for vessels without heading control. To counter this, the DPO of the shuttle tanker can pre-set a maximum limit for the heading difference in the DP system. The Sway/Heading function will then monitor the heading of the FPSO through data-link information from the vessels' DARPS system and activate the shuttle tanker`s thrusters, when necessary, to correct the relative heading (Chen, 2003).

2.4.3 DP class

IMO has released a set of guidelines for DP vessels, "Guidelines for vessels with dynamic positioning systems" (IMO, 1994). It defines a set of equipment classifications for DP vessels, which are listed in Table 2, along with the corresponding DP classifications of Det Norske Veritas (DNV) and the American Bureau of Shipping (ABS).

Table 2: DP classifications (KM, n.d., IMCA, 2007).

IMO	*DNV*	*ABS*	**Class requirements**
-	DPS 0 DYNPOS-AUTS	DPS-0	The vessel possesses manual position control and automatic heading control under specified maximum environmental conditions. Any single fault may cause position loss.
Class 1	DPS 1 DYNPOS-AUT	DPS-1	The vessel possesses automatic and manual position and heading control under specified maximum environmental conditions. Any single fault may cause position loss.
Class 2	DPS 2 DYNPOS-AUTR	DPS-2	The vessel possesses automatic and manual position and heading control under specified maximum environmental conditions. Two independent computer systems are installed so that any single fault cannot cause position loss, excluding loss of a compartment.
Class 3	DPS 3 DYNPOS-AUTRO	DPS-3	The vessel possesses automatic and manual position and heading control under specified maximum environmental conditions. A minimum of two independent computer systems and a back-up system separated by A60 class division are installed so that any single fault cannot cause position loss, including loss of a compartment due to fire or flood.

2.4.4 Bridge layout

(Chen, 2003) provides a detailed description of a typical bridge layout, related technical systems, as well as the operational process applied, for a DP class 2 shuttle tanker in tandem offloading. The bridge has a DP console with two DP computers, one active and one in standby for redundancy. The active unit is called ‘Master’ and the backup unit is called ‘Slave’. Above the DP console is the position reference system (PRS) screens, which encompasses screens for each of the PRS’ installed, i.e. Artemis, DARPS, and BLOM positioning monitoring system (PMS). Next to the DP console is the Bow Loading System (BLS) console, from which the oil transferring process is controlled. The bow loading operation can be monitored by three video cameras installed in the shuttle tanker`s bow. The live feed from the cameras is shown on the video screen, along with information about the hawser winch, loading hose connection and the separation distance between the shuttle tanker and FPSO. An illustration of a typical DP shuttle tanker bridge layout is included in appendix A2.

2.5 TRAINING OF PERSONNEL

This section provides an overview of the training scheme for DPOs onboard shuttle tankers. More specifically, it presents the offshore loading training course provided by the Ship Modelling & Simulation Centre AS (SMSC) in Trondheim, Norway. SMSC is a renowned provider of maritime courses and simulation of marine operations.

The International Marine Contractors Association (IMCA) have been influential to FPSO and shuttle tanker vessel operators, issuing multiple guidance documents concerning training and operation of DP vessels, e.g. “Guidelines for the Design and Operation of Dynamically Positioned Vessels”(IMCA, 2007) and “The training and Experience of Key DP Personnel” which is now a IMO industry standard reference (Daughdrill and Clark, 2002). It has further been a requirement for DPOs performing operations on the on the NCS, to undertake formal training in the use of DP equipment since 1987.

The training of DP shuttle tanker operators at SMSC is divided into several phases, to be performed in sequence. SMSC offers two different general certification course programs for DPOs, one program fulfilling the requirements of the Nautical Institute (NI) Operator training scheme and one program fulfilling the requirements of the DNV SeaSkill™ guidelines. Both of the aforementioned certification schemes are recognised by the Norwegian Maritime Authority (NMA) as being equivalent.

The candidates have normally been working 1-2 years at sea before first time commencing training to become a DPO. These course programs are designed to provide the candidates with adequate training to become certified DPOs, according to the candidates’ level of experience. The candidates’ has to undertake a general DP introductory course and a simulator course, designed to provide the candidates with the knowledge, understanding and abilities necessary to operate the DP desk and related equipment. This includes both theoretical education and simulator training.

Experienced DPOs may also undertake specialization and volume training courses, e.g. the Offshore Loading course program. The Offshore Loading course program consists of four courses, phase 1-4, and focuses on shuttle tanker handling in close proximity to installations. The training involves among other simulation exercises reconstructing known DP incidents. The specialisation courses can further include field specific simulator training, i.e. simulator training where the shuttle tanker, offshore installation, field layout, and sea conditions are similar to those where they later will be performing real life operations. Thus, it is possible to expose and prepare the candidates for hazardous incident scenarios identical to those that they may experience whilst performing real life operations. As the timeliness and correctness of the DPO`s actions is critical when facing e.g. a drive-off scenario, such training may prevent collisions.

According to (SMSC, 2014), the largest changes in the training of DPOs in the last decade has been the steps taken to account for the ever increasing technological sophistication of the DP systems. Among others this includes the aforementioned customisation in the training of DPOs, according to the specific vessel`s they will be operating. The new DNV DPO certification scheme differentiates based on the DP functionality of the vessels, e.g. station-keeping, shuttle tanker, advanced, rig. Moreover, the new scheme targets the DPOs’ level of experience to a larger extent than before, requiring the students to display more of their practical capabilities, along with requirements for seagoing experience and formal training. Moreover, in contrast to the NI training scheme, it is a requirement of the DNV DPO for the student to pass the final examination in order to be certified.

This chapter has introduced the main issues of performing tandem offloading operations between FPSO and shuttle tanker. As the thematic foundation for this thesis has been presented, the next chapter introduces relevant risk theory and the methodology applied in this thesis analysis.

3. THEORY AND METHOD

The purpose of this chapter is to provide the reader with a brief overview of relevant theory and methodologies on risk. Chapter 3 is divided into two main parts, the first part covering basic risk theory and the second part outlining the concepts of risk management and barrier management. Appendix A1 further includes a list of definitions for common terms found in risk literature.

3.1 BASIC RISK THEORY

This section presents some of the fundamental concepts of basic risk theory. These concepts form the basis for the scientific approach to managing risk.

3.1.1 Risk definitions

The risk literature operates with numerous definitions of the term ‘risk’, and no unified definition for the term has been agreed to. (Aven and Renn, 2010) presents several common risk definitions:

- Risk equals the expected loss.
- Risk equals the expected disutility.
- Risk is the probability of an adverse outcome.
- Risk is a measure of the probability and severity of adverse effects.
- Risk is the combination of probability and extent of consequences.
- Risk is equal to the triplet (s_i, p_i, c_i), where s_i is the *i*th scenario, p_i is the probability of that scenario, and c_i is the consequence of the *i*th scenario, i=1,2,3,..,N.
- Risk is equal to the two-dimensional combination of events/consequences and associated uncertainties (will the events occur, what will be the consequences).
- Risk refers to uncertainty of outcome, of actions and events.
- Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain.
- Risk is an uncertain consequence of an event or an activity with respect to something that humans value.

The aforementioned definitions of risk may be grouped into two main categories (Aven and Renn, 2010):

1) Risk stated as probabilities and expected values
2) Risk stated as events/consequences and uncertainties.

A new risk definition is further proposed:

"Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value" (Aven and Renn, 2010, p. 8).

In terms of international standards, it is common to define the risk according to category 1, i.e. as a combination of an event`s probabilities and consequences. Moreover, equation (1) works as an expression for practically calculating the risk, R.

$$R = \sum_i (p_i \cdot C_i) \tag{1}$$

where:

$p_i =$ probability of accidents.

$C_i =$ consequence of accidents.

The risk is calculated as the product of the probability and numerical value of the consequence, for each accident sequence i, summed over all possible accident sequences. It should however be noted that the expression is only a statistical measure of the risk, implying that its resulting value might never be observed in practice (Vinnem, 2013a).

Probability

There are two common interpretations of probability, i.e. the *frequentist*[3] interpretation and the *subjectivist*[4] interpretation. The frequentist interpretation considers the long-term relative frequency of an event, and assigns probabilities based on this. E.g. if you flip a coin a sufficient number of times and record each outcome, the number of heads and tails will eventually be equal. Thus yielding that the long-term probability of each outcome in 0.5. The subjectivist interpretation however, is based on degrees of belief for the various outcomes of an event, and is often applied in situations where there is a lack of sufficient data for applying the frequentist interpretation. In such cases, one can e.g. have a group of experts assigning probabilities for the various outcomes of an event based on their subjective judgement.

Consequence

In risk literature, the term 'consequence' describes the result of an event occurring. Consequences have an effect on the objective, which can be both positive and negative. Moreover, a single event can produce a series of consequences (ISO, 2009).

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[3] Also referred to as 'physical' or 'objective' probability interpretation.

[4] Also referred to as 'evidential', 'Bayesian' or 'subjective' probability interpretation.

3.1.2 Risk elements

In literature, risks are commonly subdivided into risk elements and classified according to what or whom the risks affect, i.e. personnel, environment or assets. More specifically, when considering offshore installations (Vinnem, 2013a) presents the following definitions for the risk elements:

- *Personnel risk*: Only applies to risk for employees, thus risk to the public is excluded. The risk element includes diving accidents, transportation accidents, major accidents, occupational accidents
- *Environmental risk*: Applies to risk for the external environment inflicted by hazards linked to production installations and associated operations. The risk element includes oil spills from emerging from blowouts, shuttle tanker accidents, leaks and seepages from production equipment, leaks and ruptures of pipeline and risers, as well as excessive contamination from releases of fluids from the installation.
- *Asset risk*: Generally applies to risk that have non-environmental and non-personnel accident consequences, which may also have potential consequences for the environment and/or personnel. The risk element includes fires accidents, crane accidents, external impacts, extreme environmental loads, ignited and unignited hydrocarbon gas or hydrocarbon fluid leaks, as well as ignited leaks of other fluids.

3.2 RISK MANAGEMENT

Risk is a fundamental element in all of an organisation`s undertakings and hence risk management constitutes an essential part of an organisation`s activities (ISO, 2009). Overall, risk management refers to the process of generating and assessing options for initiating or changing human activities or structures, in order to prevent harm to humans and assets, as well as increasing the net benefit to human society (Renn, 2005). Moreover, it can be defined as the undertakings performed to direct and control risk in an organisation (ISO/IEC, 2002).

The International Organisation for Standardization (ISO) has provided a generic guideline for the risk management, ISO 31000 (ISO, 2009), which includes a framework for the risk management process, as illustrated in Figure 5. The main steps of the ISO model, obtained from (ISO, 2009) are briefly outlined in the following:

Communication and consultation: It is important to communicate and consult with stakeholders, both internal and external, throughout the risk management process, as their risk perceptions influences their judgement of risk. The perceptions of the stakeholders ought to be identified, documented and considered during the decision making process, due to the potential for the stakeholders' views having a strong influence on the decisions made.

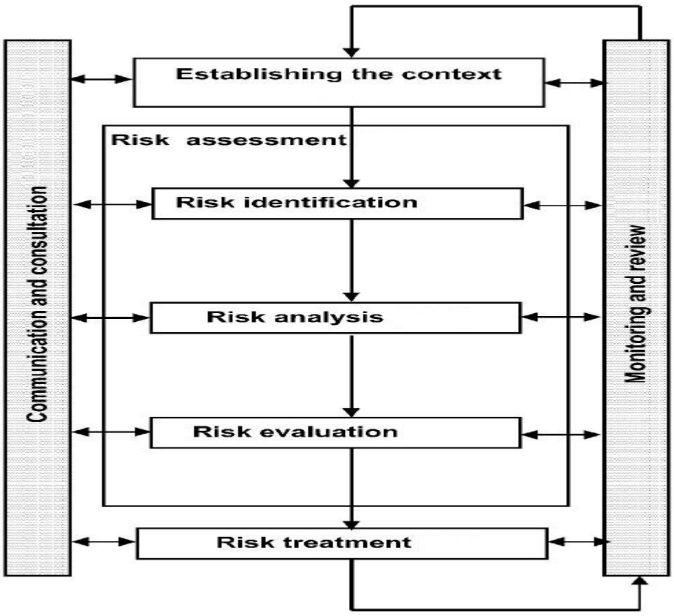

Figure 5: The risk management process. Adopted from (ISO, 2009).

Establishing the context: Establishing the context for the risk management process involves defining internal and external parameters to be considered in risk management. Moreover, it contributes to manifesting the organisation`s objectives and sets the scope and risk (acceptance) criteria for the rest of the process.

Risk identification: Risk identification involves creating a comprehensive list of risks, through the process of identifying events that have the potential for generating, enhancing, preventing, degrading, accelerating or delaying objective achievement. This list will further form the basis for the selection risks to be included in the risk analysis

Risk analysis: Risk analysis involves assessing the types, consequences and likelihood of risks. The analysis may be qualitative or quantitative, and its level of detail may vary, depending on the risk, the analysis' objective, and availability of information.

Risk evaluation: Risk evaluation has the objective of deciding on which risks that needs to be treated. A risk`s necessity and priority for risk treatment, is judged based on the result from the risk analysis.

Risk treatment: Risk treatment involves the process of considering risk treatments and deciding on the acceptability of the remaining risk levels, as well as considering the treatment`s effectiveness.

Monitoring and review: Monitoring and review can be viewed as the continuous process of re-evaluating the steps in the risk management process. Among others, this can involve assessing installed risk control measures, gaining further information about the risks, and identification of emerging risks.

3.2.1 Risk assessment

Risk assessment has the objective of identifying and exploring the types, frequencies, and probabilities of the consequential events related to a risk (Renn, 2005). Moreover, it should "*...decide on risk reducing measures in the context of a structured, systematic and documented process*" (Vinnem, 2013a, p.71). On the UKCS and NCS, it is a requirement of the authorities for operators to perform risk assessments, documenting that the level of risk is within what is found to acceptable. Upon deciding the tolerability or acceptability of risks, it is the responsibility of risk management to mitigate the consequences by deciding on applicable actions. Overall, risk assessment consists of two main parts, risk analysis and risk evaluation. The objective of risk evaluation is to assess the risk relative to the risk acceptance criteria. Further, it shall propose measures for mitigating the risk. (Rausand, 2013)

Risk analysis

Risk analysis has the objective of identifying hazards and estimate the risk to individuals, assets and the environment, through the methodical use of available information. It consists of three main steps, hazard identification, frequency analysis and consequence analysis. This involves answering three fundamental questions (Kaplan, 1991):

- What can go wrong?
- What is the likelihood of it happening?
- What are the consequences?

The first question can be answered by risk scenarios, i.e. scenarios describing the hazards or threats assessed. The second question is answered by a assigning a probability to the scenario. The last question is answered by a quantitative or qualitative description, or evaluation, of the scenario`s consequences (Nordgård et al., 2007).

In general, there are two main categories of risk analysis, quantitative risk analysis and qualitative risk analysis. Qualitative risk analysis involves performing a subjective evaluation of the probability and impact of a risk. It can involve prioritizing identified risks using a pre-defined scale, based on their likelihood and impact. Examples of qualitative risk analysis include Hazard and Operability Study (HAZOP), Safety and Operability Study (SAFOP), Preliminary Hazard Analysis (PHA), Failure Mode and Effect Analysis (FMEA).

Quantitative Risk Analysis (QRA) has the main objective of quantifying a risk`s possible outcomes and associated probabilities. A QRA will normally focus only on the highest priority risks. Moreover, the result from QRA should give a detailed demonstration the risk picture`s elements, by providing relative comparisons of mechanisms and contributions. Relevant parameters for presenting the risk may include accident scenarios, failure types, risk-contributing activities, event sequences for barrier failure scenarios, as well as cause and location of accident initiation (Vinnem, 2013a). In order to achieve the aforementioned, the methodology applied should be focused on establishing principles, methods and models that are satisfactory for describing and analysing risk (Skogdalen and Vinnem, 2011).

It is worth noting that some literature applies the abbreviation QRA to describe ‘Quantitative Risk Assessment’, the latter term including risk evaluation in addition the risk analysis. However, this thesis only applies the first mentioned meaning of the abbreviation.

Risk acceptance and evaluation

As stated by (Renn, 2005), risk exposure, incurred actively or passively, occurs due to risk constituting an integral factor in the actual activities that is designed to fulfil a particular human need or purpose. Thus, one does not expose oneself to risks for the sake of the risks themselves. In the oil & gas industry, it is common for the authorities to issue standards, setting upper limits for the level of risk that is found to be acceptable, i.e. risk acceptance criteria (Aven and Vinnem, 2005). There are several approaches to determining the acceptable level of risk, and the limits often vary between industry sectors, countries, etc. The basis for setting the criteria may include governmental requirements, standards, theoretical knowledge, norms, and experience. Usually, risk acceptance criteria are defined in a way that the risk is either accepted or rejected. It should however be noted that, as stated in (Aven and Vinnem, 2005), there are ambiguous views on the use of risk acceptance criteria among risk analysis experts and others.

On the UKCS, the UK safety case regulations (HSE, 2006) require operators to prepare a ‘safety case’ for their offshore installations, demonstrating that relevant statutory provisions have been met. Upon approval of the safety case, the installation may initiate operation. The safety case requirements include among other demonstrating that all hazards and risks that could potentially cause a major accident have been identified and evaluated, and that measures for controlling the major accident risks have been, or will be, implemented. This requires for a

QRA to be performed using the ALARP (As Low As Reasonably Practicable) principle. The principle of ALARP implies that the risk should be reduced to a level that is as low as reasonably practicable, based on cost-benefit analyses and cost/effectiveness analyses of possible risk mitigation measures. As shown in Figure 6, the standard approach for applying the ALARP principle implies classifying the risk with respect to three regions, i.e. the risk is considered either unacceptable, acceptable or tolerable.

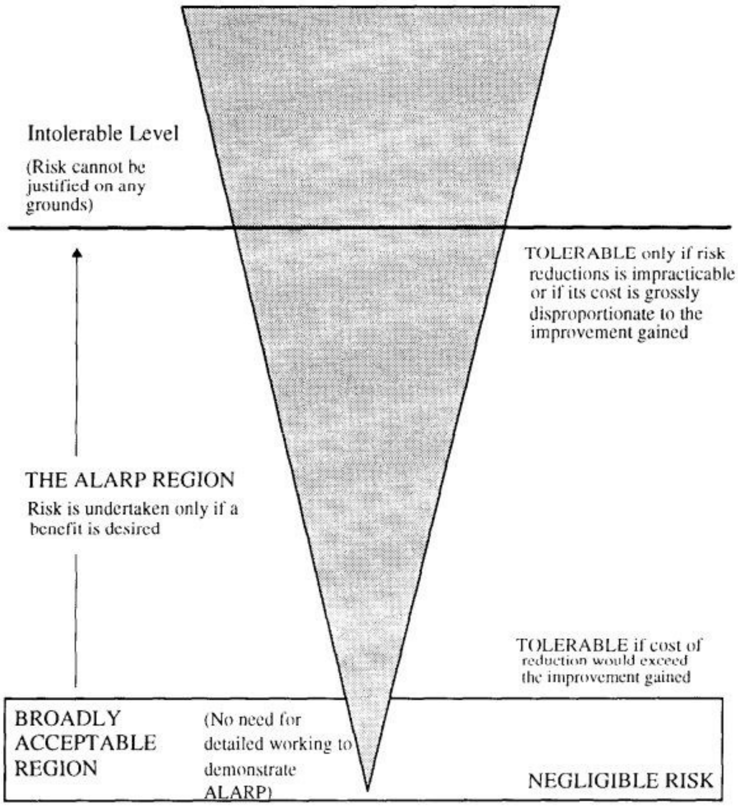

Figure 6: Levels of risk and ALARP. Adapted from (Bell and Reinert, 1992).

A risk in the unacceptable region usually implies the activity has to be abandoned, a risk in the tolerable region must be reduced according to ALARP, and a risk in the acceptable region requires no further risk management action. The risk mitigation measures should be implemented unless it can be demonstrated that the resulting costs and operational constraints are clearly disproportionate to the benefits achieved (Aven and Vinnem, 2005). Although ALARP is a British risk acceptability framework, it has been extensively adopted by other nations, including Norway.

On the NCS, the safety regime applicable to the oil & gas industry is based on the principle that it is the full responsibility of the licence holder to ensure that the petroleum activities are performed in compliance with legislative requirements (NTS, 2010). In 1981 it became a requirement of the Norwegian Petroleum Directorate (NPD) for performing QRA for all new offshore installations, as stated in their guidelines for safety evaluation of platform conceptual design (NPD, 1980). The regulations provided a cut-off criterion for the accident frequency limit, all of which accidents that occur more frequently are to be used to define design basis accidents. Further, before commencing operations on a new installation, the licence holder is required to provide documentation of the relevant requirements being fulfilled. Since then, the guideline have been replaced by new updated regulations, however the cut-off criterion is still valid. The additions to the regulations include amongst others NS 5814, which demands for a risk acceptance criteria to be defined prior to performing a risk analysis, as well as the incorporation of the ALARP principle in the risk management framework. The cut-off criterion for offshore installations has been set to a frequency of 1.0E-04 accidents per platform year, and is applicable to the FPSO – shuttle tanker collision risk (Vinnem, 2013a).

3.2.2 Human and organisational factors

This section presents the theoretical basis for the approach to human and organisational factors (HOFs) applied in this thesis. HOFs and technical factors can have a significant impact on safety barriers, and some barriers are completely dependent on human intervention in order to perform their intended function. Furthermore, HOFs are fundamental in preparing, analysing and interpreting results from the QRA, as safety barriers are defined and explained by the HOFs influence (Skogdalen and Vinnem, 2011).

The recognition of the causal relationship between human error and casualties at sea has been around for centuries. However, the concept of marine safety standards and human factors in marine operations did not receive much attention until in the late 1800s, when there was a tremendous increase in marine passenger traffic. World War II further increased the scientific research on human factors in the maritime domain, the focus being mainly on work task efficiency rather than accidents. Yet, the positive results from this research acted as a springboard for continued research into the human element of marine operations (Grech et al., 2008). The scientific area of HOFs is however vast and its theoretical platform has not been settled (Skogdalen and Vinnem, 2011). This thesis focuses on HOFs in relation to collision accidents, and the theory presented has been selected accordingly.

Human factors

Human factors is defined by (Goodwin, 2007) as the scientific discipline encompassing theories and knowledge about human behavioural and biological characteristics, that are validly applicable for specification, design, evaluation, operation and maintenance of products and systems, in order to promote safe, effective and satisfying use by individuals, groups and organisations. Human factors may thus be regarded as covering a range issues, i.e. human perception, physical and mental capabilities, individuals' interactions with their job and work surroundings, human performance under influence by equipment and system design, as well as the influence of organisational characteristics on safety related work behaviour (Skogdalen and Vinnem, 2011).

Human error

Interchangeable use of the terms 'human error' and 'human factors' occurs frequently in literature, and clear definitions rarely given. However as noted by (Goodwin, 2007, Skogdalen and Vinnem, 2011), its essential to differentiate the two, the first mentioned being the underlying causes of accidents, and the second mentioned being the immediate causes. (Grech et al., 2008) defines *human error* as an inappropriate or undesirable human decision or behaviour, resulting in, or having the potential for adverse results.

Human error is a contributing element in numerous maritime accidents and incidents. Research indicates that for every severe accident, there are a greater number of near-misses, and an even greater number of safety-critical events (Grech et al., 2008). Thus, accident statistics only show the 'tip of the iceberg'. Figure 7 shows the classic iceberg model for accidents. The ratio between the different categories may vary according to the type of industry; however, it provides an intuitive illustration of the pyramidal relationship between the categories.

The logic behind the iceberg model is that the frequency of events in the respective categories increases as one moves from top to bottom. The bottom category contains the numerous and virtually invisible, but potentially dangerous, unsafe acts and ordinary work routines that have the potential of developing into an event in one of the other categories. Consequently, only investigating accidents, incidents and near misses implies omitting a large quantity of information (Grech et al., 2008).

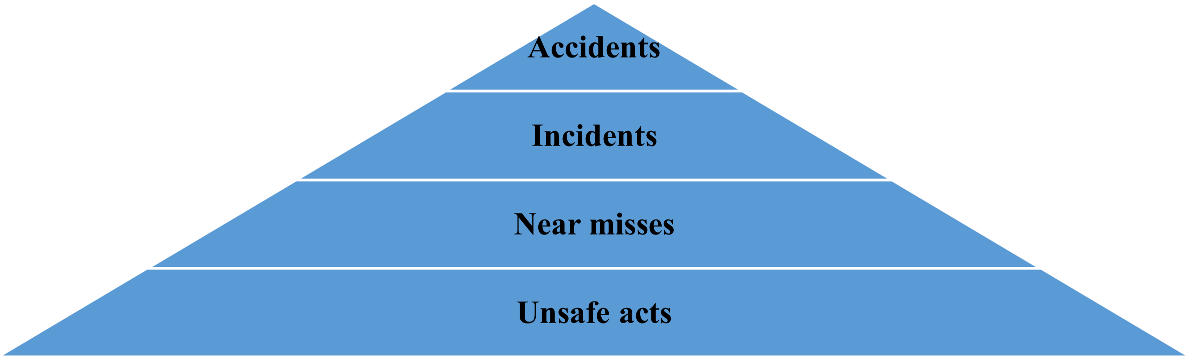

Figure 7: The classic iceberg model for accidents. Adapted from (Grech et al., 2008).

Perspectives on the human element in safety engineering

In general, there are two basic perspectives on human errors and human factors: the system approach and the person approach. The person approach focuses on unsafe acts resulting from deviant mental processes of individuals, e.g. inattention and irresponsibility. Consequently, this approach applies countermeasures directly targeting adverse human behaviour. The system approach on the other hand, views unsafe acts as the result of systemic factors, e.g. organisational processes, rather than individual factors. Further, the systematic approach views the human condition as unchangeable, and thus defences against human error should be incorporated in the system (Reason, 2000).

Organisational factors

(Øien, 2001) states that the field of research on risks emerging from organizational factors, emerged from the realization that human error and technical failure were not the definitive answer as to what was the root cause of every major accident. Amongst the first to take action upon the new insight, was the US Nuclear Regulatory Commission, which launched several research projects on safety performance indicators in the beginning of the 1980's. This resulted in the nuclear organisation and management analysis concept (NOMAC).

Today, IMO has recognised that although human errors are commonly found to be primary causal contributors to accidents, investigators should not explicitly focus on the personnel directly involved in the accidents (sharp-end personnel), but rather take into consideration the conditions surrounding the sharp-end personnel and the organisation that permitted the hazardous conditions to exist (Chen et al., 2013). People in a work environment are influenced by three areas, namely the organisation, the job, and personal factors. These areas are further directly influenced by the organisation`s communication systems, training systems and operational procedures (Stranks, 2005). These "surrounding" conditions are known as 'organisational factors'.

Organisational factors are characterised by an organisation`s design of job positions and work task division, as well as the selection, training, cultural indoctrination and coordination of the workforce, in order to perform their activities. In relation to safety, the key aspects for an organisation in the oil & gas industry includes factors relating to complexity, size and age of installation, and factors determining the organisational safety performance, e.g. communications, coordination, leadership, manning (Skogdalen and Vinnem, 2011).

In relation to organisational factors, the system approach accounts for both internal (e.g. personal characteristics) and external conditions (e.g. work organisation) influencing human behaviour, by recognizing that although individuals may influence the operational risk[5], the organisational factors plays a key role in determining the organisations exposure to the risk imposed by individuals.

3.2.3 Risk Influencing Factors

RIFs are identified through the process of grouping comparatively steady conditions influencing the risk into sets, a single RIF representing the average level of one set of conditions. Moreover, the RIFs may be improved through specific actions. (Vinnem et al., 2003b) presents the following category divisions and corresponding definitions of RIFs, which are also utilized in this study:

- Operational RIFs:
    - Activities essential to ensure safe and efficient tandem loading operations on a daily basis. Specifically, it comprises requirements and conditions in relation to shuttle tanker technical dependability, state of operational dependability of the composite loading system as well as other external interfaces and conditions.
- Organisational RIFs:
    - Organisational RIFs are related to the management's philosophies and strategic choices in relation to the technical and operational foundation, along with control, support and management of daily activities in shuttle tanker operations.
- Regulatory RIFs:
    - Regulatory RIFs are related to requirements and regulatory activities from authorities.

RIFs can be an important tool for identifying which factors that interact and influence risk. The interactions of such factors can be further investigated, using the sociotechnical system model. The sociotechnical system model provides a systematic methodology for assessing human, organisational, and technological factors, as well as how their interactions influence system performance. The model, as presented in Figure 8, consists of seven main areas (Grech et al., 2008):

- *Individual*: Factors relating to humans as an individual, e.g. individual physical or sensory limitations, human physiology, psychological limitations, individual workload management and experience, skill, knowledge.

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[5] Risk of loss, which originate from the fact that people, processes and systems of an organisation are imperfect. (Skogdalen and Vinnem, 2011)

- *Group*: Factors relating to interpersonal interaction, e.g. teamwork, communication, and leadership.
- *Practice*: Factors relating to interaction between the individual and practice, i.e. how the humans obtain system knowledge through practice.
- *Technology*: Factors relating to the interaction between the individual and technology, e.g. equipment, usability, human machine interaction (HMI).
- *Physical environment*: Factors relating to the surrounding working environment, e.g. physical workspace environment, weather/visibility conditions, lightning conditions.
- *Organisational environment*: Factors relating to company and management, e.g. procedures, policies, norms, rules.
- *Society and culture*: Factors relating to the socio-political and economic environment surrounding the organisation.

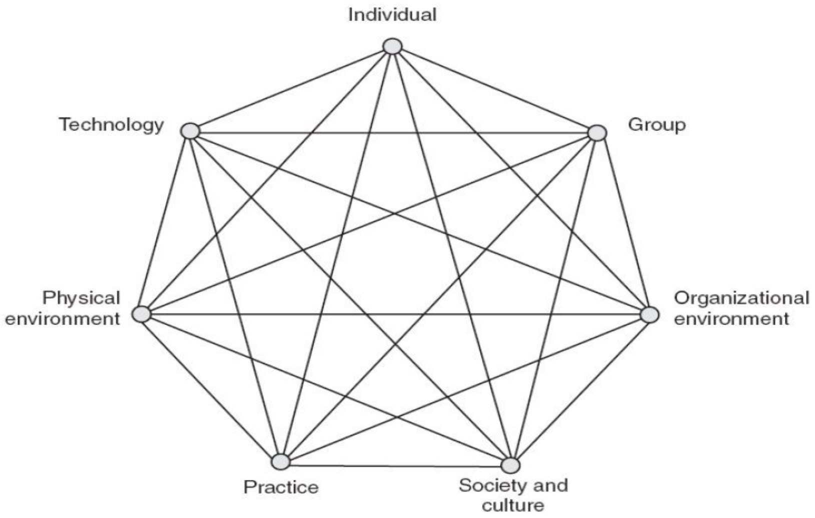

Figure 8: The sociotechnical system model by Thomas Koester (Grech et al., 2008).

3.2.4 Barriers and barrier management

This section provides a presentation of relevant theory on barriers and barrier management. As the barrier concept is treated differently in literature, depending on the context, the focus in this thesis is directed towards applications in the oil & gas industry. Moreover, barrier analysis- and management methodologies developed specifically for assessing risk relating to offshore installations, are presented.

Barriers are important measures for risk mitigation in any system. As previously stated, hazards can be interpreted as sources of physical harm, which can transform into an accident by means of a hazardous event occurring. The barrier concept is about separating something valuable from a hazard by installing a barrier between the two. (NTS, 2010, Skogdalen and Vinnem, 2011, Vinnem, 2013a) presents a set of definitions for the terms barrier functions, barrier systems and barrier elements. Their respective definitions being as follows:

- *Barrier function*: Functions intended to prevent, control or mitigate undesired or accidental events. The term ‘intended’, i.e. planned, suggests that at least one of the functions’ purposes is risk reduction (Skogdalen and Vinnem, 2011).
- *Barrier system*: System designed and implemented to perform one or more barrier functions.
- *Barrier element*: A component of the barrier system, which isolated is not capable of performing the required barrier system function.
- *Barrier influencing factor*: factor that influences barrier performance.

Safety barriers

Safety barriers are defences implemented in a system to protect people, assets and the environment from hazards, i.e. safety barriers are implemented in order to minimise the probability of hazardous events and/or limit the consequences of such events. Safety barriers can be either proactive or reactive, depending on if their intended function is to provide protection pre or post the event (Xue et al., 2013). The defence can be everything from a single technical unit to a complex socio-technical system. It is further common for safety barriers to be required and specified in legislation and standards within different industries (Skogdalen and Vinnem, 2011). In relation to safety engineering, it is moreover common to view the barrier as a means of protecting humans from an energy source, as shown in Figure 9.

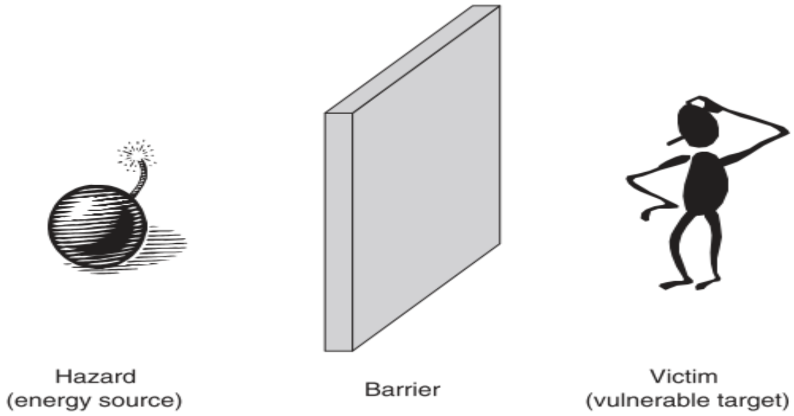

Figure 9: Energy model for barriers (Sklet, 2006b).

Figure 10 further illustrates relationship between the various definitions relating to safety barriers. The safety barrier function is realised by the safety barrier system. Moreover, the safety barrier function describes the intention of the barrier, i.e. how the barrier is to perform in order to accomplish the task it has been given. This means that if the barrier function is accomplished, it should have a direct and substantial effect on the frequency and/or the consequences of an undesired event or accident (Sklet, 2006a).

The safety barrier system can further be classified as passive or active, the main difference being that passive barriers are built into the system design and are able perform their function independent of input external control systems, e.g. an operator or a control system, whilst active barriers are dependent on such input (Sklet, 2006b). Further classification may also include classifying the barriers as physical, technical or human/operational systems. Physical barriers, e.g. firewalls, are usually performing their function nonstop and do not require activation. Technical barriers, e.g. emergency shutdown system, are activated upon the realisation of a hazard. Human/operational barriers, e.g. safety distances and third party control of work, can either be continuously activated or activated upon demand (Sklet, 2006b). The barrier performance may further be characterised by their attributes, i.e. reliability/availability, response time, functionality/effectiveness, robustness, and triggering event or condition (Skogdalen and Vinnem, 2011).

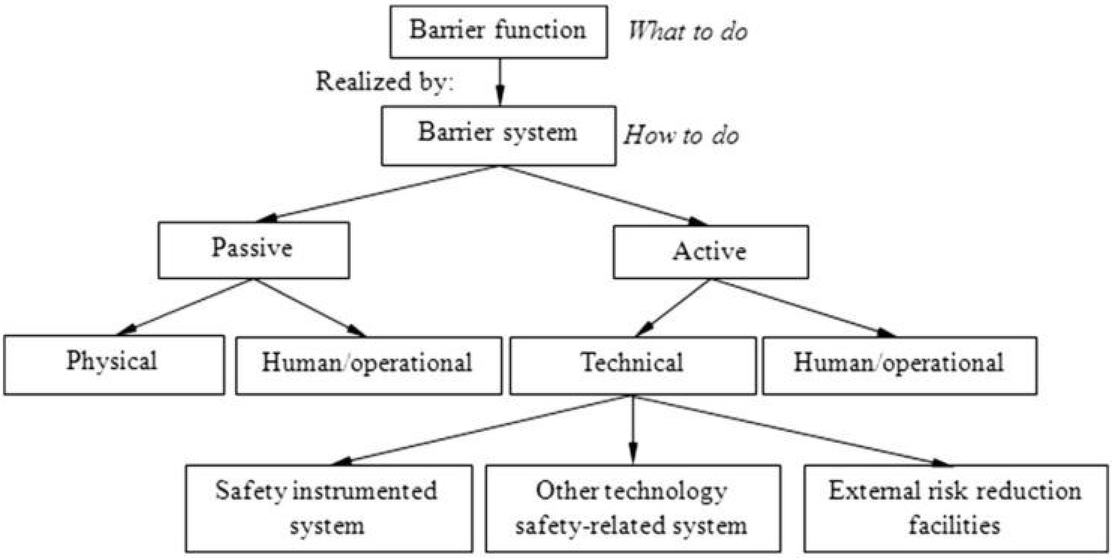

Figure 10: Safety barrier classification (Sklet, 2006b).

Barrier analysis

As presented in Section 3.2.1, it is a requirement on both the NCS & the UKCS for performing risk assessment of new offshore installations. As safety barriers are key for reducing risk, safety barrier analysis is an important formal requirement of QRA. Furthermore, in order to assess the influence of human and organisational factors, it is essential to define and model safety barriers. In cases where HOFs dominate a particular hazard mechanism, there should be performed a comprehensive analysis of operational barriers (Skogdalen and Vinnem, 2011). There are many different methods for performing barrier analysis, e.g. 'Barrier and Operational Risk Analysis' (BORA), the Operational Condition Safety (OTS) method, the Bow-tie method. No matter which method applied, the barrier analysis should identify the barrier systems and their functions, performance requirements, barrier influencing factors, as well as assess how barrier performance can be increased.

This thesis applies only applies the bow-tie method explicitly in its barrier analysis. However, the Swiss cheese model, shown in Figure 11, is included in this section as it provides an illustrative method for communicating how accidents may occur in complex systems. It is a conceptual framework, conveying the fact that accidents are not caused by isolated failures, but are rather the result of several failures, on different system levels, occurring simultaneously. A breach in a system`s defences is illustrated by the red arrow, imitating the accident trajectory. Normally, the defence layers will be interacting and supporting each other. But in some instances, the "holes" may align, creating an accident trajectory (Grech et al., 2008). The Swiss cheese model for a particular accident can be built by examining the barriers in the system and their failure modes. The "holes" in the barriers are present because of either latent conditions or active failures, the former often being connected to organisational factors (Xue et al., 2013).

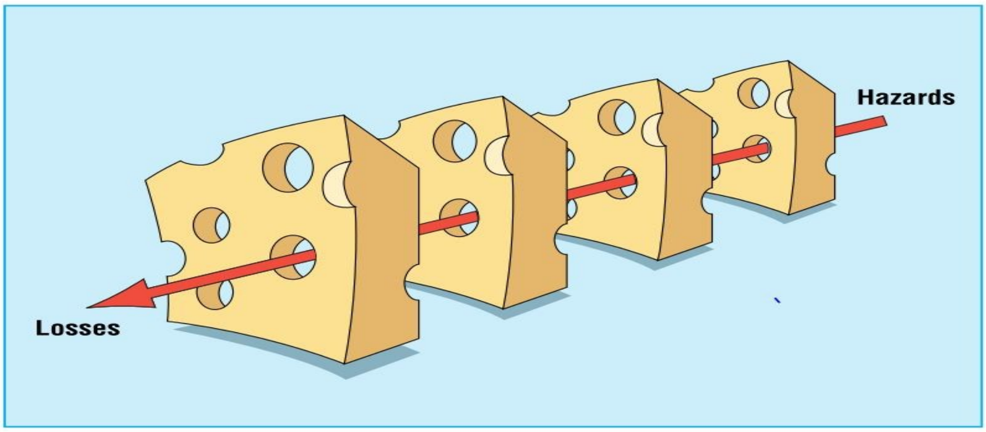

Figure 11: The Swiss cheese model (Reason, 2000).

Bow-tie analysis

A bow-tie diagram, as shown in Figure 12, provides a graphical presentation of an accident scenario, illustrating the connections between causes and consequences for the TOP event.

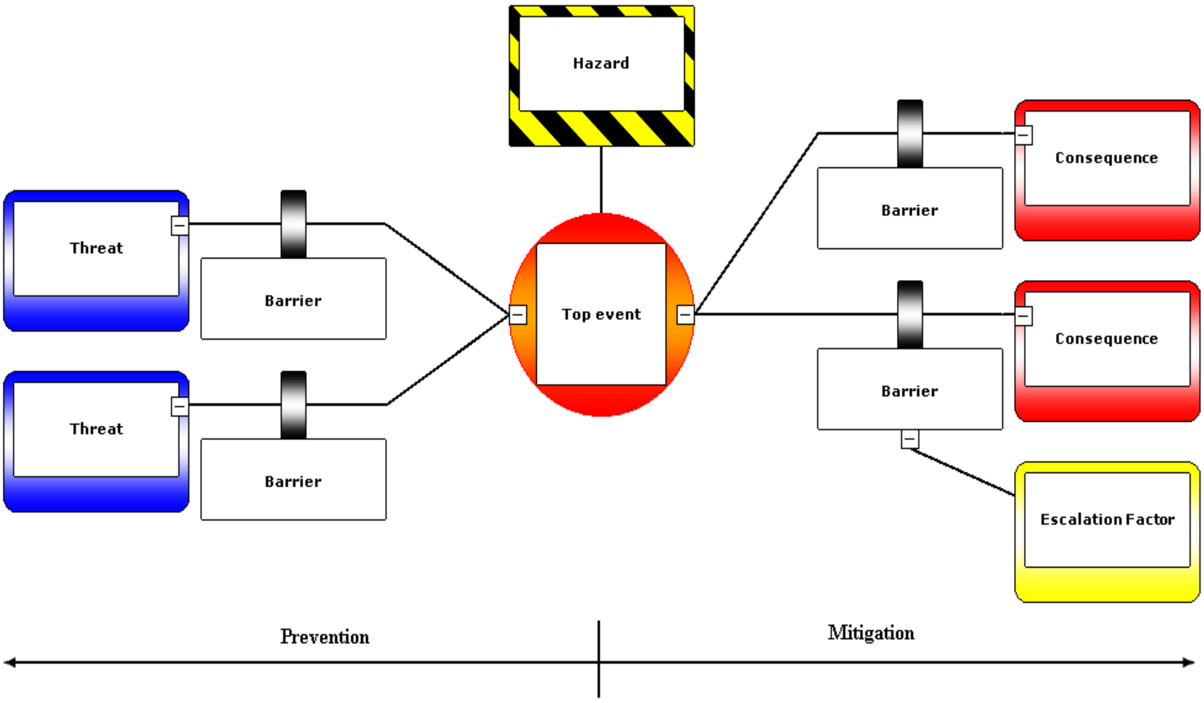

Figure 12: Bow-tie diagram.

It is in essence a combination of a fault tree on the left-hand side and an event tree on the right hand-side. Hence it can aid in the process of understanding of which combinations of primary events that can cause the top event to occur, and the consequence resulting from a particular safety barrier`s failure (Khakzad et al., 2012). This insight can further be applied to introduce new barriers in the system and for evaluation of barrier performance.

The bow tie analysis in this thesis was performed using BowTieXP from CGE Risk Management Solutions. The main steps in performing such an analysis are as follows (CGE, n.d.):

- Identify the hazard(s) present in the system (Hazard)
- Identify what happens if the hazard is released (TOP event)
- Identify what can cause the hazard to be released, and how control can be lost? (Threats)
- Identify the potential outcomes (Consequences)
- Identify measures for preventing or limiting the effect upon a release of the hazard (Barriers).
- Identify the barrier failure modes (Escalation factors)

4. ANALYSIS OF FPSO – SHUTTLE TANKER COLLISION RISK

Chapter 3 have presented the general theoretic and methodological basis for this thesis approach to risk. In this chapter, the information provided in chapter 2 and chapter 3 is further applied to investigate the collision risk in FPSO-shuttle tanker tandem offloading operations. Moreover, this chapter provides this thesis' risk analysis and it is divided into three main parts:

- *Part 1* establishes the overall risk picture in relation to collisions between DP shuttle tanker and FPSO when performing tandem offloading operations in the North Sea.
- *Part 2* provides a review of previous research performed on the specific topic of this thesis.
- *Part 3* presents this thesis' risk analysis, in which qualitative and quantitative methods are applied to investigate the collision risk. HOFs and technical factors are assessed, before a barrier analysis is performed. Moreover, the collision frequency model applied to investigate incident data for the UKCS & NCS from 1995-2013, is outlined.

4.1 THE RISK PICTURE

(Chen and Moan, 2002) found the incident frequency for FPSO-shuttle tanker tandem offloading operations in the North Sea to be relatively high, estimating the collision frequency to be in the order of one collision per four hundred offloading operation. As the shuttle tanker and FPSO both have large masses, and consequently large momentums, it implies that the collision damage potential is also large. If the shuttle tanker collides with the FPSO, it may cause extensive deformation of the FPSO stern. This involves a significant risk of oil spill into the ocean or water ingress into the damaged vessels. Moreover, it may also cause damage to the flare towers that have to be located in the stern area due to the crew`s living quarters being located in the bow section. Thus, a collision has the potential of causing a chain reaction of dangerous events.

4.1.1 Accident scenarios

(Chen, 2003, Vinnem et al., 2003b, Skogdalen et al., 2009), presents four accident scenarios relating to FPSO-shuttle tanker collisions during tandem offloading, shown in Table 3.

Table 3: Collision scenarios for tandem offloading operations.

Initiating event			
Drive-off	*Drift-off*	*Surging*	*Yawing*
Shuttle tanker is driven away from its targeted/wanted position by its own thrusters in offloading operation.	Environmental forces push shuttle tanker in the direction of FPSO.	Asynchronous relative surge motions between shuttle tanker and FPSO.	Significant mean heading differences and asynchronous relative yaw motions between shuttle tanker and FPSO.

Principally, a drive-off can be in any direction. However, due to the shuttle tanker being positioned astern of the FPSO during tandem offloading, only a drive-off in forward can result in a collision (Skogdalen et al., 2009). Furthermore, since a shuttle tanker waiting at the field will be positioned on the FPSO's leeward side, in order to prevent drifting accidents, a drift-off scenario's influence on the collision frequency is normally fairly low (Vinnem, 2013a). Therefore, this thesis only investigates the drive-off scenario, which is also considered the most critical by the aforementioned studies.

4.1.2 Collision experiences from FPSO – shuttle tanker offloading

(Leonhardsen et al., 2001) reports three collisions involving FPSOs on the NCS in the period 1997-2001, one of which happened during offloading between FPSO and shuttle tanker. There were no reported collisions involving FSUs during the same period. The shuttle tanker Knock Sallie collided with 'Norne FPSO' in 2000, upon completion of a cargo offloading operation, due to the thrusters suddenly giving maximum thrust when switching the DP system from weathervane to auto position. The collision energy has later been estimated to be 31[MJ] (Chen and Moan, 2005). The accident investigation found the accident to be the result of a malfunctioning DP system as well as a corresponding mal operation and slow reaction from the DPO.

In 2006, the shuttle tanker 'Navion Hispania' collided with Njord Bravo FSU during connection. The initiating event was a blackout on the shuttle tanker, causing it to lose most of its thrust capacity and subsequently hit the aft of the FPSO. The collision energy is estimated to have been about 61 [MJ]. The accident investigation revealed that following the loss of thrust capacity, the DP system was nonetheless maintained in auto positioning mode. Several system failures, mal operation of the DP system, inadequate training of personnel and not following procedures, were amongst the main causes for the accident (Kvitrud et al., 2012).

For the UKCS, the author has not found detailed reports of the collision incidents, which are available to the public. However, the following collision incidents and vessels involved, have been identified from (Chen and Moan, 2002, Bradbury, 2009):

- The shuttle tanker Clipper collided with Emerald FSU on 28.02.96.
- The shuttle tanker Futura collided with Gryphon FPSO on 26.07.97.
- The shuttle tanker Aberdeen collided with Captain FPSO on 12.08.97.
- The shuttle tanker Nordic Savonita collided with Schiehallion FPSO on 25.09.98.
- The shuttle tanker collided Lord Rannoch collided with Schiehallion FPSO on 08.10.09

4.1.3 Reporting of collision incidents

On the NCS, regulations for petroleum activity demands that incidents related to permanently installed installations are reported to the NPD. The NPD has been collecting data on incidents and reports on condition deviations for installations on the NCS since the mid-1970s. The collected data, to be used for statistical and analytical purposes, is put into the CODAM database and graded according to their level of severity, i.e. insignificant, minor, major (Leonhardsen et al., 2001).

The HSE Offshore Safety Division (HSE OSD) have been maintaining a database of vessel/platform collision incidents on the on the UKCS since 1985. However, it was found that the database contained numerous inconsistencies and unconfirmed data. This information gap was addressed by the HSE OSD in (Robson and Britain, 2003), which presents an updated database of UKCS collision incidents, compiled from several collision incident sources. Yet they found it probable that the database was still suffering from a degree of under-reporting, mainly from incidents with little or no damage to the units involved. Several projects on accident statistics have been performed since then, e.g. (DNV, 2007, Funnemark, 2001).

Today, the reporting requirements of incidents involving floating units operating on the UKCS are dependent on the operation mode and geographical location at the time when the incident occurred. It can be either the HSE OSD, the HSE Field operations Division (HSE FOD), or the Marine Accident Investigation Branch (MAIB) (DNV, 2007).

The likelihood of under-reporting to the incident databases, as mentioned in (Robson and Britain, 2003), is probably also relevant for the incident databases on the NCS. However, in the last decade, as procedures for incident reporting, have improved along with a greater degree of transparency in offshore safety reporting, the likelihood of underreporting may have decreased. Amongst the issues that have been discussed is the definition of ‘near-miss’ incidents, i.e. what incident are to be classified as such.

4.2 PREVIOUS PROJECTS ON THE SUBJECT AND LESSONS LEARNED

This section provides a general overview of the major research papers published on the subject of FPSO – Shuttle tanker collision risk. It is divided in two subsections, according to if the research was published pre or post year 2003. This is in compliance to the research objectives of this master thesis’, i.e. to investigate and compare the current situation to the situation at the time when the JIP report was released. Further, two reports, which the author finds to be the most influential on this field of research, is presented more in detail.

4.2.1 Pre 2003

(IMCA, 1999) presents the results from a frequency study on collisions incidents involving DP shuttle tankers performing offloading, covering all station-keeping incidents reported to IMCA from 1979 up until August 1998. The study includes all offshore export facilities and is not limited to the North Sea. The study reports 134 such incidents spread over 9946 offloadings, and 16 of those incidents are identified as forward drive-offs, of which 12 resulted in collision. The drive-off forward frequency is estimated to 1.6E-03 per offloading and the collision frequency is estimated to 1.2E-03 per offloading. It should however be noted that these frequencies are average frequencies, encompassing all offshore export facilities. Furthermore, the frequencies are estimated from data collected during almost two decades, a period in which there was a tremendous development in the technological equipment applied in offloading operations.

(Leonhardsen et al., 2001) summarizes the NPD`s operational experience of FPSOs on the Norwegian Continental Shelf (NCS) pre 2001. At the time when the report was published, five FPSOs and three FSUs were in operation on the NCS. The FPSOs were all turret moored, weathervaning vessels, positioned at water depths ranging from 85-380 m. The study revealed that all but one of the reported 'high energy collisions'[6] on the NCS from 1982-2000 was related to the DP system either malfunctioning or being mal operated. It was also reported one drive-off during positioning for FPSO offloading. Furthermore, the study assessed the overall collision frequency for FPSOs/FSUs on the NCS to be 0.154 per year, which is more than 2.5 times the overall collision frequency of gravity-based structures (GBS). However, the report notes that their data shows that the collision frequency for FPSO cargo offloading operations is significantly lower, 0.051 per year. In comparison, loading buoy cargo offloading operations has a collision frequency of 0.078 per year.

(Chen and Moan, 2002) presents a collision modelling approach for FPSO – shuttle tanker offloading operations. The model integrates human actions, technical events and their interaction when causing an unintended powered forward movement of the shuttle tanker. The study further investigates the failure prone situations, identified by the model, in order to investigate the chain of events and possible recovery actions in a shuttle tanker initiated recovery scenario. Applying the perspective of human action timing, the success of the recovery

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[6] Collision involving either vessels above 5000[tonnes], high-velocity impacts from vessels below 5000 [tonnes], or unauthorized vessels (Leonhardsen et al., 2001).

is analysed, and recommendations are made for measures that can mitigate the failure of recovery in design and operation.

4.2.2 Post 2003

(HSE, 2005) provides a review of incidents involving DP shuttle tankers performing offloading from FPSO/FSU on the UKCS, covering the period from 1998 to August 2004. It reports 19 incidents involving loss of position and collision with loading point (or very high hawser tension), in the course of 66829 DP hours. Based on this, the frequency is estimated to be 2.76E-04 per DP hour.

(OGUK, 2009) provides the most comprehensive published collection of accident and incident statistics for offshore units on the UKCS, covering the period 1990-2007. Statistical data were collected from four different incident databases, namely COIN/Orion (UK HSE OSD), Offshore Blowout Database (SINTEF), WOAD (DNV), MAIB (UK Marine Accident Investigation Branch). Overlapping records in the databases were removed and average annual incident frequencies are presented per type of installation. For monohull units, i.e. FPSOs and FSUs, there have been 17 occurrences of collisions/accidental contacts between installation and visiting vessel, e.g. tugs, supply vessel, shuttle tanker, etc., from 1990-2007. Moreover, the incidents were distributed with eight incidents and nine incidents, occurring in the periods 1990-1999 and 2000-2007 respectively. The average incident frequency for 2000-2007 is estimated to 0.071 per unit year. The estimate is based on a total of 127.1 unit years.

(Chen et al., 2010) presents a probabilistic modelling of the risk of a collision involving a geostationary FPSO and a shuttle tanker in direct offloading. Opposed to turret-moored FPSOs, geostationary FPSOs do not weathervane and direct offloading from the latter presents a relative recent addition to North Sea shuttle tanker operations. A case study is performed, the result from which demonstrate that the collision risk level is significantly reduced in the direct offloading compared to the tandem offloading.

(Kvitrud et al., 2012) investigates 13 position incidents involving shuttle tankers performing offloading operations on the NCS, that occurred in the period 2000-2011. It provides the most updated review of such incidents on the NCS, per mid. 2014. The first section of the article is devoted to presenting an overview of the current regulations and guidelines applicable to FPSOs/FSUs and shuttle tankers on the NCS. The second section offers a statistical overview of the collisions that occurred. The third section provides a short review the 13 position incidents, i.e. the collisions, near collisions and other incidents (i.e. loss of position control incidents, in which position control was recovered). A discussion of the necessities for improvement is provided in the last section of the article.

Further, (Kvitrud et al., 2012) found that up until year 2000, there were many incidents and collisions during FPSO/FSU shuttle tanker offloading operations. In the years 2001-2005, a period in which several major research projects concerning such operations were performed, there was only one position incident reported to the Norwegian Petroleum Safety Authority (PSA). However, as shown in Figure 13, since 2006 there has been at least one incident each year up until 2011. Based on this, (Kvitrud et al., 2012) states that the improvements made in the early 2000`s appear to have disappeared.

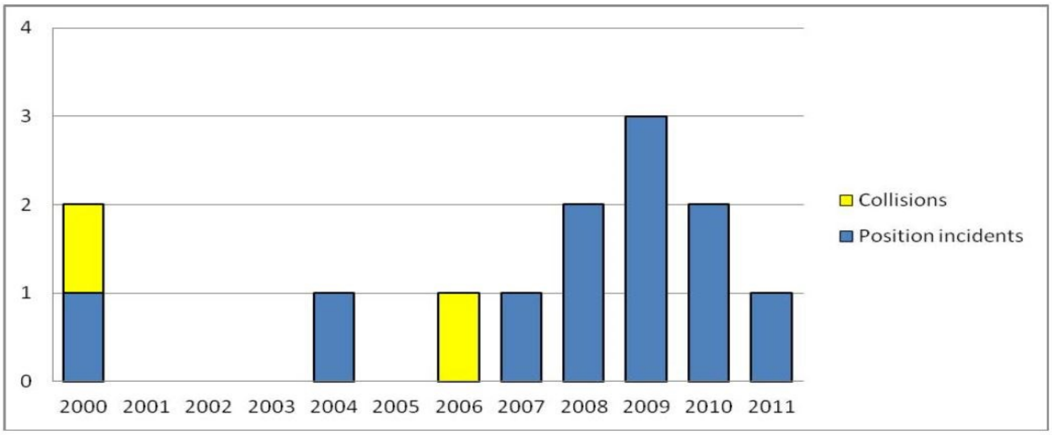

Figure 13: Collisions and position incidents involving offshore shuttle tankers, reported to the PSA in the period 2000-2011 (Kvitrud et al., 2012).

Moreover, the study found the average age of the shuttle tanker at the time of collision to be 3.5 years, whilst for the shuttle tankers involved in near collision and position related incidents, the average age was 9.7 years and 10.7 years respectively. Based on this, it is suggested that the reason for new shuttle tankers seemingly being more likely to be involved in collision incidents, is due to the new on-board equipment not being adequately tested as well as the new teams operating the vessels.

4.2.3 'FPSO Operational Safety'JIP project

From 1996-2003, the R&D project 'FPSO Operational Safety' was performed as a Joint Industry Project (JIP). It was funded by HSE, Statoil, and Exxon. In addition, Navion contributed as technology sponsor. The overall objective of the JIP project was to integrate human reliability science into predictive models and tools for analysis of safety of FPSOs. In order to achieve this, there was a need for developing such models and tools. Further, it was intended to test out the methodology on selected case studies and illustrate the possible results from project implementation.

It was found that previous risk assessments performed on FPSO operations, failed to adequately consider Human and operational factors, which resultantly lead to such factors being ignored during the design. Further, numerous additional failure scenarios were identified.

The project had several objectives in relation to the FPSO – Shuttle tanker collision risk:

- To demonstrate the importance of HOF for the collision risk.
- Identification and evaluation of factors that from a HOF point of view determines the collision risk.
- To propose potential risk reduction measures relating to HOF for the collision risk and indicate importance.

A risk assessment of tandem offloading operations between FPSO and shuttle tankers on the NCS & UKCS was performed, covering position incidents from 1995-2003. The study`s main focus was on drive-off incidents, but also other potential position incident scenarios such as fishtail/heading deviation, and surging. Further, a detailed risk assessment was made for six incidents, considering various field configuration parameters, i.e. FPSO with/without heading control, shuttle tanker DP class, offloading interface system, and FPSO-shuttle tanker separation distance. The main contributors to the collision frequency, considering a drive-off scenario, were considered based on expert assessments and experience from previous incidents involving FPSO and shuttle tanker. Incidents where there was adequate information available were also assessed in terms of the time usage in the different stages of recovery actions. Results showed that for the incidents that had resulted in a collision, the minimum time and maximum time for initiating recovery action, was 40 seconds and 120 seconds respectively. Moreover, for the incidents that did not result in a collision, time for initiating recovery action was found to be close to 40 seconds.

Observations from the incidents investigated in detail, indicated that the main contributors to drive-off incidents are ‘shuttle tanker positioning and control system’, ‘shuttle tanker crew competence’, ‘FPSO positioning and control system’, and ‘shuttle tanker work organisation’. The shuttle tankers’ positioning and control system was found to be a contributor in all six incidents. Identified causes were DP system receiving erratic input from PRS, and the DPO having problems figuring out the DP system`s response upon certain inputs, due to the systems complexity. The average contribution was considered as more than 30%.

Shuttle tanker crew competence was found to be a contributor in five of the incidents. It was identified that inadequate competence amongst the crew had caused mal operation of the DP system, as well as that the DPO`s reaction time when experiencing system failures/unintended movements, was too slow, contributing to the incidents. The average contribution was considered more than 30%. Further, FPSO positioning and control system, and shuttle tanker work organisation was found to have had a significant influence in two incidents and three incidents respectively. An overall ranking of the operational RIFs was made, as presented in Table 4. It shows that the competence of the crew as well, as the positioning and control system on board the vessels involved in the offloading operation, is considered as essential contributors to the collision risk.

Table 4: Overall ranking of operational RIFs (Top 10) (Vinnem, 2013b).

No.	RIF description	Ranking
1.14	ST crew competence	1
1.6	ST positioning and control system	2
1.2	FPSO positioning and control system	3
1.11	FPSO crew competence	4
1.9	ST-FPSO technical interface	5
1.10	Operational procedures	6
1.17	ST-FPSO operational interface	7
1.16	ST organisation of work	8
1.20	Environmental conditions	9
1.7	ST maintenance, repair and modifications	10

Table 5 further presents a ranking of the operational RIF groups (definitions provided in Section 3.2.3), based on the aforementioned assessments. It shows that the combination of “Technical and Human/Operational” factors is assessed to have the greatest contribution to the collision frequency, followed by “Human/Operational dependability” and “Technical *and* Human/Operational *and* External”.

Table 5: Ranking of operational "RIF groups" (Vinnem, 2013b).

Ranking	Ranking of RIF group/ RIF group combination	Contribution
1.	Technical *and* Human/Operational	40%
2.	Human/Operational dependability	15%
3.	Technical *and* Human/Operational *and* External	15%
4.	Technical dependability	10%
5.	Human/Operational *and* External	10%
6.	Technical *and* External	8%
7.	External conditions	2%

The study further presents several risk mitigation measures for FPSO-shuttle tanker offloading operations, which covers HOFs, shuttle tanker positioning system, shuttle tanker man-machine interface, as well as FPSO specific features and FPSO shuttle tanker interface.

4.2.4 'Probabilistic evaluation of FPSO-tanker collision in tandem offloading operation'

This report presents the PhD thesis of Dr. Ing. Haibo Chen, undertaken at the Norwegian University of Science and Technology. The overall objectives of this study was to analyse the collision risk between FPSO and shuttle tanker in tandem offloading operation, considering both operational and technical aspects, by creating a quantitative frequency model. Further, the developed model was to be applied on case studies from the North Sea, in order to identify measures for mitigating the collision risk during such operations. The author was conscious that a lack of focus on human and organisational aspects in quantitative offshore risk analyses, had led to a risk mitigation approach that was concentrating on hardware failures. Generally, this approach had proved to be an inefficient approach for reducing risk in intricate marine operations.

The collision frequency model developed in this study divides the position incidents into two phases, an initiating phase and a recovery phase. The initiating phase comprises the shuttle tanker experiencing an uncontrolled forward movement; more specifically the study focuses on shuttle tanker drive-off forward scenarios. By the use of statistical data from previous studies and incident databases, along with expert judgements of shuttle tanker DPOs, the drive-off frequency is described on a macroscopic level. Results from the analysis indicate a drive-off frequency of in the range of 5.4E-03 to 2.0E-02 per offloading and a collision frequency of 3.0E-03 per offloading. The drive-off frequency is further investigated on a microscopic level by performing a closer study of nine events involving drive-off during tandem offloading. This involved studying investigation reports, as well as having interviews and discussions with people involved in these events.

Results from the study further shows that the drive-off frequency can effectively be reduced by focusing on minimising the situations where failures are prone to occur, i.e. situations where the relative motions of the shuttle tanker and FPSO are large. Such situations are further explored by the study in a time-domain simulation code, SIMO, which`s result show that e.g. coordination of the mean heading between the FPSO and shuttle tanker, and dedicated DP software for tandem offloading, can effectively minimize the relative motions.

The recovery phase comprises the recovery actions of the FPSO and shuttle tanker to avoid the collision, the focus in this study being on shuttle tanker DPO initiated actions. The available response time for the DPO, i.e. the time available for initiating recovery action in order to prevent contact between the vessels, is assessed to be marginal. The information processing phases of the DPO, in relation to initiating action when faced with a drive-off scenario, is modelled using an information-decision-execution model. The model result is further used along with expert judgment and results from a survey among DP officers and shuttle tanker captains, to find realistic estimates of the time window necessary for the operator to initiate recovery action.

The results from the assessment of the recovery phase indicated that the time window available for recovery action initiation was insufficient, suggesting that incidents of failed recovery action may be the consequence of insufficient time for the operator to initiate action. Based on this, it is recommended that the time window available for recovery action initiation should be increased. The effect from substantially increasing the distance separating the FPSO and shuttle tanker during offloading, is further investigated. Numerical estimates for necessary separation distances are obtained based on parametric drive-off simulations in which the operator reaction time is varied. It is suggested that the results can be used in selecting optimal field configuration for FPSO – shuttle tanker tandem offloading.

The study further recommends that the DPO should be assisted in initiating recovery action, since the reaction time can be reduced by means of early detection and/or reduced decision-making time. Various measures to reducing the time for detecting and diagnosing signs of abnormal vessel behaviour, as well as means for increasing situational awareness, are identified and discussed. The human factor perspective of the collision in FPSO-shuttle tanker tandem offloading operations is particularly elucidated by the findings of the investigation, e.g. procedures, training of personnel and MMI.

4.3 RISK ANALYSIS

In order to enable comparison of the risk levels presented in this thesis against the results of (Chen, 2003) and (Vinnem et al., 2003b), the analysis of the collision risk is performed using the same framework as the aforementioned studies. This involves investigating the risk by applying both quantitative and qualitative methods.

This thesis' qualitative risk analysis encompasses an assessment of HOFs and technical factors, as well as a barrier analysis. The quantitative risk analysis encompasses an investigation of incidents and collisions, using a collision frequency model and simple statistical analysis. Moreover, the quantitative analysis covers all reported incidents on the UKCS and NCS in the time period from 1995-2013, and was performed using Microsoft Excel. The specific framework and models applied is outlined in the following sections.

4.3.1 Describing the shuttle tanker collision hazard

The theory presented in this section is forms the basis for the subsequent section, which deals with HOFs and technical factors in tandem offloading operations

(Vinnem et al., 2003b, Chen and Moan, 2002) found the prevalent understanding of the FPSO-shuttle tanker collision hazard, viewing it as being almost completely determined by the shuttle tanker`s operational and technical capabilities, to be an oversimplification, that neglects the human factor. Applying the classifications of (Vinnem et al., 2003b, Vinnem, 2013a, Chen, 2003), the tandem offloading collision failure model, for a scenario where the collision is initiated by a shuttle tanker drive-off, is divided in two phases with the following characterising parameters:

- The *initiation* phase, where the shuttle tanker has an uncontrolled powered forward movement (UPFM), i.e. drive-off. Characterising parameter: Resistance to drive-off.
- The *recovery* phase, where the recovery action proves insufficient for avoiding a collision, i.e. failure of recovery (FOR). Characterising parameter: Robustness of recovery.

The characterising parameters can then be applied in order to assess the influence of various field configurations for FPSO – shuttle tanker offloading, on both HOF and technical related aspects of the collision risk. Table 6 provides an overview of the parameters and related factors in the collision failure model in tandem offloading operations. As seen from the table, the failure frequency of both the shuttle tanker and FPSO is dependent on the DPO/station-keeping operator, as well as the possibility of the main engines, control systems or reference systems suffering a breakdown.

(Vinnem et al., 2003b) found that the shuttle tanker is especially vulnerable to drive-off when there is excessive relative motion, i.e. yaw and surge motions, between the shuttle tanker and FPSO. In such situations, the shuttle tanker may have e.g. insufficient thruster capacity, causing a heading deviation, upon which DPO may choose to take manual control. Thus, there is a subsequent increased risk of technical failure or erroneous action. Further, (Chen and Moan, 2005) found that surging and yawing of the FPSO has a significant contribution to the occurrence of situations where there is excessive relative surge and yaw motions.

Table 6: Definition of parameters and related factors in collision failure model for tandem offloading (Vinnem, 2013a).

Phase	Characterising parameter	Related factors
'*Initiation phase*'	'*Resistance to drive-off*': Factors concerning the control of vessel movements, on both FPSO and shuttle tanker.	For shuttle tanker: ▪ Station-keeping system, i.e. DP, PRS(s), vessel sensors, main CPP(s), thruster(s), and related propulsion systems. ▪ DPO. For FPSO: ▪ Station-keeping system, i.e. DP (if present), main CPP(s), vessel sensors, thruster(s), and related propulsion systems. ▪ Station-keeping operator.
'*Recovery phase*'	'*Robustness of recovery*': Factors concerning the shuttle tankers ability to initiate successful recovery in drive-off situations, i.e. initiate collision-avoiding actions upon a drive-off.	Available time (time window): ▪ FPSO – shuttle tanker separation distance ▪ DP class and capacity of main propulsion system of the shuttle tanker. ▪ Operational phase Necessary time for initiating action: ▪ Alarm design and setting ▪ Level of attention and job attitude. ▪ Training and operational experience of operator (operator competence).

In relation to parameter 'Robustness of recovery', it is worth noting that the recovery actions are initiated and performed by the shuttle tanker DPO. Due to the aforementioned and the limited time available for action initiation in order to be able to avoid a collision, the human action-time perspective is relevant for addressing the robustness of recovery. Such a perspective provides a tool for determining what factors influence the time available for action initiation (time window) and what factors influence the time needed for the DPO to initiate action (reaction time). It is assumed that the robustness of recovery is greater the longer the time window and/or the shorter the reaction time (Vinnem, 2013a).

Based on HOFs and technical factors, it is possible to assess the DPO`s information processing when facing drive-off scenarios. (Chen, 2003) presented an Information-Decision-Execution model for such purposes, as shown in Figure 14. The first stage of the model addresses how the DPO becomes aware of the drive-off. This involves detecting and observing abnormal signals, e.g. the DPO may observe a sudden increase in thruster output on the DP control panel (detection), upon which he may start actively searching for information to what is causing it (observation). The second stage of the model addresses how the DPO processes the information (state evaluation) and decides on what task(s) he considers the appropriate response to the situation (task formulation). This involves assessing the criticality of the situation and the available response time. The third stage of the model addresses how the DPO performs and confirms the execution of the task(s) he has decided on, i.e. how the formulated tasks are converted into a series of muscle commands, upon which the DPO verify that the execution is accomplished.

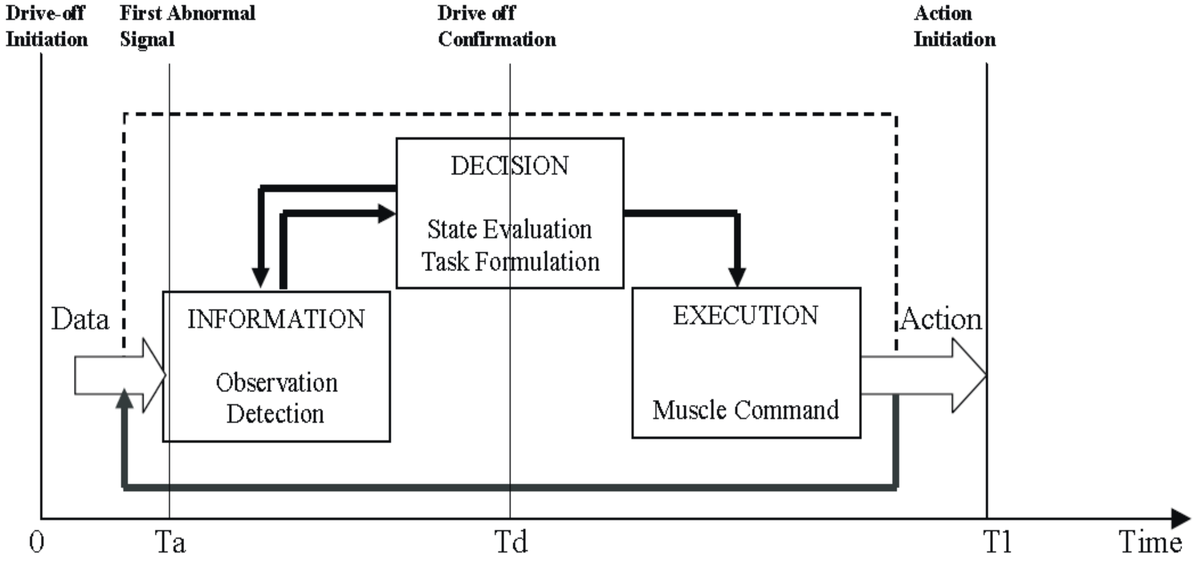

Figure 14: Information-Decision-Execution model for DPO reaction in drive-off scenarios (Chen, 2003).

4.3.2 Human, organisational, and technical factors in offloading operations

In the following section, selected human, organisational, and technical factors are assessed in relation to their relevance in tandem offloading operations. As previously stated, this thesis applies the system approach, more specifically it applies the sociotechnical system model as presented in (Grech et al., 2008), which was outlined in Section 3.2.2. The assessment is further based on the findings of (Vinnem et al., 2003b), as presented in Section 4.2.3. The study found that in relation to the collision risk in offloading operations, the immediate causes could be associated with technical dependability RIFs, human/Operational dependability RIFs and external conditions RIFs. Moreover, their observations indicated that the main contributors to drive-off incidents are 'shuttle tanker positioning and control system', 'shuttle tanker crew competence', 'FPSO positioning and control system', and 'shuttle tanker work organisation'.

Individual factors

Performing operations in a maritime environment implicates the use of multiple human abilities, e.g. human senses, perception, situation awareness, decision-making, physical strength and motor skills. Moreover, the aforementioned abilities are influenced by personal factors (e.g. age, gender.), maritime experience level, transient forms of impairment (e.g. fatigue, drugs.), and permanent forms of impairment (e.g. medically related disorders) (Grech et al., 2008). Thus, the concept of performance-shaping factors, i.e. features influencing the operators' performance when carrying out tasks, is vital for understanding how human factors influence offloading operations. In the following, performance-shaping factors found relevant for the DPO are reviewed, i.e. factors relating to work-rest cycles, mental workload and psychological stress.

In relation to work-rest cycles, general fatigue is highly important. General fatigue can be viewed as the effect of the accumulated stresses inflicted on the operator on an everyday basis, which includes the intensity and duration of mental work, time of the day the work is performed, as well as the operator's prior amount of sleep. Such factors must be balanced by restitution (Grech et al., 2008). During offloading operations, the operator is likely to be negatively influenced by all of the aforementioned stresses, implying the possibility of fatigue reducing their work performance. The nature of offloading operations demands for a DPO to monitor the shuttle tankers position for the entire duration of the operation, a task that normally requires high levels of concentration. Additionally, offloading operations are often performed at night, a time of the day, which is associated with reduced human alertness. Although the shuttle tanker is in auto DP mode, the DPO must stay alert and be prepared to respond swiftly upon position abnormalities. Consequently, long continuous hours on watch-keeping duty and night-time operations can reduce the DPO`s operational performance, which may further have an impact on the operational risk. As it has been found difficult to measure operator fatigue's contribution to accidents directly, quantifications are commonly based on operator performance measures and subjective ratings.

Mental workload describes the degree of mental effort required by an operator when performing his duties and it increases along with the work tasks' complexity. Moreover, the mental workload in marine operations is dependent on a number of factors, which includes the number of tasks to be performed, time allocation for completing tasks, level of task difficulty, required degree of accuracy/proficiency, individual factors, and factors related to the working environment. By reviewing the aforementioned factors, it is clear that an operator facing a high workload has the option to compensate by increasing the effort or by reducing task performance (Grech et al., 2008). As mentioned in Section 2.4.4, during offloading operations, the DPO must continuously monitor several parameters, presented on multiple displays. Due to the long duration of offloading operations and the use of auto DP mode, the DPO will experience long periods of inactivity. This can lead to the DPO becoming distracted from his work tasks, which poses a risk, especially when considering a drive-off scenario. In addition, shuttle tanker DPOs have described that it is not uncommon for various low-level alarms to go off frequently on the bridge, and the DP system`s user interface is often designed so that it is not possible to separate a high-level alarm from a low-level alarm (SMSC, 2014). Hence, the alarms can be a major source of distraction to the DPOs.

Psychological stress onboard marine vessels can be described as when crew members perceive it as being impossible, or nearly impossible, to accommodate tasks and demands (internal and/or environmental). This can may cause the crew to neglect aspects of their tasks, as psychological stress is prone to inflict a narrower focus on the affected individual (Grech et al., 2008). As DP systems are becoming increasingly more advanced, the demands for the DPOs' system understanding also increases. This may inflict stress, especially on less experienced DPOs. Moreover, considering a drive-off scenario, there may be multiple alarms sounding (e.g. position warnings and warnings related to the imminent cause of position loss). The DPO will be fully aware of the time pressure for initiating emergency action. However, as it is first necessary to identify what is the correct emergency response, the DPO is likely to be under immense psychological stress. This may impede his situational awareness and obstruct the process of initiating emergency action.

Communication and collaboration

The close proximity of the vessels involved in tandem offloading operations demands for effective collaboration and comprehension between the personnel involved. Thus, it is important that the personnel have insight and sufficient information about relevant operational aspects concerning both vessels, not just their own. As stated by (Grech et al., 2008), good communication and team collaboration is essential to the vessels' safety, as failure of such may lead to accidents.

In any phase of dual vessel operations, operational procedures should be discussed and agreed to by appropriate representatives from both vessels (IMCA, 2007). This is important as shared knowledge and mutual context of the participants involved in human communication, is fundamental to the meaning and understanding of what is communicated (Grech et al., 2008).

On board the DP shuttle tanker, the master is the person responsible for the safety and operations. This includes both the vessel and the crew. He is further responsible for coordinating his vessel`s operations with other vessels participating in dual vessel operations. On board the FPSO/FSU, the commanding officer is the offshore installation manager. He enjoys the same responsibilities as the master on board the shuttle tanker. Furthermore, both the master and offshore installation manager has the power to abort operations if they think that the safety of personnel, vessel, equipment or environment is compromised (IMCA, 2007).

Training of personnel

Investigations of previous accidents have shown that operator action is essential for the outcome of a position incident. Thus, human operator risk control is tremendously important (Vinnem, 2013b). There is a relatively short time window available for the operator to detect, make a decision, and initiate recovery. Consequently, training of DP personnel is important factor for offloading operations.

It is critical that the DPO has an in-depth understanding of the vessel`s behaviour, i.e. how the vessels inertia influences the vessel`s stopping distance and how the vessel gains momentum upon a sudden increase in thruster pitch or power (IMCA, 2007). This is further supported by (SMSC, 2014), describing the biggest risk factors in tandem offloading operations to be inexperienced personnel facing a drive-off scenario, and their understanding of the shuttle tanker`s motions. (IMCA, 2007) further states that the necessary level of training and experience of DPOs on a specific vessel may vary, but ensuring sufficient training of DPOs is nonetheless key to performing safe and reliable operations. It is further stated that complete records of key DP personnel`s training and experience should be kept for competence assurance. This is further supported by (Daughdrill and Clark, 2002), stating that because incorrect human intervention potentially can initiate a drive-off scenario, it is critical to ensure adequate training and operation of officers involved in vessel position-keeping related activities.

Human-Machine Interaction (HMI)

Human interaction with technology plays a fundamental part of modern maritime operations, e.g. computers, navigational equipment, advanced DP systems and communication have all become standard features of modern DP shuttle tankers. As the vessels become more technically advanced, it is vital to ensure that the technology is adapted to the operators' skills, capabilities, and limitations. Moreover, the technology must be integrated with the work system onboard the vessels (Grech et al., 2008). The interaction between technology and individuals are referred to as Human-Machine Interaction (HMI) or Man-Machine Interaction (MMI_2).

(Grech et al., 2008) presents a several issues relating to HMI. For DP shuttle tanker tandem offloading operations, the author has found the following HMI issues relevant: equipment usability, ergonomic equipment design, training and support of operators, operators' reliance and dependency on technology, integration of new technology, and consideration of human factors aspects when developing new technologies.

Equipment usability describes the degree to which the operator can apply a product swiftly and easily (Grech et al., 2008). Absence of usability in technology may understandably be a hinder to efficiency and become a source off errors. For DP operated vessels, it is very important for the user interface to be designed so that the DPO can effortlessly monitor parameters relevant to position keeping and make adjustments if necessary.

Automation is widely applied in many ship technologies, e.g. AIS, electronic navigation charts, DP systems. The use of such technologies increases technologic dependency, which may be a source of system vulnerability, e.g. if the technology is causes confusion to the operator or malfunctions. (Bainbridge, 1983) states that process automation may increase problems relating to human operators, instead of removing them. Moreover, it is stated that as system designers frequently seek to remove the human intervention to the largest extent possible, they still end up leaving the operator to perform the tasks that they are unable to remove. Several ironies of automation, relevant to DP offloading operations, are also presented; automation may cause degradation the operators manual control skills and obscure the operators' overview of the process control. The first mentioned could be especially critical in a drive-off scenario, as the

DPO`s may not respond as efficient. The second mentioned may also have an impact on the DPO`s response as he may be unaware of the exact system state, due to him only passively monitoring the DP system. Furthermore, automation may cause alteration of the task it was designed to support, introduce new types of human error, and reduce the operators possibilities for detecting errors and initiate recovery (Grech et al., 2008).

Design and integration of technology

Section 2.4.4 provided a description of the bridge onboard a shuttle tanker, featuring a variety of controls and displays. Optimal design of controls and displays is key to ensure safe and reliable ship operations. The level of effort and the amount of time that is necessary for a crewmember to respond to an event depends on multiple factors, i.e. the degree of prior experience with the systems, the complexity of the decision, the degree of correlation between the required response action and the event causing the need for action, how expected the event was to the crewmember, and the degree of feedback given. Moreover, the crewmembers response time is dependent on the controls' and displays' compatibility, i.e. the displays' location relative to their associated displays, and the specific control actions needed in response to the displays (Grech et al., 2008). E.g. if the DPO is required to take manual control during offloading operations, he must also be able to observe relevant data about the shuttle tanker`s machinery, DP status, PRS status, etc., simultaneously as he is using joysticks to control the vessel. Facilitating the aforementioned has implications for the bridge layout. In addition, the DP-controller's response should ideally match the DPO`s expectations for the response. (Grech et al., 2008) states that due to the increasing prevalence of one-man bridge operation, and navigational systems and piloting components becoming increasingly integrated, optimisation of the displays and controls is possibly more crucial than ever.

In terms of DP operations, visual warnings and audible warnings (i.e. alarms) are exceptionally important. As there are numerous shipboard systems operating simultaneously, warnings are essential to alert the DPO of abnormalities in the systems. Moreover, warnings must fulfil two critical objectives, i.e. attract attention and provide understandable information so that the operator can initiate the right corrective action, and their efficiency is influenced by their positioning, size and intensity (Grech et al., 2008).

4.3.3 Barrier analysis for drive-off scenario

The bow-tie method is found to be suitable for investigating the drive-off scenario. This thesis applies the same main analytical principles as (Vinnem et al., 2003b), using RIFs to investigate the collision frequency in FPSO – Shuttle tanker operations, in relation to barriers. Further, the basis for this thesis' selection of elements to include in the barrier analysis, is the assessment of HOFs and technical factors presented in Section 4.3.2, as well as a influence diagram for the shuttle tanker-FPSO collision risk during tandem offloading operations[7] presented in (Vinnem et al., 2003b). The barrier analysis is further inspired by the work of (Henningsgård, 2013).

As described in Section 4.3.1, the collision risk failure model for a drive-off scenario can be divided into two phases, the initiation phase and the recovery phase. In line with the rest of the thesis, only the drive-off forward scenario is considered. Further, using the bow-tie perspective to examine the drive-off scenario, the event also can be divided into two stages accordingly:

- Left hand side:
    - Initiation phase: How can a drive-off be prevented?
- Right hand side:
    - Recovery phase: What recovery actions can be initiated to avoid collision?

The bow-tie analysis will focus on preventing an uncontrolled powered forward motion of the shuttle tanker (drive-off forward) leading to a collision. Hence, it should be noted that the barrier analysis is limited to the recovery phase, i.e. barriers for avoiding a collision *after* a drive-off has been initiated. As this is a coarse risk assessment, technical considerations of the identified barriers are not provided. Furthermore, it does not consider safety barriers relating to the process of offloading hydrocarbons, e.g. loading hose, emergency shutdown valves, etc.

As presented in Figure 15, the TOP event in this barrier analysis is 'DP shuttle tanker drive-off forward, whilst offloading in the North Sea', and three barrier systems are included in the analysis, i.e. alarms, automatic recovery, and manual recovery.

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[7] Included in appendix A5.

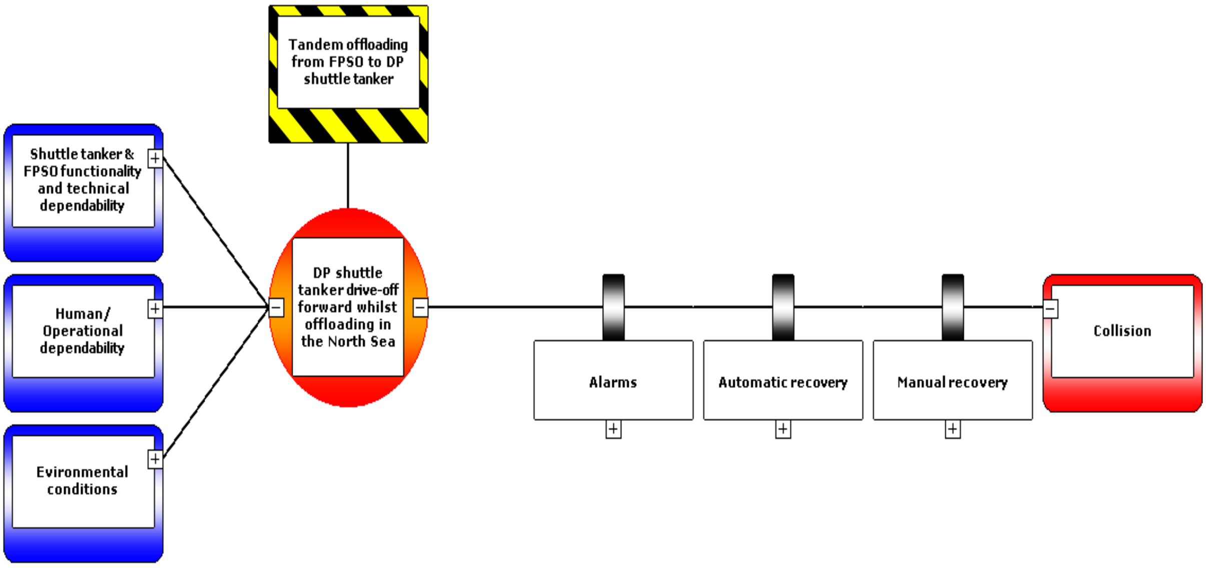

Figure 15: Bow-tie for recovery phase in drive-off scenario, overview.

Alarms

In this context of the drive-off scenario, alarms are technical barriers designed to respond to position loss. As shown in Figure 16, two main barrier-influencing factors have been identified:

- No alarm.
- DPO does not respond to alarm.

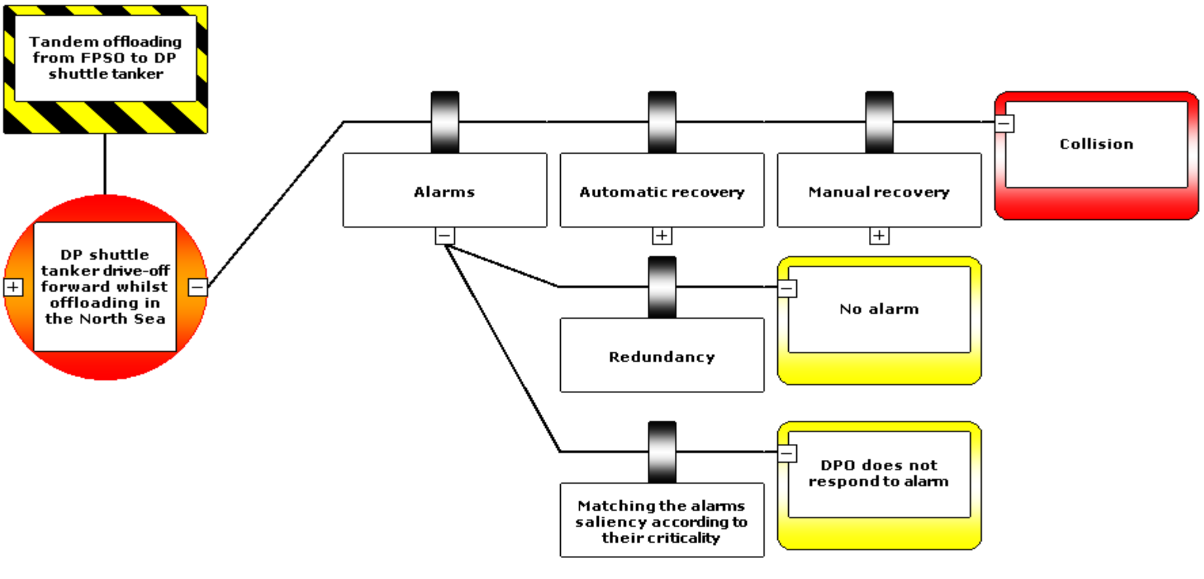

Figure 16: Bow tie for recovery phase in drive-off scenario, alarms.

Section 4.3.2 provided a discussion of alarms and their influence in a drive-off scenario, and the subject is thus only discussed briefly in the following. If the alarm does not sound, the DPO may use longer time identifying a position loss, which implies a longer reaction time. This may lead to there being insufficient time for the DPO to initiate recovery action. Hence, there ought to be redundancy for the alarms, in order to reduce the likelihood of no alarms sounding. Further, if a DPO has problems understanding the criticality of an alarm, he may not respond efficiently to the situation, which can also increase the reaction time. Thus, the alarms' saliency should match their criticality.

Automatic recovery

The short window of time available for initiating recovery action in a drive-off scenario is a major issue for a human operator. Therefore, an automatic recovery system ought to be in place, initiating recovery action almost immediately upon an alarm for position loss. As shown in Figure 17, one main barrier-influencing factor has been identified:

- DP system failure

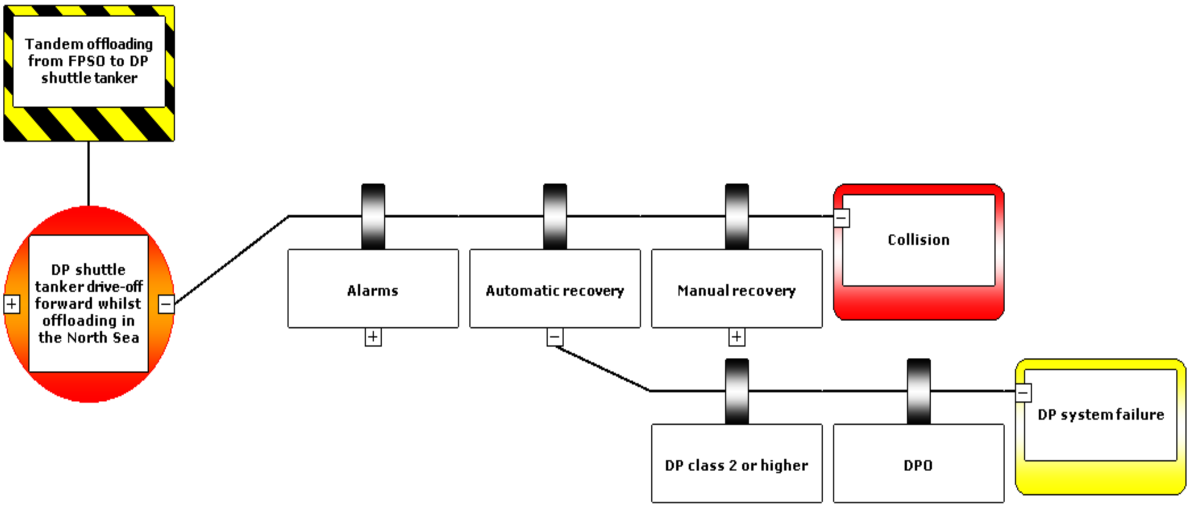

Figure 17: Bow-tie for recovery phase in drive-off scenario, automatic recovery.

The DP system will perform corrections to the shuttle tanker`s position and thus it ought to have DP class 2 or higher, in order to increase its reliability. Moreover, the DPO will monitor the recovery process and be ready to perform manual recovery upon a DP system failure.

Manual recovery

The final barrier system in this barrier model is manual recovery, which involves the DPO taking full control over the shuttle tanker`s manoeuvring. As shown Figure 18, three main barrier-influencing factors have been identified:

- DPO situational awareness
- DPO performance
- ST heading towards FPSO

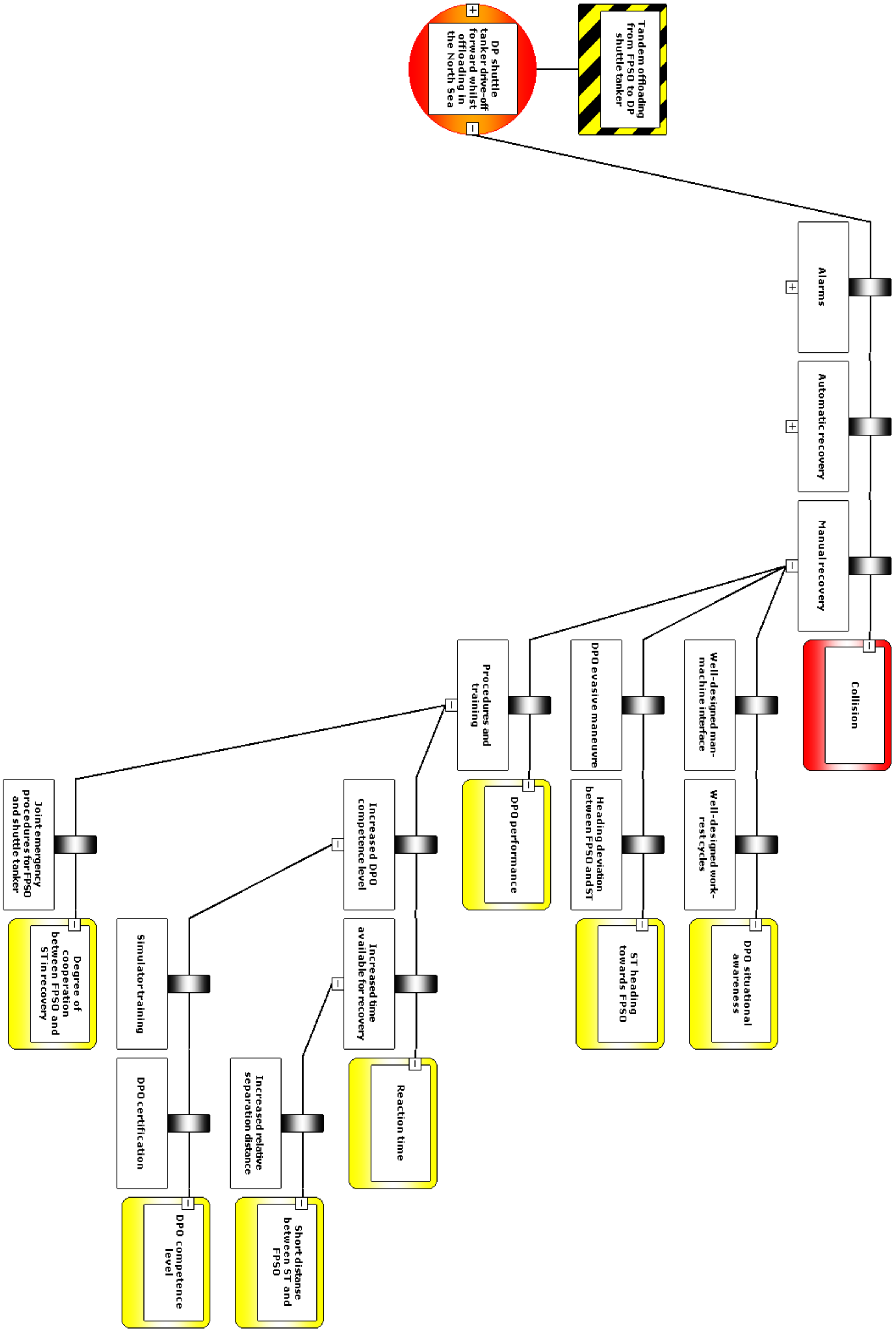

Figure 18: Bow-tie for recovery phase in drive-off scenario, manual recovery.

The first two factors have already been discussed in Section 4.3.2, and hence they are only discussed briefly in the following.

DPO situational awareness

The design of the man-machine interface and work-rest cycles has been identified as the main barrier elements. When the DPO is required to take manual control, he must also be able to observe relevant data about the shuttle tanker`s machinery, DP status, PRS status, etc., simultaneously as he is using joysticks to control the vessel. Facilitating the aforementioned has an important role in the design of the man-machine interface, which can further have an effect on the DPO`s situational awareness.

The design of DPOs' work-rest cycles is important as it can have a large impact on their general fatigue. Poorly designed work-rest cycles may cause the DPO becoming negatively influenced by stress, implying the possibility of fatigue. Moreover, long continuous hours on watch-keeping duty and night-time operations can reduce the DPO`s alertness, which may further cause the DPO to become distracted and reduce his situational awareness.

Shuttle tanker heading towards FPSO

As the shuttle tanker is positioned with its bow heading towards the FPSO`s stern during tandem offloading, it also implies the two vessels being on collision course when a drive-off is initiated. In relation to this, two barrier elements were identified, DPO evasive manoeuvre and having a heading deviation between the FPSO and shuttle tanker.

DPO performance

The main barrier elements identified for DPO performance are procedures and training, which was discussed in Section 4.3.2. The DPO`s reaction time and the degree of cooperation between FPSO and shuttle tanker in the recovery, are of vital importance for avoiding collision. The DPO`s reaction time could be addressed by ensuring that the DPO competence level increased through certification standards and simulator training. Moreover, by increasing the relative separation distance, the available time for recovery will also increase. Lastly, the cooperation between FPSO and shuttle tanker in the recovery phase could be improved by establishing joint emergency procedures for FPSO and shuttle tanker.

4.3.4 Collision frequency model

In order to estimate the collision frequency for shuttle tankers performing tandem offloading from FPSO, one must first determine the approach for investigating the collision risk. This means deciding on whether to model and analyse the risk using a probabilistic model (e.g. as (Chen and Moan, 2004)), using statistical methods (e.g. as in (PSA, 2014a)), or using a combination of the two aforementioned. Regardless of the chosen methodology, it is essential that the approach covers the nature of such operations and provides an unbiased presentation of the results. This could involve considering the frequency of offloading operations, length of stay during field visits, separation distance between shuttle tanker and FPSO during operations, etc. This thesis applies the collision frequency model of (Chen and Moan, 2004) , as presented in equation (2).

$$Pr(collision) = Pr(UPFM) \cdot Pr(FOR|UPFM) \tag{2}$$

where:

$Pr(UPFM)$ = probability that the shuttle tanker has an uncontrolled powered forward movement, a drive-off.

$Pr(FOR|UPFM)$ = probability that the recovery action proves insufficient for avoiding a collision, i.e. a failure of recovery.

It is a probabilistic model for collisions between DP shuttle tankers and FPSOs during tandem offloading. However, it is important to highlight that in practise, there is not possible to perform a real numerical validation of the drive-off probability and the collision probability. Instead, one uses frequencies to note the respective probabilities (Vinnem, 2013a). Moreover, $Pr(collision)$ can also be estimated by dividing the total number of collisions by the total number of offloadings, yielding the same result as equation (2).

Model rationale

The following part of this section provides an explanation and rationale for how the model is applied in this thesis' risk analysis. The rationale for estimating the probabilities is explained based on a general collision probability model presented in (Vinnem, 2013a).

The system investigated in this analysis encompasses the shuttle tanker and the FPSO during all phases of tandem offloading operations, i.e. approach, connection, offloading, disconnection, departure.

Traffic volume

The traffic volume can be estimated based on the frequency of tandem offloading operations at the respective oil fields. A reasonable estimate for the offloading frequency on a particular field can be derived by obtaining statistics of the field's yearly oil production and then divide that number by the storage capacity of the FPSO. The result will provide a conservative estimate for the number of offloadings, as it assumes that the FPSO`s storage capacity is fully utilized, which may not always be the case.

Probability of the vessels being on collision course

A collision between two vessels will not occur unless the vessels are on a collision course, thus in that sense the occurrence of such a situation is a fundamental constraint for collisions. In a general collision model, it is customary to assume that that a vessel will not change its heading towards the platform as long as the installation is observable from the vessel, thus one assumes that the process up until the point of observation determines the probability of a vessel being on collision course, P_{CC} (Vinnem, 2013a). However, in the case of tandem offloading between shuttle tanker and FPSO, this assumption is not applicable. When a shuttle tanker is performing tandem offloading operations, it is in fact required to change its course so that its bow is heading in the direction of the FPSO`s stern. During the approach, this means having a controlled powered forward movement towards the stern of the FPSO until reaching the predetermined separation distance. Further, during the rest of the offloading, up until the point when the shuttle tanker has finished offloading and has changed its course for departure, one must assume that a drive-off situation may be expected at any point. Thus, the probability of the shuttle tanker being on collision course with the FPSO is equal to the drive-off frequency, $P(UPFM)$, which can be estimated from incident statistics. $P(UPFM)$ is thus assumed to be dependent on the time spent offloading, i.e. the frequency of offloadings. The resulting expression for the probability of collision course is then as shown by equation (3):

$$P_{CC} = P(UPFM) = \frac{number\ of\ drive\ off\ incidents}{number\ of\ offloadings} \tag{3}$$

(Vinnem, 2013) states that one aspect of the approach, that might be of concern, is that one assumes the navigator to be performing the approach operation responsibly. Although most navigators will in fact perform the approach in a responsible manner, there might be one individual that does not. That individual is singlehandedly likely to account for 90 % of the collision risk. This is a dilemma when trying to select a representable value for the collision risk. However, as it is impossible to model the behaviour of the irresponsible person, such input is not included in the model.

Probability of failure of shuttle tanker initiated recovery
Following the logic of our adapted model, P_{FSIR} describes the probability of a collision given that the shuttle tanker has experienced drive-off, $\Pr(FOR|UPFM)$, which can be estimated from incident statistics. Thus, we obtain the following expression, equation (4):

$$P_{FSIR} = \Pr(FOR|UPFM) = \frac{number\ of\ collisions}{number\ of\ drive\ off\ incidents} \tag{4}$$

Moreover, it implies that $\Pr(FOR|UPFM)$ is assumed to be exclusively dependent on the recovery actions of the shuttle tanker.

Probability of failure of offshore installation initiated recovery
It is assumed that the offshore installation, i.e. the FPSO, cannot initiate recovery actions to avoid collision, i.e. $P_{FIIR} = 0$. Thus, the only vessel to be included in the model is the shuttle tanker. This assumption is justified by the fact that the FPSO is moored, and that the time available for recovery is in all likelihood too short for the FPSO to be able to disconnect its mooring and change its position. It should be noted that there is the possibility of the FPSO`s crew to become aware of a potential collision first, and then alert the shuttle tanker`s crew. However, it is found difficult to model such intervention accurately, and it is thus not explicitly considered in the model.

Incident frequencies
In order to estimate the incident frequencies, i.e. the drive-off frequency and the collision frequency of DP shuttle tankers during tandem offloading, it was necessary to do extensive research and review of available reports and databases for offshore accidents on the NCS and UKCS. The work of the UK HSE and the Norwegian PSA has provided key in obtaining incident data. This work has further been supplemented by the research of several experts investigating shuttle tanker collision risk, e.g. Professor Jan Erik Vinnem (Preventor, NTNU), Dr. Haibo Chen (Scandpower) and Arne Kvitrud (PSA). However, the extent of the available and applicable data for incidents on the UKCS post 2007 and on the NCS post 2011 is limited. As pointed out by (Chen, 2003), DP Shuttle tanker tandem offloading operations from FPSO/FSU was not performed on a large scale before the mid-1990s, thus making it difficult to obtain detailed statistics for tandem offloading operations performed prior to this. In addition, as mentioned in Section 4.1.3, drive-off incidents not resulting in collisions may not have been

reported. Further, the technical and operational systems applied in the past may differ from current systems that are more sophisticated.

When assessing frequencies, the choice of how to denote the frequency is very important. The general definition of frequency is ‘the number of occurrences of a recurring event per unit time’. In the field of statistics, the definition is slightly modified, expressing frequency as the number of occurrences of an event in a study. Thus, the definition is adapted to account for the finite length and size of the time interval and population size of the study. For the purposes of this thesis, relevant frequency denotations include ‘per installation year’ and ‘per offloading operation’. However, as stated by (Vinnem, 2013a), the frequency of offloading operations greatly varies between different installations, ranging from a dozen times a year to several times per week, thus making per ‘installation year’ a fuzzy expression of the collision risk. It would imply defining an ‘average installation’, which would not be representable for any actual existing installation. Moreover, it complicates comparison between different installations. Hence, it is found that ‘per offloading’ is the best way to denote the frequency, accounting for the individual oilfield`s characteristics whilst simultaneously enabling intercomparison.

Deriving the number of offloading operations

In order to find an estimation for the number of offloading operations performed each year, it was first necessary find the production figures from the relevant oil fields on the UKCS and NCS. This was obtained through the publicly available databases of the UK Department of Energy & Climate Change (DECC) (DECC, 2014) and the NPD (NPD, 2014) respectively. The number of offloading operations for a particular FPSO was then obtained by dividing the production figures from its associated oil fields, by the FPSO`s storage capacity. Complete production and offloading statistics for FPSOs/FSUs on the UKCS & NCS, covering the time period from 1995 to 2013, is included in Appendix A6.

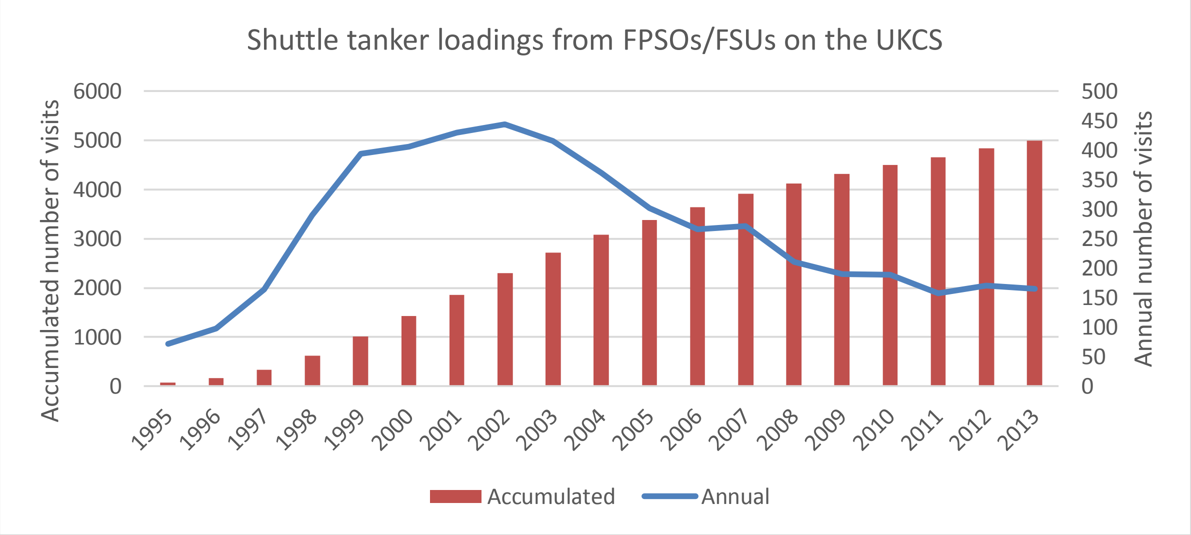

Figure 19: Shuttle tanker offloadings from FPSOs/FSUs on the UKCS.

Figure 19 shows the number of shuttle tanker offloadings from FPSOs/FSUs on the UKCS in the period 1 January 1995 to 31 December 2013. The total number of offloading operations is estimated to 5001 operations. As mentioned in Section 2.3.1, there are a substantial number of fields on the UKCS that uses taut hawser based offloading. These fields have been excluded from the volume of offloading operations presented above.

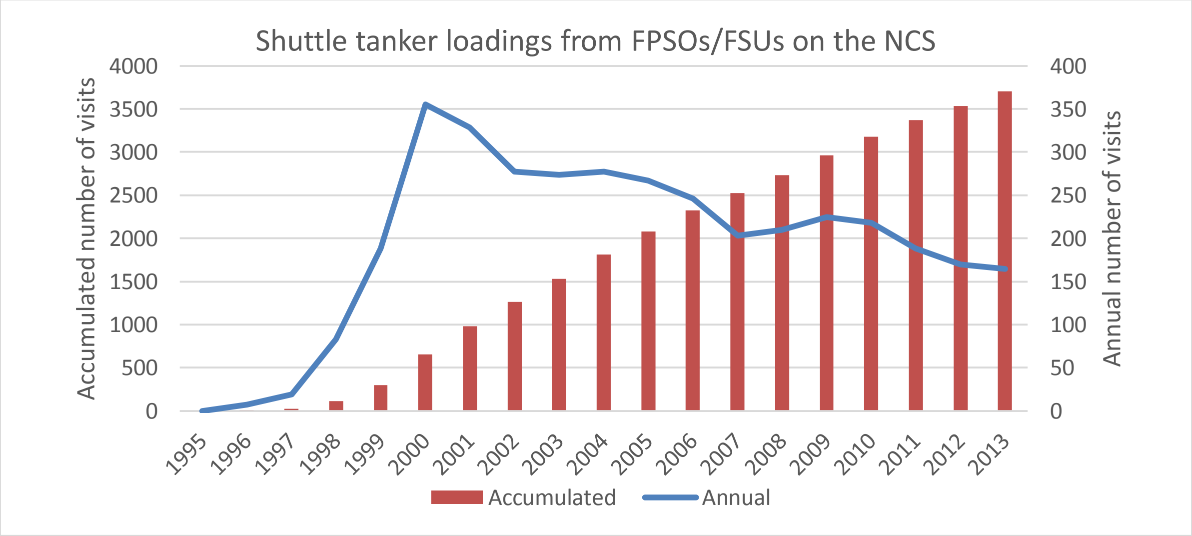

Figure 20: Shuttle tanker offloadings from FPSOs/FSUs on the NCS.

Figure 20 shows the number of shuttle tanker offloadings from FPSOs/FSUs on the NCS in the period 1 January 1995 to 31 December 2013. The total number of offloading operations is estimated to 3701 operations. There is one field on the NCS that uses taut hawser based offloading, the Glitne field, and it has been excluded from the volume of offloading operations presented above.

4.3.5 Statistical analysis of trends

When assessing trends relating to incident frequencies, it is important to ensure that the statistical analysis is unbiased, i.e. ensuring that no statistic is calculated in a way that produces inferences that consistently underestimate or overestimate the population's characteristics (Walpole et al., 2007). Further, it is key to eliminate any sources of "false signals", thus ensuring that the trends demonstrated are representative for the development on the UKCS & NCS. Statistical normalization is important in this relation, enabling frequency comparison based on a normalised parameter, e.g. frequency of incidents per offloading (PSA, 2014b).

The trend analysis of the incidents is in this thesis is performed using 90% prediction intervals, which enables identification of possible trends based on comparison between the observed value and the prediction interval. Comparison of observed values and the prediction interval is to be interpreted as follows:

- If the observed value lies in the lower region of the prediction interval, the observed value is significantly lower than the average for the period witch the prediction interval represents.
- If the observed value lies in the upper region of the prediction interval, the observed value is significantly higher than the average for the period witch the prediction interval represents.
- If the observed value lies in the middle region of the prediction interval, the observed value represents no statistically significant change, i.e. there is no statistically observable trend.

The method for calculating the prediction intervals, which was obtained from (PSA, 2014b), is outlined in the following:

Assume a set of measurements for the occurrences in an event category, is recorded in year 1,2,…,k. Further, let x_1, x_2, x_3, …, x_k denote the number of occurrences each year.

A prediction, X^*_{k+1}, for the number of incidents in the present year, X_{k+1}, is then estimated based on the observed values, x_1, x_2, x_3,…, x_k. Moreover, a 90% prediction interval [a,b] is calculated, representing an interval in which it is believed that there is a 90% probability that X_{k+1} will fall within.

The Poisson distribution is then applied in order to express uncertainty, i.e. the number of incidents in the present year is predicted using the average of the previous years, and the uncertainty is given by the Poisson distribution. The rationale behind this method is based on one assuming that the occurrence of events is a “stable process”, where the number of events in each interval is relatively constant. Hence, it is reasonable to predict next year`s number of incidents based on the average of the preceding years, and define the uncertainty by the Poisson distribution.

5. RESULTS FROM QUANTITATIVE RISK ANALYSIS

This section provides a statistical presentation and assessment of the overall risk picture in tandem offloading operations between DP shuttle tankers and FPSOs. In order to perform a thorough assessment of possible trends and developments for the incident frequencies, it was found appropriate to first provide an overall assessment, and then examine the incident frequencies before and after the JIP-project report, (Vinnem et al., 2003b), was released. Appendix A7-A11, presents calculations and plots from which the results were obtained. Moreover, this chapter solely presents observations from the statistical analysis. Discussion and interpretation of the data is omitted, as such is addressed in the first section of chapter 6.

Table 7 and Table 8 shows the estimated 90% prediction intervals for selected periods. The numbers inside the parentheses in the tables' period column shows the years from which the average, used to predict the intervals, was created. As seen from the tables, the intervals for the UKCS, the NCS, and the UKCS & NCS aggregated, are equal within the periods 1995-2013 and 2004-2013. Moreover, all of the estimated prediction intervals start at zero. The respective 90% prediction intervals are shown graphically in the right corner of the graphs in Figure 22, Figure 23, Figure 40, and Figure 41.

Table 7: 90% prediction intervals for incident frequency per offloading.

Period	**UKCS & NCS**	**UKCS**	**NCS**
1995-2013 (03-12)	0.0E+00 - 4.2E-03	0.0E+00 - 4.2E-03	0.0E+00 - 4.2E-03
1995-2003 (95-02)	0.0E+00 - 7.0E-03	0.0E+00 - 5.6E-03	0.0E+00 - 5.6E-03
2004-2013 (04-12)	0.0E+00 - 4.9E-03	0.0E+00 - 4.9E-03	0.0E+00 - 4.9E-03

Table 8: 90% prediction intervals for collision frequency per offloading.

Period	**Average interval**	**UKCS & NCS**	**UKCS**	**NCS**
1995-2013	(2003-2012)	0.0E+00 - 4.2E-03	0.0E+00 - 4.2E-03	0.0E+00 - 4.2E-03
1995-2003	(1995-2002)	0.0E+00 - 7.1E-03	0.0E+00 - 5.6E-03	0.0E+00 - 5.6E-03
2004-2013	(2004-2013)	0.0E+00 - 4.9E-03	0.0E+00 - 4.9E-03	0.0E+00 - 4.9E-03

5.1 INCIDENT FREQUENCY

This section presents the results from a statistical analysis of all reported incidents on the UKCS and NCS in the period 1995-2013. The first part of the analysis comprises the entire period, before the two periods 1995-2003 and 2004-2013 are analysed separately.

Table 9 shows all reported incidents involving DP shuttle tankers performing tandem offloading from FPSO on the UKCS & NCS, in the period 1995-2013. The data is sorted by the year the incident occurred, along with information concerning geographic location, phase of operation in which the incident occurred, type of incident, and the shuttle tanker`s DP class. For one incident that occurred in 2003, it was not possible to determine the shuttle tanker DP class.

Table 9: Incidents on the UKCS & NCS 1995-2013.

Year	***Sector***	***Phase***	***Cause***	***Type of incident***			***DP class***
				Near-miss	*Collision*	*Other*	
1996	UK	Loading	DP failure		X		DP1
1997	UK	Loading	Operator error		X		DP1
1997	UK	Loading	PRS failure		X		DP1
1997	UK	Loading	PRS failure			X	DP1
1998	UK	Loading	CPP failure			X	DP1
1998	UK	Loading	Operator error		X		DP1
1999	UK	Approach	DP failure	X			DP1
1999	Norway	Loading	DP failure	X			DP2
1999	Norway	Loading	DP failure	X			DP2
1999	UK	Disconnection	FPSO thrusters tripped	X			DP1
2000	Norway	Approach	DP failure	X			DP2
2000	Norway	Disconnection	Manually initiated drive-off		X		DP2
2000	UK	Connection	Operator error	X			DP1
2000	Norway	Loading	Operator error			X	DP2
2000	Norway	Connection	Technically initiated drive-off	X			DP2
2001	Norway	Loading	PRS/DP failure	X			DP2
2001	UK	Loading	Technically initiated drive-off	X			DP1
2002	UK	Loading	Engine failure			X	DP1
2002	UK	Loading	Rapid wind change	X			DP1
2003	UK	Loading	Technically initiated drive-off	X			?
2004	Norway	Loading	DP failure	X			DP2
2006	Norway	Connection	Black-out		X		DP2
2007	Norway	Loading	PRS failure			X	DP2
2008	Norway	Loading	Rapid wind change			X	DP2
2009	Norway	Loading	Engine failure			X	DP2
2009	Norway	Connection	Operator error	X			DP2
2009	UK	Approach	PRS-failure		X		DP2
2011	Norway	Loading	CPP failure			X	DP2
Total				13	7	8	

5.1.1 1995-2013

In the period 1995-2013, there have been 28 reported incidents involving DP shuttle tankers performing tandem offloading from FPSO on the UKCS & NCS. As shown in Figure 21, the geographical distribution of the incidents is uniform, 14 incidents occurring on each of the continental shelves.

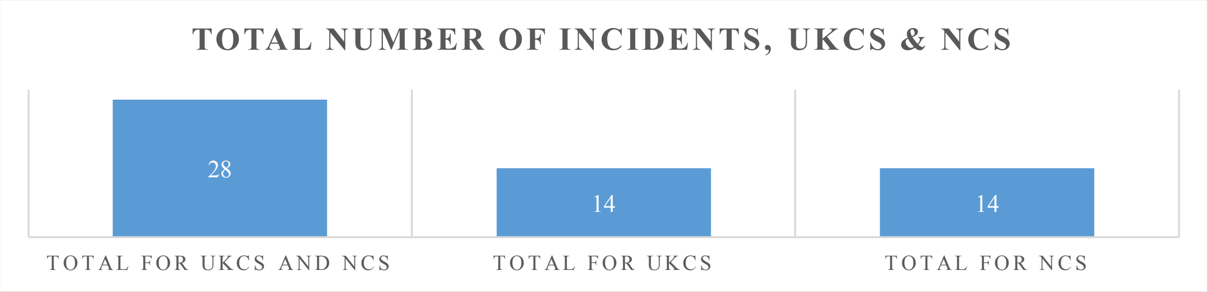

Figure 21: Geographical distribution of incidents, UKCS & NCS 1995-2013.

Figure 22 shows the number of incidents per year on the UKCS & NCS, from 1995-2013. As seen from the figure, year 2013 represents no statistically significant change in the number of incidents compared to the last 10 years. It is worth noting that there has only been one incident during the last four years, and none during the last two years, which may indicate a minor improvement.

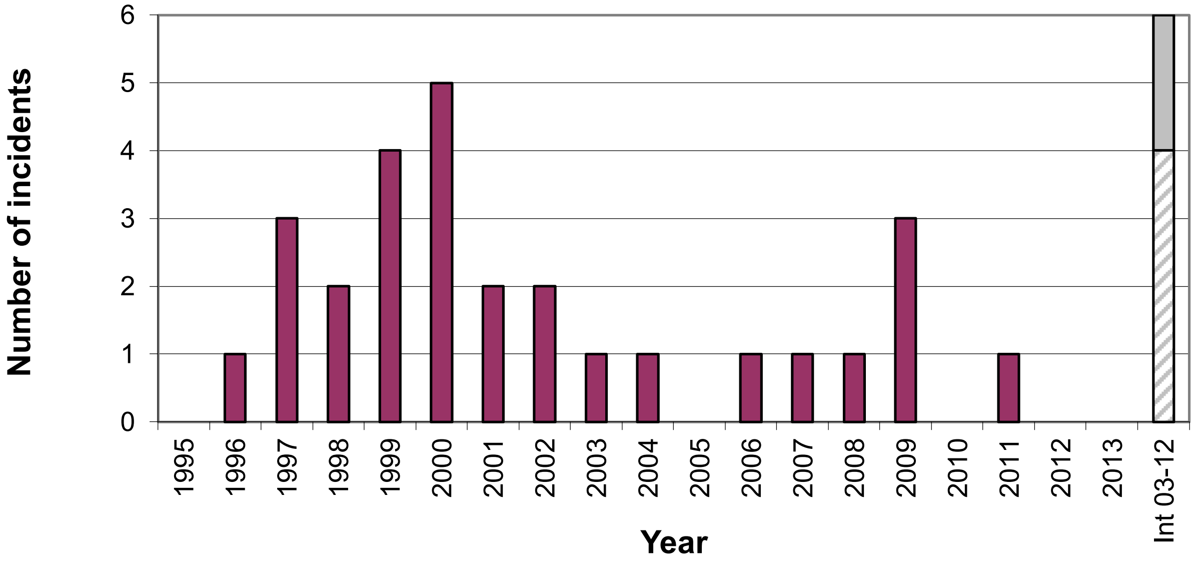

Figure 22: Number of incidents per year, UKCS & NCS 1995-2013.

Figure 23 further shows the number of incidents per year on the UKCS & NCS, normalised per offloading. The incident frequency has been considerably reduced since its peak year in 1997 (1.6E-02 incidents per offloading). It is not possible to determine if there has been a statistically significant reduction in 2013, nonetheless it appears that the incident frequency has improved slightly.

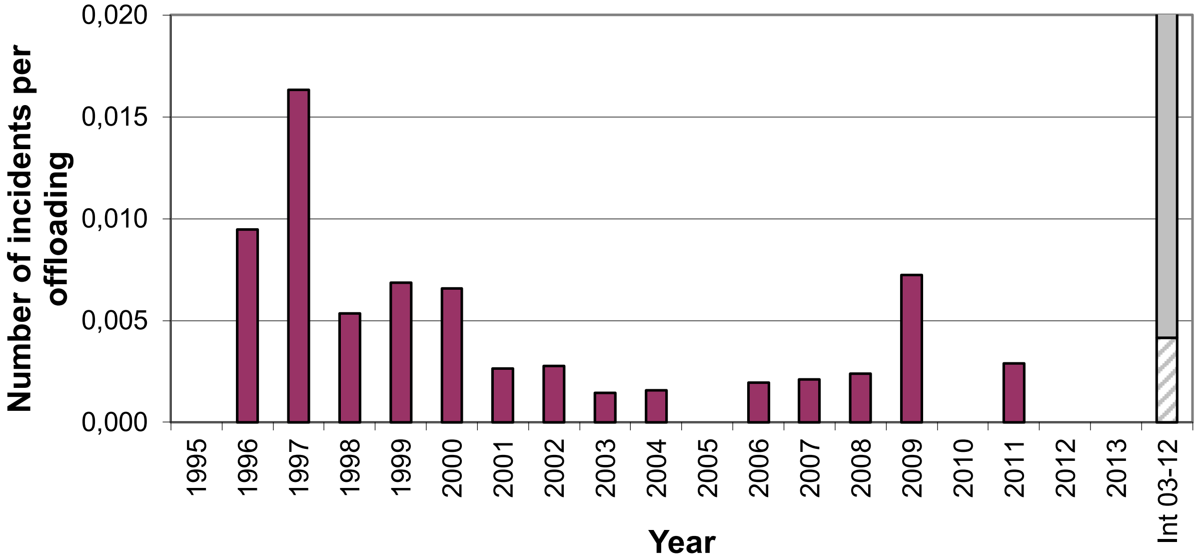

Figure 23: Number of incidents per offloading, UKCS & NCS 1995-2013.

The distribution of incidents between each operation phase, as presented in Figure 24 show that there is a predominance of incidents occurring during loading, representing approximately 68% (19/28) of the incidents.

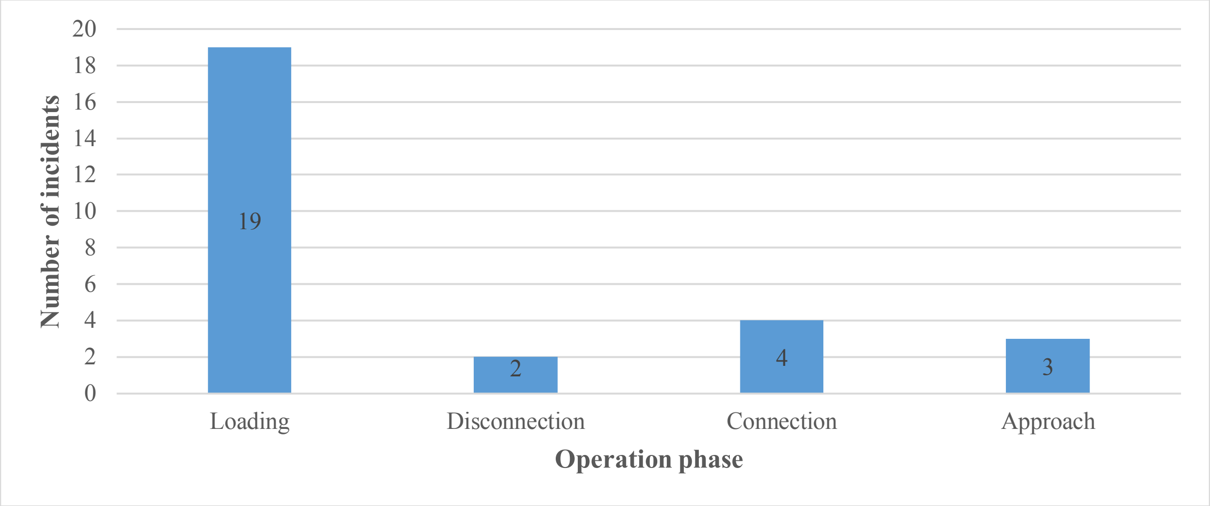

Figure 24: Number of incidents per operation phase, UKCS & NCS 1995-2013.

The distribution of incidents per failure cause on the UKCS & NCS, as presented in Figure 25, shows that DP failure [21% (6/28)], PRS failure [18% (5/28)] and operator error [18% (5/28)] occur most frequent.

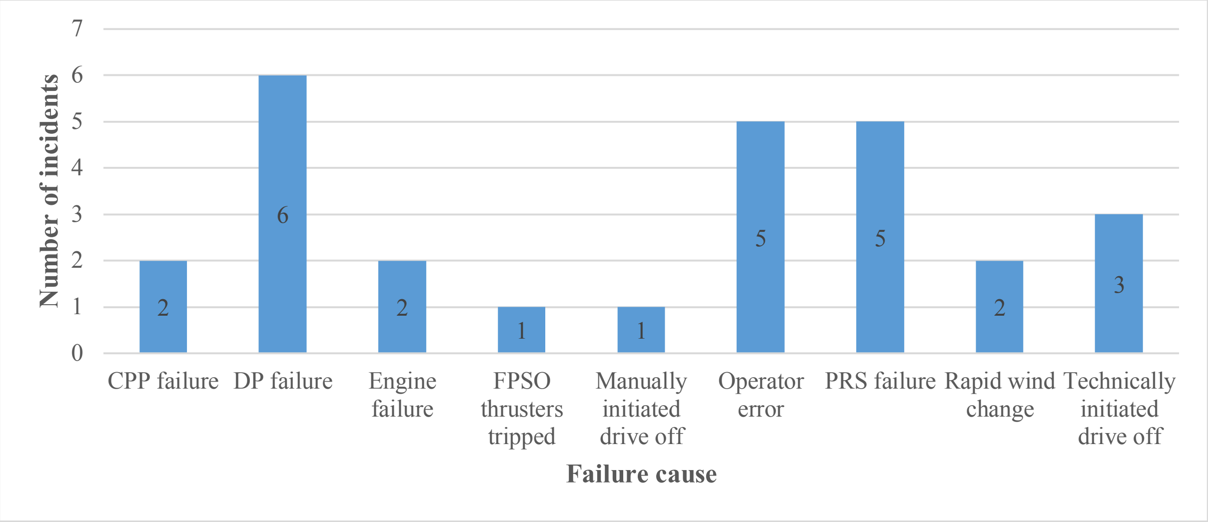

Figure 25: Number of incidents per failure cause, UKCS & NCS 1995-2013.

A further breakdown of the incidents according to their geographical distribution was made in order to investigate possible geographical differences. As shown in Figure 26, there is little variation between the two continental shelves in relation to which part of the operation the incidents occurred. Incidents have been prone to occur during the loading phase on both the UKCS and NCS, representing 71% (10/14) and 64% (9/14) respectively.

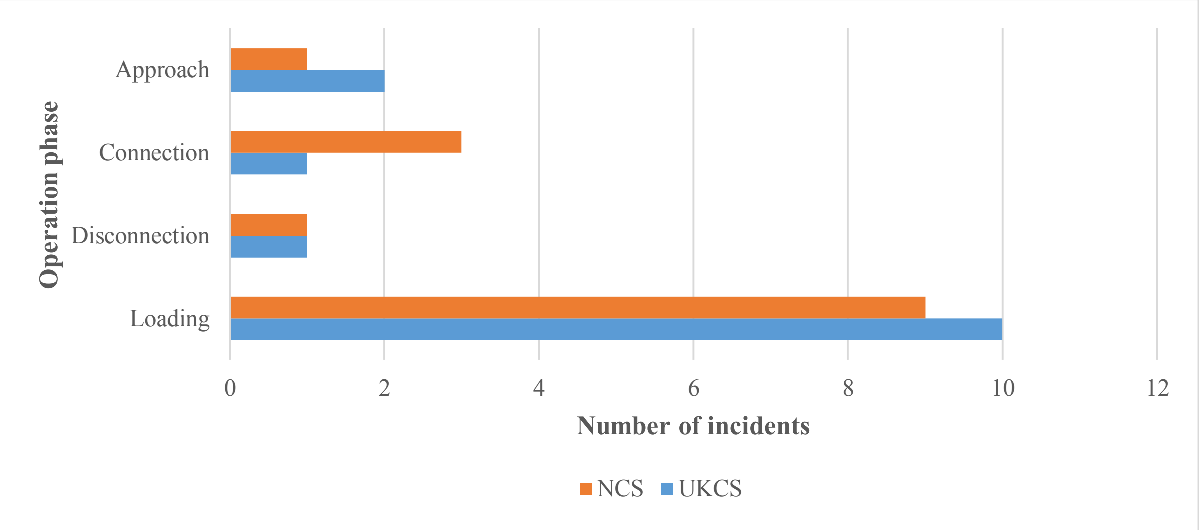

Figure 26: Geographical distribution of incidents by operation phase, UKCS & NCS 1995-2013.

Moreover, Figure 27 presents the failure causes according to their geographical distribution. It shows that operator error has occurred more frequently on the UKCS, representing 21% (3/14) of the incidents versus 14% (2/14) on the NCS. PRS failures are distributed likewise, constituting 21% (3/14) on the UKCS and 14% (2/14) on the NCS. However, in the case of DP failure and manually initiated drive-offs, the number of incidents are considerably different. DP failure has been the cause of 14% (2/14) of the incidents on the UKCS, compared to 29% (4/14) of the incidents on the NCS. Moreover, manually initiated drive-off has contributed to 7% (1/14) of the incidents on the NCS, whilst there are no such incidents reported on the UKCS.

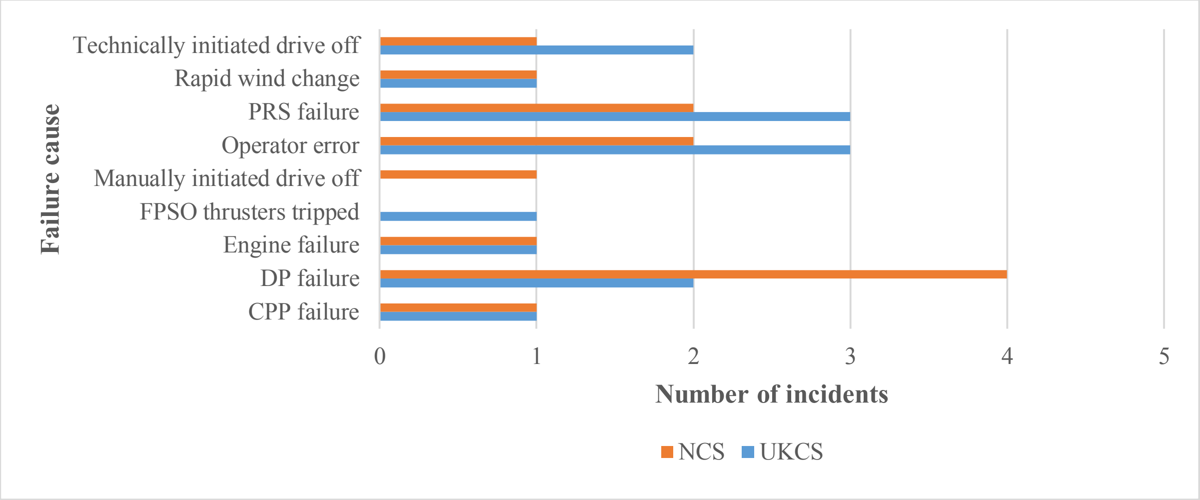

Figure 27: Geographical distribution of incidents per failure cause, UKCS & NCS 1995-2013.

5.1.2 1995-2003

There was reported a total of 20 incidents in the period 1995-2003, which constitutes more than two thirds [71% (20/28)] of the total number of incidents reported since 1995. Figure 28 shows the number of incidents per year on the UKCS & NCS, from 1995-2003. As seen from the figure, year 2003 represents no statistically significant change in the number of incidents compared to the previous eight years. Moreover, it shows that the absolute number of incidents per year increased towards year 2000, before declining in the three following years.

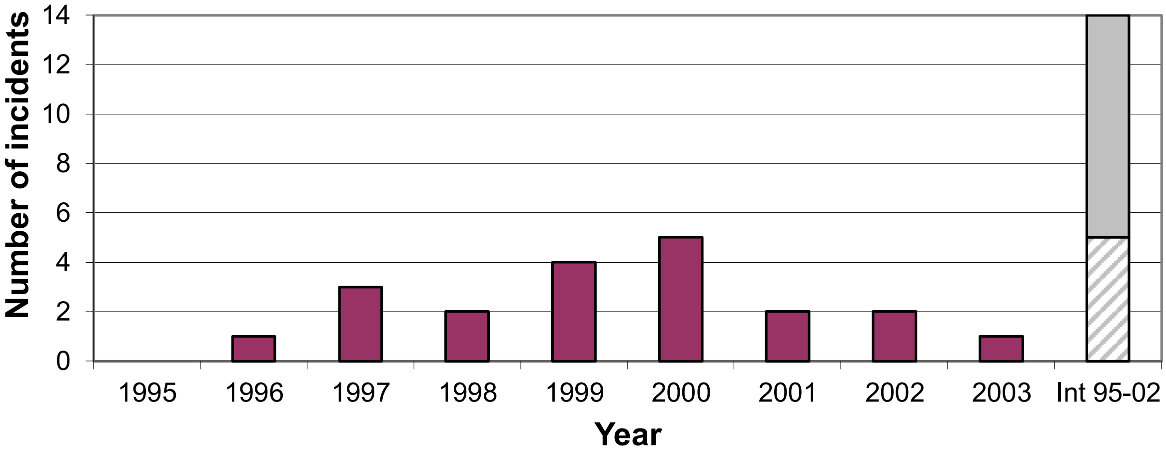

Figure 28: Number of incidents per year, UKCS & NCS 1995-2003.

Figure 29 further shows the number of incidents per offloading on the UKCS & NCS in the period 1995-2003. It is not possible to determine if there has been a statistically significant reduction in 2003, compared to the previous eight years. Nonetheless, it shows that the incident frequency per offloading was drastically reduced from 1997 to 1998, before declining further in each of the following years up to 2003.

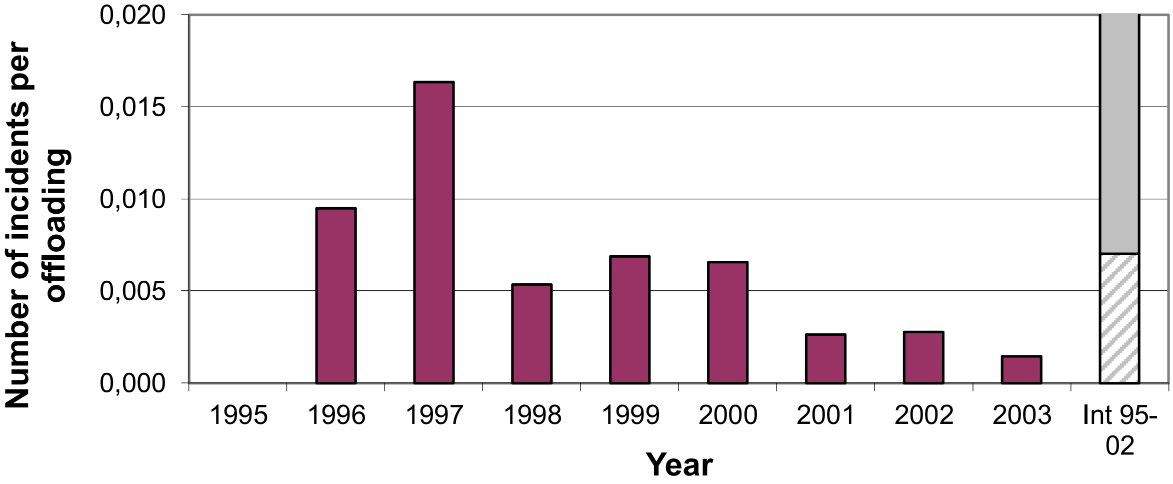

Figure 29: Number of incidents per offloading, UKCS & NCS 1995-2003.

The distribution of events between each operation phase, as presented in Figure 30, show that there is a predominance of incidents occurring during loading, representing 70% (14/20) of the incidents. The number of incidents occurring in the other operation phases is evenly distributed, representing 10% [2/20] each.

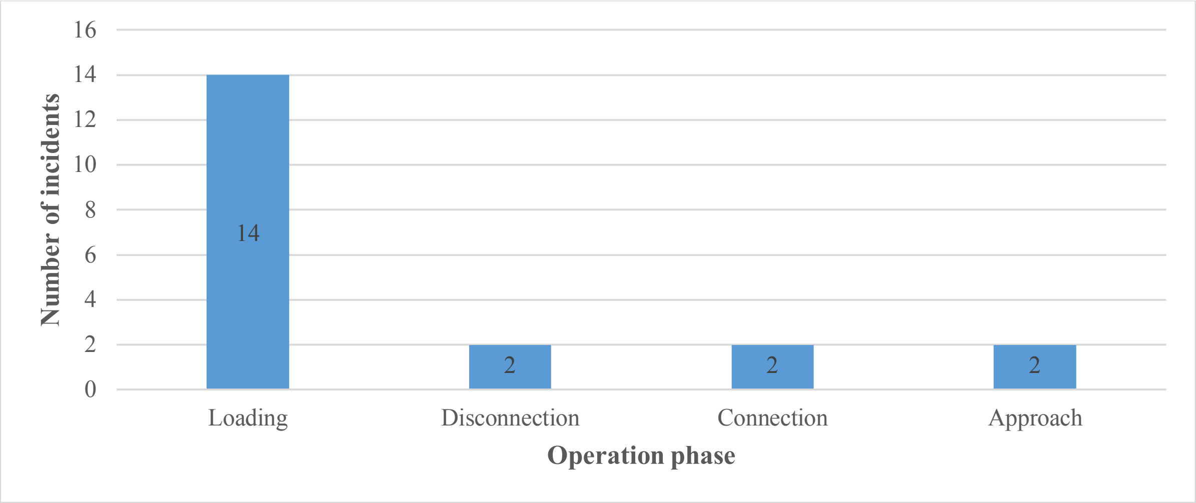

Figure 30: Number of incidents per operation phase, UKCS & NCS 1995-2003.

The distribution of incidents per failure cause on the UKCS & NCS, as presented in Figure 31, shows that DP failure [25% (5/20)] operator error [20% (4/20)] and PRS failure [15% (3/20)] occur most frequent.

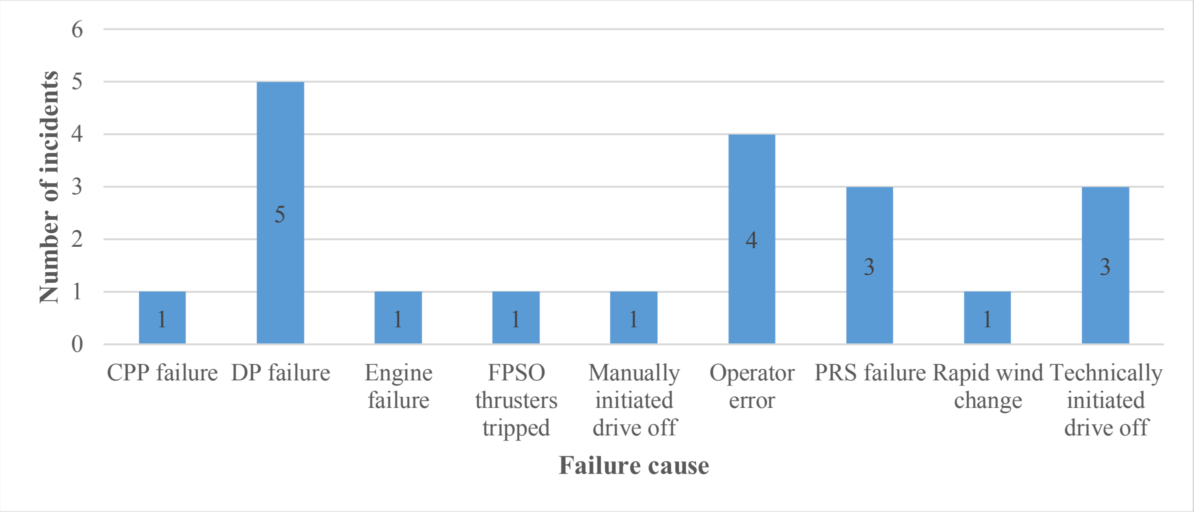

Figure 31: Number of incidents per failure cause, UKCS & NCS 1995-2003.

In terms of their geographical distribution, as presented in Figure 32, the UKCS has the greater contribution to the number of incidents, representing 65% (13/20) of the incidents. The operation phase in which the incidents have occurred show little variation, with the exception that there has been more than twice the number of loading incidents on the UKCS compared to the NCS. Furthermore, incidents have been prone to occur during the loading phase on both the UKCS and NCS, representing 77% (10/13) and 57% (4/7) respectively.

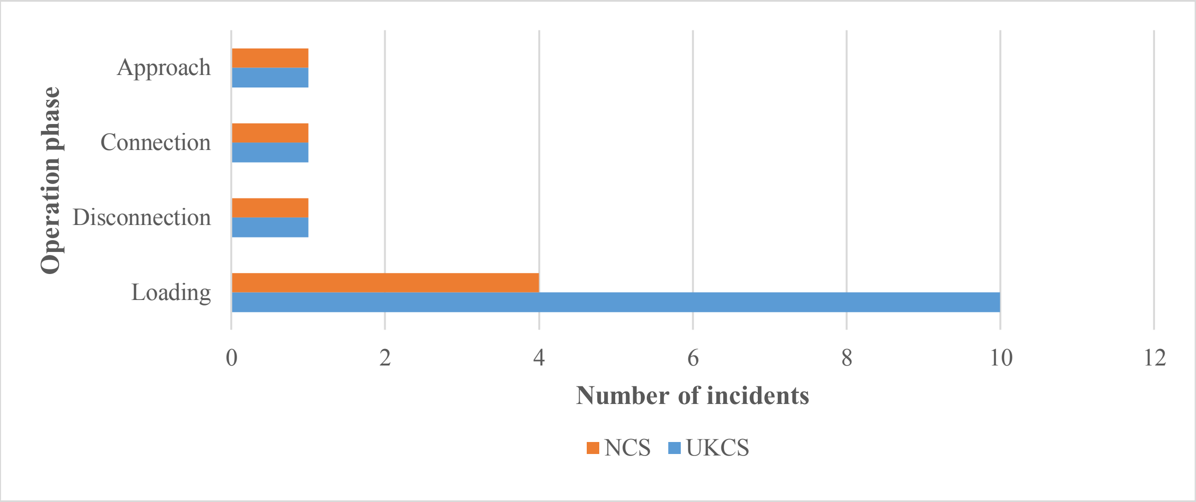

Figure 32: Geographical distribution of incidents by operation phase, 1995-2003.

Their geographical distribution of incidents per failure cause, as presented in Figure 33, shows that operator error has occurred more frequently on the UKCS, representing 23% (3/13) of the incidents, versus 14% (1/7) on the NCS. PRS failure is more evenly distributed, constituting 15% (2/14) on the UKCS and 14% (1/14) on the NCS. However, in the case of DP failure, the proportions of incidents are considerably different. DP failure has been the cause of 15% (2/13) of the incidents on the UKCS, compared to 43% (3/7) of the incidents on the NCS.

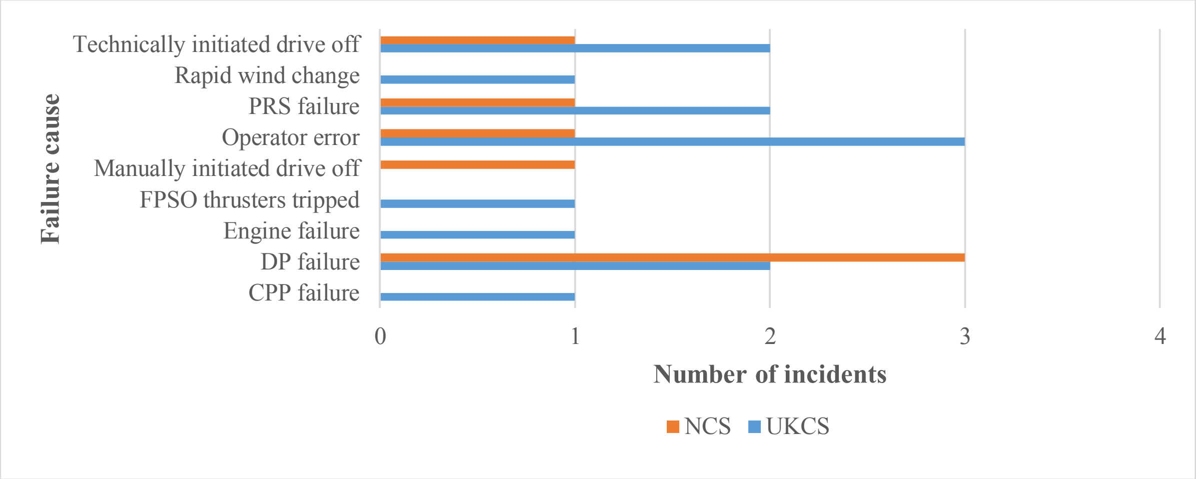

Figure 33: Geographical distribution of incidents per failure cause, 1995-2003.

5.1.3 2004-2013

There were reported eight incidents in the period 2004-2013. As seen from Figure 34, which presents the number of incidents per year on the UKCS & NCS during the period, year 2013 represents no statistically significant change in the number of incidents compared to the previous nine years. Moreover, the figure indicates no observable pattern in that the absolute number of incidents per year.

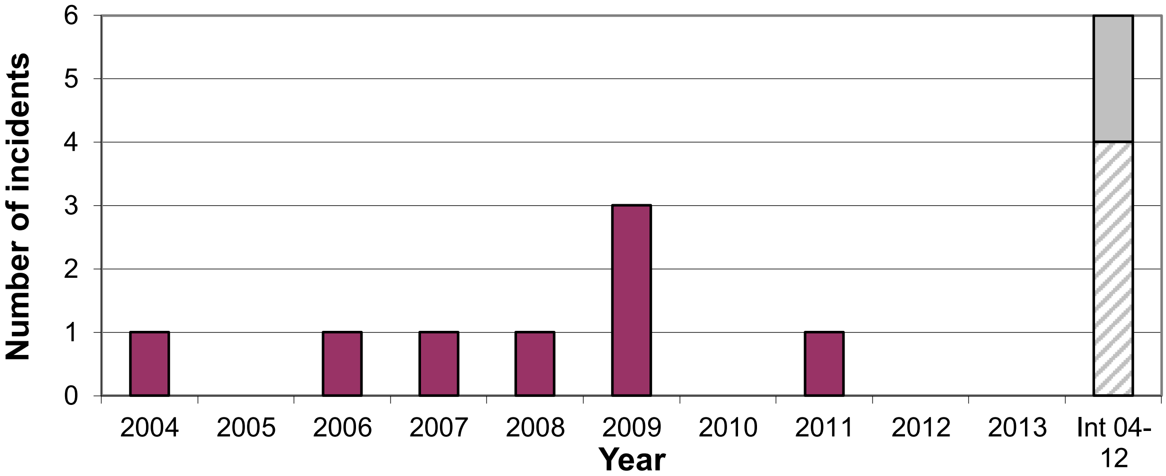

Figure 34: Number of incidents per year, UKCS & NCS 2004-2013.

Figure 35 shows the number of incidents per offloading on the UKCS & NCS in the period 2004-2013. It is not possible to determine if there has been a statistically significant reduction in 2013, compared to the previous nine years, nor is it possible to observe any pattern for the frequency development during the period.

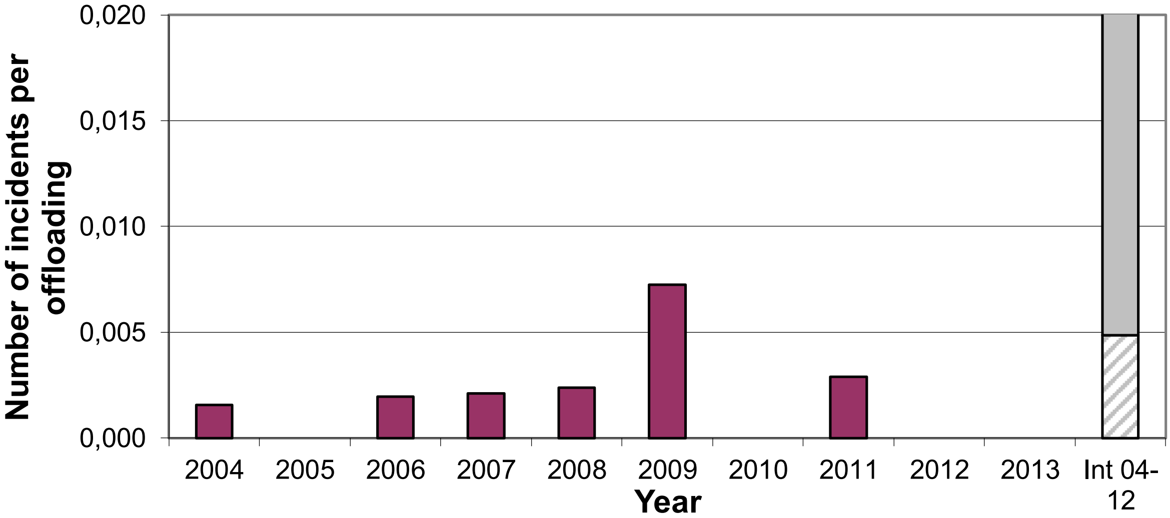

Figure 35: Number of incidents per offloading, UKCS & NCS 2004-2013.

The distribution of events between each operation phase, as presented in Figure 36, show that there is still a predominance of incidents occurring during loading, representing approximately

63% (5/8) of the incidents. However, the number of incidents occurring in the other operation phases is not so evenly distributed, as it was in the period 1995-2003. It is worth noting that there were no incidents during disconnection.

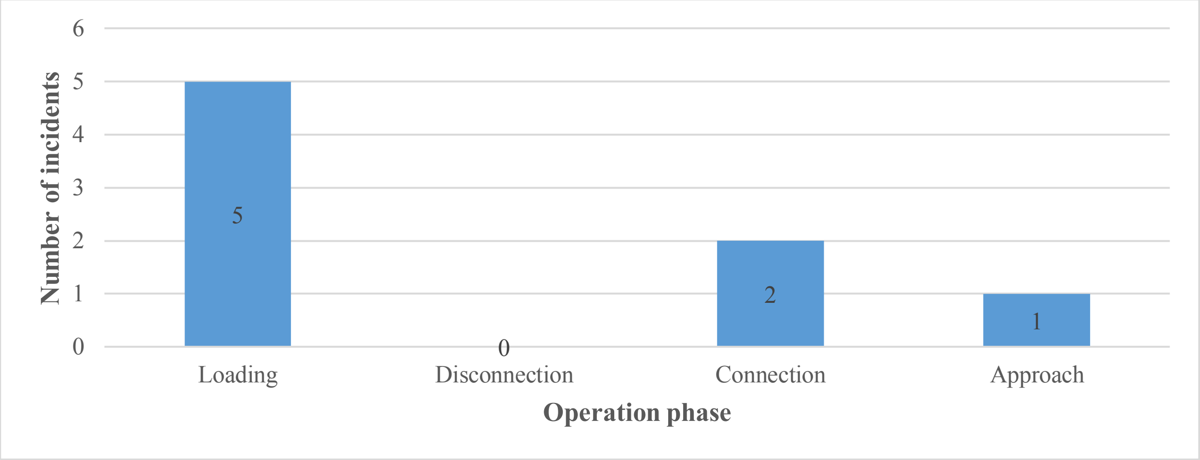

Figure 36: Number of incidents per operation phase, UKCS & NCS 2004-2013.

The distribution of incidents per failure cause on the UKCS & NCS, as presented in Figure 37, shows that PRS failure [25% (2/8)] occur most frequent. The rest of the incidents are evenly distributed among the different failure cause categories. It is worth noting that operator error has been reported as the failure cause in only one the event, which stands in stark contrast to the period 1995-2003. Moreover, there have been no cases of either technically nor manually initiated drive-offs, nor has there been any case of FPSO initiated incidents.

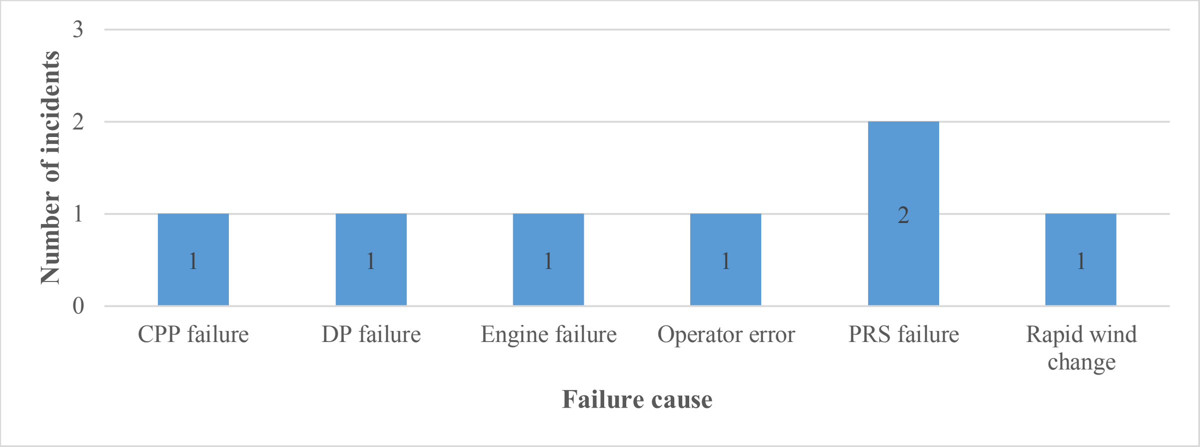

Figure 37: Number of incidents per failure cause, UKCS & NCS 2004-2013.

The geographical distribution, as presented in Figure 38, shows that the NCS has a considerably greater contribution to the number of incidents, representing 88% (7/8) of the incidents. Moreover, all of the incidents during the loading phase have occurred on the NCS, representing 71% (5/7) of the NCS's incidents.

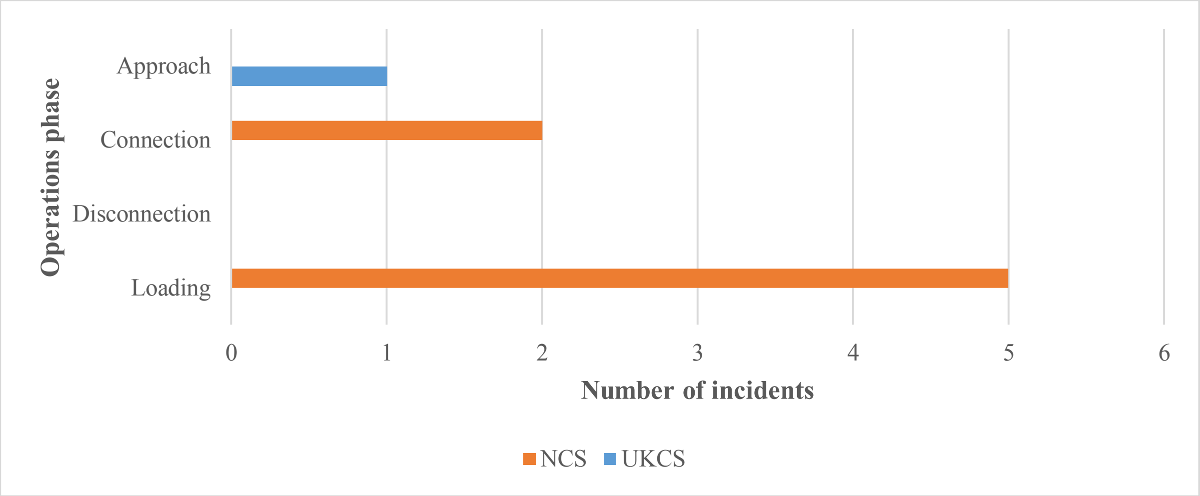

Figure 38: Geographical distribution of incidents by operation phase, UKCS & NCS 2004-2013.

The geographical distribution of the failure causes, as presented in Figure 39, shows that the incidents on the NCS are evenly distributed among the different failure causes. Thus, there is observed no predominant failure cause.

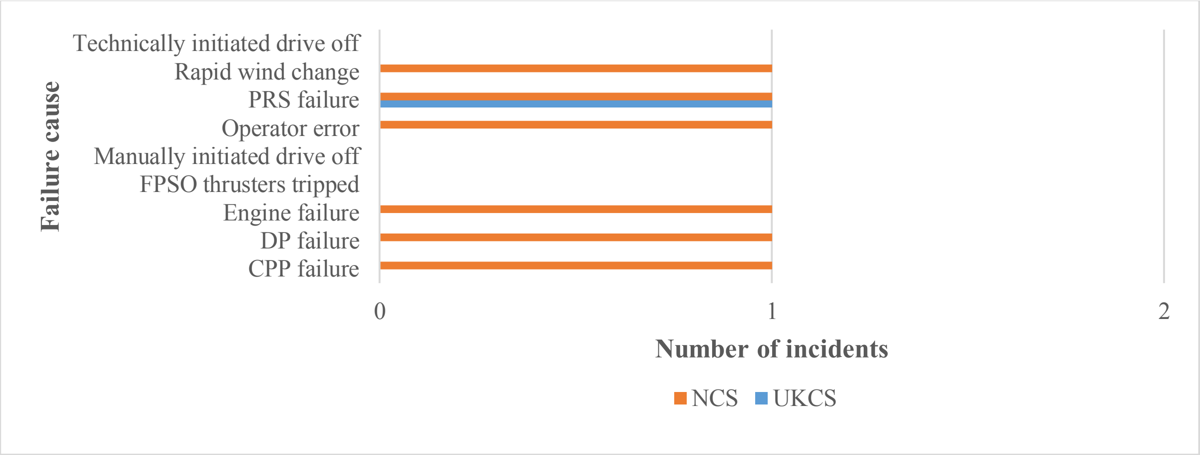

Figure 39: Geographical distribution of incidents by operation phase, UKCS & NCS 2004-2013.

5.2 COLLISION FREQUENCY

This section presents the results from a statistical analysis of all reported collision incidents on the UKCS and NCS in the period 1995-2013. The first part of the analysis comprises the entire period for the UKCS & NCS aggregated. The second part presents the results from analysing the UKCS and NCS separately.

5.2.1 Overall collision frequency

In the period 1995-2013, there have been reported seven collisions involving DP shuttle tankers performing tandem offloading from FPSO on the UKCS & NCS. Figure 40 presents the number of collisions on the UKCS & NCS, along with the year in which they occurred. The greatest number of collisions occurred in 1997. Moreover, there has not been reported any collisions during the last four years. However, it is not possible to observe any statistically significant increase/decrease for 2013 compared to the previous 10 years.

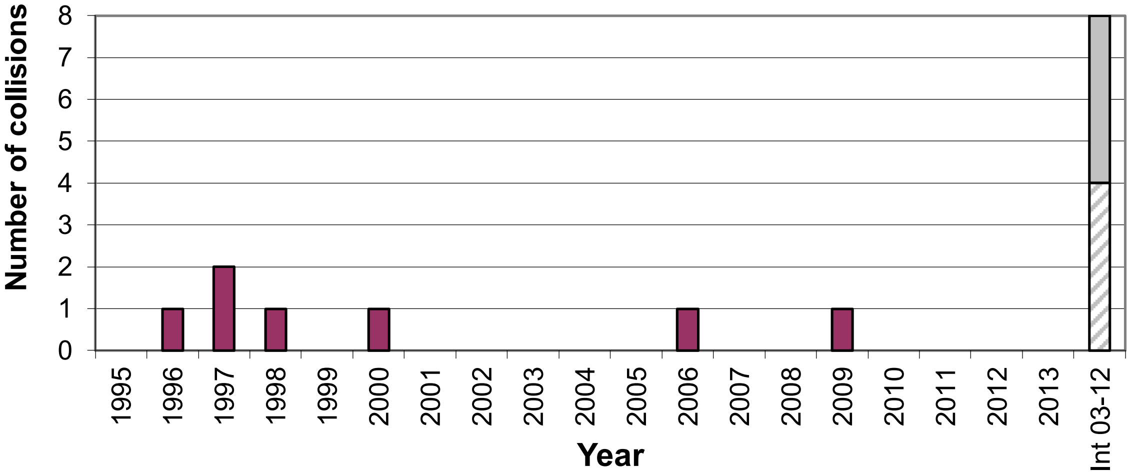

Figure 40: Number of collisions per year, UKCS & NCS 1995-2013.

Figure 41 presents the number of collisions per offloading on the UKCS & NCS, calculated for each year from 1995-2013. As seen from the figure, 1996-1997 had the highest collision frequency when accounting for the number of offloading operations performed. Furthermore, although one collision occurred in each of the years 1996, 1998, 2000, 2006 and 2009, the number of collisions per offloading is considerably higher for 1996 than the rest. This highlights the importance of accounting for the number of offloading operations performed.

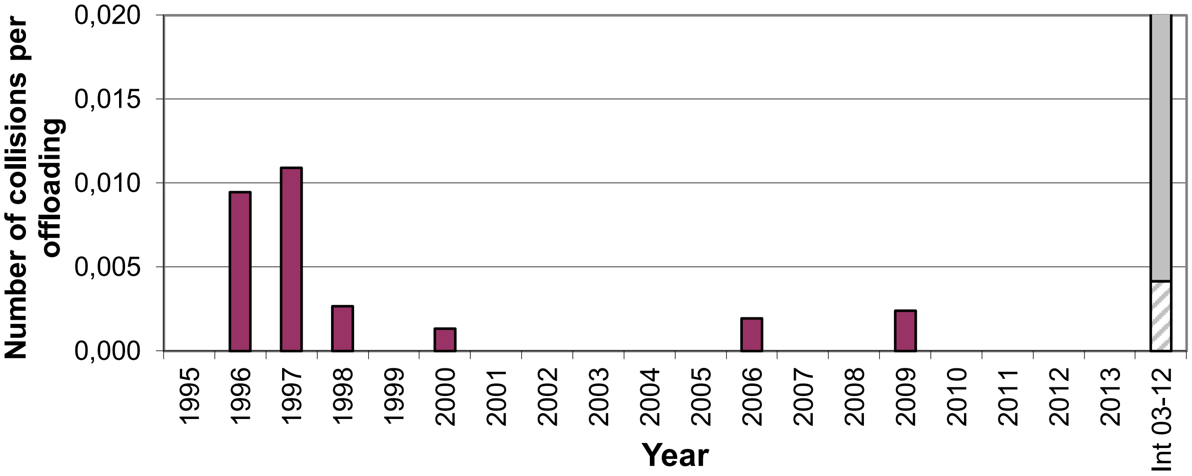

Figure 41: Number of collisions per offloading, UKCS & NCS 1995-2013.

Probabilities for events related to collisions during FPSO – shuttle tanker tandem offloading, estimated from UKCS and NCS incidents aggregated, is presented in Table 10. Although presented as probabilities, they should rather be interpreted as event frequencies. This also applies to the probabilities presented in Table 11 and Table 12.

As shown in Table 10, both the drive-off frequency and the collision frequency have been reduced, when comparing 1995-2003 versus 2004-2013. The drive-off frequency has been reduced by 76% (3.8E-03 vs. 9.0E-04) and the collision frequency has been reduced by 63% (1.2E-03 vs. 4.5E-04). However, the probability of failure of recovery given a drive-off has already occurred, has increased by 61% (3.1E-01 vs. 5.0E-01).

Table 10: Incident frequency per offloading for collisions and related events, UKCS & NCS.

Period	Pr(drive-off)	Pr(failure of recovery|drive-off)	Pr(collision)
1995-2013	2.3E-03	3.5E-01	8.0E-04
1995-2003	3.8E-03	3.1E-01	1.2E-03
2004-2013	9.0E-04	5.0E-01	4.5E-04

The geographical distribution of collisions on the UKCS & NCS, as presented in Figure 43, shows that in the period 1995-2013, the UKCS has had more than twice the number of collisions compared to the NCS (five vs. two collisions respectively). Hence, the UKCS represents 71% (5/7) of the total number of collisions on the UKCS & NCS. The greater part of these collisions occurred between 1995 and 2003. In this period, the UKCS had four collisions, representing 80% (4/5) of the total number. However, in the following period, from 2004-2013, only one collision occurred on each of the continental shelves.

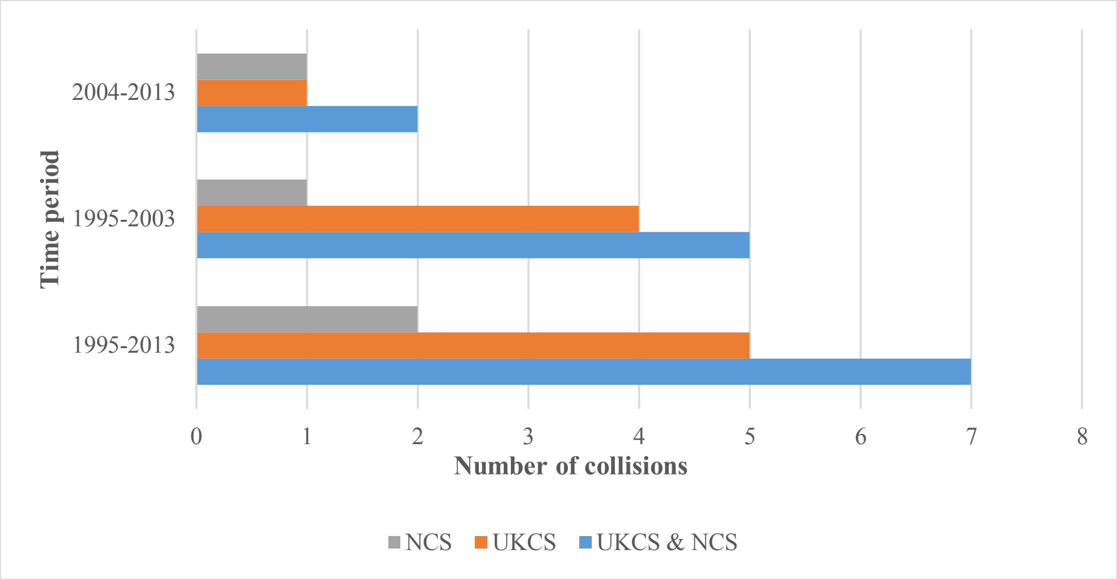

Figure 42: Geographical distribution of collisions, for selected time periods.

5.2.2 NCS

Table 11 shows the probabilities for the events related to collisions during FPSO – shuttle tanker tandem offloading, estimated from NCS incidents only. It shows a reduction of nearly 64% (3.9E-03 vs. 1.4E-03) for the drive-off frequency and a reduction of more than 29% (6.5E-04 vs. 4.6E-04) for the collision frequency, when comparing 1995-2003 versus 2004-2013. However, the probability of failure of recovery given a drive-off has already occurred has increased by 94% (1.7E-01 vs. 3.3.E-01).

Table 11: Incident frequency per offloading for collisions and related events, NCS.

Period	Pr(drive-off)	Pr(failure of recovery|drive-off)	Pr(collision)
1995-2013	2.7E-03	2.0E-01	5.4E-04
1995-2003	3.9E-03	1.7E-01	6.5E-04
2004-2013	1.4E-03	3.3E-01	4.6E-04

5.2.3 UKCS

Table 12 shows the probabilities for the events related to collisions during FPSO – shuttle tanker tandem offloading, estimated from UKCS incidents only. It shows a reduction of 88% (3.7E-03 vs. 4.4E-04) for the drive-off frequency and a reduction of close to 71% (1.5E-03 vs. 4.4E-04) for the collision frequency, when comparing 1995-2003 versus 2004-2013. In contrast, the probability of failure of recovery given a drive-off has already occurred, shows an increase of 150% (4.0E-01 vs. 1.0E+00).

Table 12: Incident frequency per offloading for collisions and related events, UKCS.

Period	Pr(drive-off)	Pr(failure of recovery|drive-off)	Pr(collision)
1995-2013	2.2E-03	4.5E-01	1.0E-03
1995-2003	3.7E-03	4.0E-01	1.5E-03
2004-2013	4.4E-04	1.0E+00	4.4E-04

6. DISCUSSION

The following discussion is divided into three parts. The first part concerns the results from the thesis' risk assessment, the second part concerns possible ways to reduce the risk in tandem offloading operations significantly, the last part concerns the methods applied in this thesis.

6.1 RESULTS: THE CURRENT SITUATION IN RELATION TO THE COLLISION FREQUENCY

This thesis set out to investigate the current situation in relation to the collision frequency, in tandem offloading operations between FPSO and shuttle tanker in the North Sea. Moreover, it sought to assess possible trends and developments for the incident frequencies, following the conclusion of the JIP project "FPSO Operational safety". In the following, the time periods 1995-2003 and 2004-2013, are referred to as 'period 1' and 'period 2' respectively. Moreover, FPSO/FSU is referred to as FPSO.

In relation to the overall incident frequency, this thesis finds that there has been 28 incidents involving DP shuttle tankers performing offloading from FPSO, on the UKCS & NCS from 1995 to 2013. There have been reported at least one incident each year from 1996 to 2004, and from 2006 to 2009, and the last reported incident occurred in 2011. However, more than two thirds of the incidents (20 out of 28 incidents) occurred in period 1. Hence, the results show that there has been a reduction in the absolute number of incidents since 2003. Moreover, the results from the statistical analysis of the incidents suggest that there have also been an improvement in the incident frequency per offloading since 2003. It is however not possible to observe a statistically significant reduction in the incident frequency. The reason for this result may be that the total number of incidents in the analysis is too small for one to observe a statistically significant trend.

The distribution of incidents between each operations phase shows a predominance of incidents occurring during the loading phase on both the UKCS and NCS, and the predominance was observable in data for both period 1 and period 2. Thus, the loading phase confirms its position as the most vulnerable in terms of incidents occurring. However, considering the time spent in each operations phase, the loading phase commonly representing 80-90% of an offloading operation`s total duration, the result may not be that surprising. Still, a DP shuttle tanker is in auto DP mode during the loading phase, yielding that problems relating to the positioning system may be relevant. This suspicion is confirmed by investigation of the failure causes, the most common being 'DP failure', 'PRS failure' and 'operator error'. This result complies with that of (Vinnem et al., 2003a), which found the RIFs ‘Shuttle tanker positioning and control system’ and ‘Shuttle tanker crew competence’, to be major contributing factors in their investigation of tandem offloading incidents that had occurred between 1995 and 2002. It should however be noted that this thesis applies similar incident data for period 1.

There are notable differences between period 1 and period 2, in terms of failure causes. The failure cause ‘operator error’, which occurs in four incidents in period 1, only occurs in one incident in period 2. This may indicate that the competence level of the DPOs has improved. However, there is also a reduction in the number of incidents involving ‘DP failure’, five incidents in period 1 versus one incident in period 2. Thus, it may be that improvements to the DP system, both in terms of technical reliability and HMI, have caused both reductions. The evidence is inconclusive. The incident data further indicates that ‘manually initiated drive off’ has only occurred on the NCS. However, the last mentioned might be due to different terminologies being applied to describe the failure, e.g. a failure cause that was classified as an operator error in the UKCS reports, might have been classified as a manually initiated drive-off in NCS reports.

A closer investigation of the results reveals some possible issues relating to the quality of the incident data for the UKCS in period 2. The incident data indicates that there has only occurred one incident on the UKCS in the last 10 years (since 2003), which is highly suspicious considering that there are 13 reported incidents on the UKCS in the preceding nine years. This implies a reduction in the number of incidents of more than 92%. In comparison, on the NCS there are reported seven incidents in each of the corresponding time periods. The suspicion towards the correctness of the number of incidents on the UKCS in period 2 increases further if the number of offloadings is taken into consideration. For period 2, it yields a difference between the UKCS and NCS in the incident frequency per offloading, of nearly 88% (3.2E-03 for the NCS vs. 4.0E-04 for the UKCS). In contrast, for period 1, the difference the NCS and UKCS in incident frequency per offloading is 4% (4.6E-03 vs. 4.8E-03). Thus, the result indicates a strange difference in the development between the two continental shelves.

In relation to collision incidents, this thesis finds that there have been seven collisions involving DP shuttle tankers performing offloading from FPSO on the UKCS & NCS from 1995 to 2013, and more than two thirds of the collisions (five vs. two collisions) occurs in period 1. Hence, the results show that there has been a reduction in the absolute number of collisions since 2003. The results from the statistical analysis of the collisions further suggest that there have been an improvement in the collision frequency since 2003. It is however not possible to observe a statistically significant reduction in the collision frequency. As for the incident frequency analysis, the reason for this result may be that the total number of incidents in the analysis is too small for one to observe a statistically significant trend.

Based on all incidents from 1995 to 2013, the collision frequency for the UKCS & NCS is estimated to 8.0E-04 per offloading. Only including incidents from period 2, the collision frequency is estimated to 4.5E-04 per offloading. As a conservative estimate, the collision frequency for the UKCS & NCS aggregated per mid-2014, is estimated to lie the range of 4.5E-04 to 8.0E-04 per offloading, equivalent to one collision in every 2222 to 1250 offloadings. Assuming that an FPSO is offloaded 50 times per year, the collision frequency is further estimated to lie in the range of 2.3E-02 to 4.0E-02 per year. This corresponds to one collision every 25 to 45 years. It should however be noted that the collision frequency is likely to be in the lower region of the aforementioned intervals.

Further, when investigating the two continental shelves separately, estimates for the collision frequency shows consistency. Analysis of the NCS and UKCS s separately shows that a conservative estimate for the collision frequency lie in the range of 4.6E-04 to 5.4E-04 per offloading for the NCS and in the range of 4.4E-04 to 1.0E-03 per offloading for the UKCS. In comparison, (Chen, 2003) estimated the collision frequency to be 3.1E-03 per offloading. Thus, this thesis' presents lower estimates for the collision frequency. Still, the frequency estimates of this thesis appear reasonable, as incident data show a decreasing trend in the number of incidents in the last 10 years.

Furthermore, as presented in Section 3.2.1, the cut-off criterion for design loads applicable to offshore installations on the NCS, has been set to a frequency of 1.0E-04 accidents per platform year. Assuming once more that an FPSO is offloaded 50 times per year, the collision frequency per year for the NCS lies in the range of 2.3E-02 to 2.7E-02. Hence, the accident frequency of FPSOs on the NCS is more than two decades higher than the required frequency. This further implies that the FPSOs have to be designed to withstand the collision impact of a shuttle tanker. The investigation of the Navion Hispania collision with Njord B FSU revealed that the collision energy was about 61 MJ. Yet, the regulations only explicitly require that the FPSO should be designed against an impact load no of less than 14 MJ. It is up to the operators themselves to determine if a greater design load is necessary. Thus, it is the author's opinion that the current regulations fail to address the collision risk adequately between FPSO and shuttle tanker. As pointed out by (Kvitrud et al., 2012), a design load in the order of magnitude 50-100 MJ is often more appropriate.

The drive-off frequency shows a substantial improvement when comparing period 1 and period 2. Based on all incidents from 1995 to 2013, the drive-off frequency for UKCS & NCS is estimated to be 2.3E-03 per offloading. Only including incidents from period 2, the drive-off frequency is estimated to be 9.0E-04 per offloading. As a conservative estimate, the drive-off frequency for the UKCS & NCS aggregated, per mid-2014, is estimated to lie in the range of 9.0E-04 to 2.3E-03 per offloading. These estimates are lower than that of (Chen, 2003), which found the drive-off frequency to lie in the range of 5.4E-03 to 2.0E-02. However, considering the considerable efforts that have been made to reduce the collision risk since their study was performed, this thesis' estimates appear reasonable. As in the case of the collision frequency, it should be noted that the drive-off frequency is likely to be in the lower region of the aforementioned intervals.

However, the probability of failure of recovery given a drive-off has already occurred, Pr(failure of recovery|drive-off), shows an increase in period 2, compared to period 1. In other words, the probability of successful recovery action upon a drive-off incident has decreased. This could imply that the reduction in the collision frequency is due to an improved robustness in relation to the initiation of drive-off events, and that the issues relating to recovery actions remain unresolved. Considering the possibility of there being a degree of underreporting to the incident databases, the increase can of course be the result of collisions being reported to a higher degree than near-miss incidents. Still, the estimated frequencies for UKCS, NCS, as well as the UKCS & NCS aggregated, all indicate an increase for Pr(failure of recovery|drive-off) in period 2. The evidence is inconclusive.

Based on all incidents from 1995 to 2013, Pr(failure of recovery|drive-off) for the UKCS & NCS is estimated to 3.5E-01. Only including incidents from period 2, the collision frequency is estimated to 5.0E-01. Hence, Pr(failure of recovery|drive-off) for the UKCS & NCS aggregated, per mid-2014, is estimated to lie in the range of 3.5E-01 to 5.0E-01. This estimate is comparable to that of (Chen and Moan, 2004), which estimated Pr(failure of recovery|drive-off) to be in the range of 3.5E-01 to 7.6E-01, for a shuttle tanker having a separation distance of 80m to the FPSO. However, their estimates were based on a human reaction time model, which applied reaction time estimates from shuttle tanker captains and DPOs, along with the lognormal distribution. Hence, the basis for the two studies' estimates is different. Nevertheless, this thesis' estimate lies well within the estimate of (Chen and Moan, 2004) and thus appears reasonable.

6.2 MEASURES FOR REDUCING THE COLLISION FREQUENCY

Overall, risk mitigation measures for avoiding drive-off incidents resulting in a collision, are concerned with either avoiding a drive-off from occurring in the first place (initiation), or increasing the chance of successful recovery after a drive-off has been initiated (recovery). The risk mitigation measures may be targeted at the crew, technical systems employed onboard the vessels during offloading operations, the vessels themselves, or the field configuration. Moreover, the effect of the risk mitigation measures may be enhanced if several measures are applied in combination.

Previous studies and guidelines have proposed several measures for reducing the collision risk. E.g., (Vinnem et al., 2003b, Vinnem et al., 2003a, Chen, 2003, Chen and Moan, 2005, Chen, 2013) proposed measures, which included among other:

- Automatic initiation of recovery action by the DP system.
- Facilitating early detection and identification of drive-off by the DP system and/or DPO.
- Increasing the relative distance between FPSO and shuttle tanker.
- Joint emergency procedures for FPSO and shuttle tanker, e.g. the FPSO turning its stern in one direction and the shuttle tanker turning its bow the other way.
- Avoiding failure prone situations, e.g. situations where there are excessive surge/sway movements between the vessels.
- Selecting the vessels' outfitting so that they are better equipped in terms of successfully managing drive-off events, or in way that reduces the chance of a drive-off occurring in the first place. E.g. by increasing the vessel`s thruster power, manoeuvring capabilities, DP system reliability, etc.

The following discussion is concerned with possible measures for significantly reducing the collision risk in FPSO-shuttle tanker offloading operations, considering a drive-off scenario. In this relation, the author finds the following issues especially important to address:

- *Ensuring that there is sufficient time for initiating successful recovery action.*
- *Ensuring that the DPOs' competence level is adequate.*
- *Facilitating successful recovery by cooperation between the shuttle tanker and FPSO.*
- *Facilitating successful recovery by altering the field configuration.*

Ensuring there is enough time for initiating successful recovery action

Senior instructors at SMSC, mentioned the following factors to have the greatest influence on the DPO`s reaction time when facing a drive-off scenario (SMSC, 2014):

1) The duration of time that the operator has been on active watch duty.
2) The operator`s level of experience.
3) The complexity of the DP system.

The first factor can be addressed by introducing a stricter requirement for the maximum length of continuous watch duty for the DPOs. As presented in Section 3.2.2, the intensity and duration of mental work, time of the day the work is performed, as well as the operator's prior amount of sleep, are of decisive importance for human fatigue. Hence, work-rest cycles can have a significant influence on human performance in a drive-off scenario. (Grech et al., 2008) states that while the evidence is not conclusive, there is a tendency for increased risk of incidents and errors when the duration of shifts exceeds eight hours, and when work is performed at night. Considering that offloading operations commonly has a duration of 20 hours, it is evident that a single DPO should not be on continuous watch-keeping duty for the entire operation. Better-designed shift schedules and fatigue management programs, as suggested by (Grech et al., 2008), may be effective countermeasures against fatigue from lengthy working hours. In relation to night work, the simplest remedy would be only to perform offloading operations during daytime. However, the long duration of an offloading operation makes it practically impossible to comply fully with the aforementioned. Still, planning the operation so that the most critical phase of the operation, i.e. the loading phase, is performed in daytime may effectively reduce the risk.

Another option could be to require the DP shuttle tanker to have two DPOs on the bridge at all times during offloading operations. This could enable better work-rest cycles, as the two DPOs can have shorter hours of continuous high concentration work on active watch-duty. Additionally, by rotating between being on active watch-duty and observing, the two DPOs collective performance may increase. Two of the biggest actors in North Sea, Teekay and Statoil, have already introduced this kind of work arrangement, requiring two DPOs to be present at the bridge during offloading operations. Their watch schedule rotation is 1 hour on active watch duty and 1 hour in standby (SMSC, 2014).

A dual DPO work arrangement may also address the second factor, operator`s level of experience. If there is only one DPO present at the shuttle tanker bridge, the vessel is more or less entirely dependent on his recovery actions in terms of avoiding a collision. However, by having two DPOs present on the bridge, the impact of a single DPO`s alertness and experience on the collision probability, may be reduced. A less experienced DPO may perform operations under the supervision of a more experienced one. Thus, such an arrangement can have a positive influence on the overall competence level of DPOs. Furthermore, if needed, the two DPOs can offer each other inputs and advice on what to do, which can be extremely important in high stress situations, e.g. a drive-off scenario. What is more, if one looks to the aviation industry, there is in fact a requirement for a pilot and a co-pilot on all commercial flights, in order to increase the reliability of the human operator. The two pilots alternate between the roles of controlling and monitoring the flight. Thus, the rationale for requiring a dual operator work arrangement, have already been recognized by other industries and the marine industry ought to consider doing likewise.

The third factor, DP system`s complexity, is a highly relevant issue as today`s DP systems are becoming far more advanced and require more extensive training of the operators than previously. E.g., there are more alarm systems and the general complexity of the DP controller has increased. As one of the instructors at SMSC described it, the first DP systems only had an On/Off switch, whilst today`s systems have numerous DP settings and operational modes (SMSC, 2014). Thus, it is relevant to raise questions about this development. Is it possible that the DP system`s controller interface has become too advanced for the people operating them? If this is the case, then it is critical that the DP system developers address the issue, ensuring that the there is a stronger focus on HMI in the development process of the DP system. E.g., the controllers and software ought to be designed not only for intuitive operability during normal operations, but also for operational deviations.

Furthermore, there are numerous unique alarm systems onboard ships, which can be a problem to the operator due to their loudness and triggering frequency. In (SMSC, 2014) it was mentioned that it was common for DPOs to experience situations where non-critical alarms are triggered, often involving numerous alarms sounding at the same time. This can cause the DPOs to become overwhelmed, which can further cause them to pay less attention to, or even ignore alarms. In addition, numerous alarms, both critical and non-critical, occurring simultaneously can also make it more difficult to identify which alarm must to be responded to first. (Grech et al., 2008) suggested a countermeasure to this, an approach that involves matching the alarms saliency to their criticality for the system. This can be a simple, yet effective, measure facilitating a faster response by the DPO in a drive-off scenario.

Ensuring that the DPOs' competence level is adequate.

The DPOs' competence level is of course a major factor when performing operations in close proximity to another vessel. Hence, the training of personnel should be a high priority for shuttle tanker operators. However, this can be a challenge as some companies are pressing to reduce the amount of training for their personnel. Compared to the NI DPO certification, the new DNV DPO certification effectively reduces the amount of formal training required to become a certified DPO. It is thus relevant to consider the possible implications of reducing formal training requirements, as the DP systems onboard the shuttle tankers are becoming more advanced. As some companies are already pressing for the training to be shortened, it may be argued that it has become even more crucial that the institutions responsible for educating DPOs remain faithful to their responsibility for up-keeping formal competence standards. This implies ensuring that their students are not only able to fulfil the certification standards in terms of test results, but that they are also capable of applying their skills and knowledge in actual operations. This can require numerous hours of simulation training for unexperienced students. Furthermore, as offloading operations do not normally require the DPO to perform emergency actions, it is necessary also for experienced personnel to undergo simulator training of such events on a regular basis to maintain their skillset.

Another issue is the possibility that the DP system`s sophistication is causing the DPOs to become too reliant on the DP system. During tandem offloading operations, it is not uncommon for the DPO having to use manual control, e.g. due to a faulty DP or operational requirements. Further, in a drive-off scenario there are several challenges for the DPO to conquer, in a very limited time, in order to have a successful recovery of the shuttle tanker. Thus, providing the DPOs with an in-depth understanding of the of the DP system working and limitations should be a key objective in the education of DPOs.

Facilitating successful recovery by cooperation between the shuttle tanker and FPSO.

(Daughdrill and Clark, 2002) suggests that when shuttle tankers and FPSOs are performing offloading operations, they ought to be considered as a system rather than two distinct entities. Applying this perspective, a natural suggestion would be to incorporate this in the offloading procedures, i.e. ensuring that system performance specifications and operations manuals consider the various interactions between the FPSO and the shuttle tanker. Although IMCA recommends for joint emergency procedures for the shuttle tanker and FPSO, (SMSC, 2014) states that according to their experience, it is in fact uncommon for such procedures to be in place. Further, it has been a challenge that the crew aboard the FPSO and shuttle tanker does not have any in-depth understanding of the counterpart`s operations. On the other hand, (SMSC, n.d.) states that it has recently been a development in the training of DP operators, where the oil companies have started to require joint training for crew onboard shuttle tankers and FPSOs. Thus, some measures are being made to address the issue, which can ultimately facilitate better cooperation, and an understanding of the operational activities and problems facing their counterpart in tandem offloading. Still, there is potential for improvement on the issue of cooperation between shuttle tanker and FPSO. As previously mentioned, the issue has been presented in previous studies on the subject. However, it seems that the industry has failed to address it adequately. Thus, this thesis recommends once more that joint emergency procedures for FPSO and shuttle tanker ought to be established.

Facilitating successful recovery by altering the field configuration

A fundamental hazard of the tandem offloading operations from FPSO to shuttle tanker, is that the traditional tandem configuration involves the shuttle tanker having its bow heading in the direction of the FPSO`s stern. This is not ideal, considering the possibility of a drive-off forward scenario. The relative separation distance between the shuttle tanker and FPSO is small, hence the shuttle tanker`s chance of stopping the forward motion or steering clear of the FPSO is limited. However, with the introduction of geostationary FPSOs in the North Sea, a new offloading configuration concept has been proposed. The concept involves the shuttle tanker maintaining a small heading difference to the FPSO, so that its bow is only heading towards the FPSO in short periods.(Chen et al., 2010, Chen, 2013) presented the ‘direct offloading’ configuration and provided an assessment of the collision risk when applying such a configuration in offloading operations from a geostationary FPSO, i.e. a FPSO that is, in contrast to a weather-vaning FPSO, spread moored. This thesis suggests that one should investigate the possibility for applying the same configuration to ship-shaped FPSOs.

Figure 43 provides an illustration of the direct offloading configuration applied to shuttle tanker offloading from a ship-shaped FPSO. The green sector is the loading sector, in which the shuttle tanker weathervanes whilst offloading. The blue sector is the pickup zone, in which the shuttle tanker can be positioned to receive the messenger line from the FPSO. The yellow sector is a “barrier sector”, i.e. if the shuttle tanker comes within this sector, it indicates that the vessel is experiencing station-keeping problems. The red lines marks the end of the minimum/maximum excursion limits for the shuttle tanker`s relative separation distance during offloading. If this line is breached, the shuttle tanker has a position loss (Chen et al., 2010).

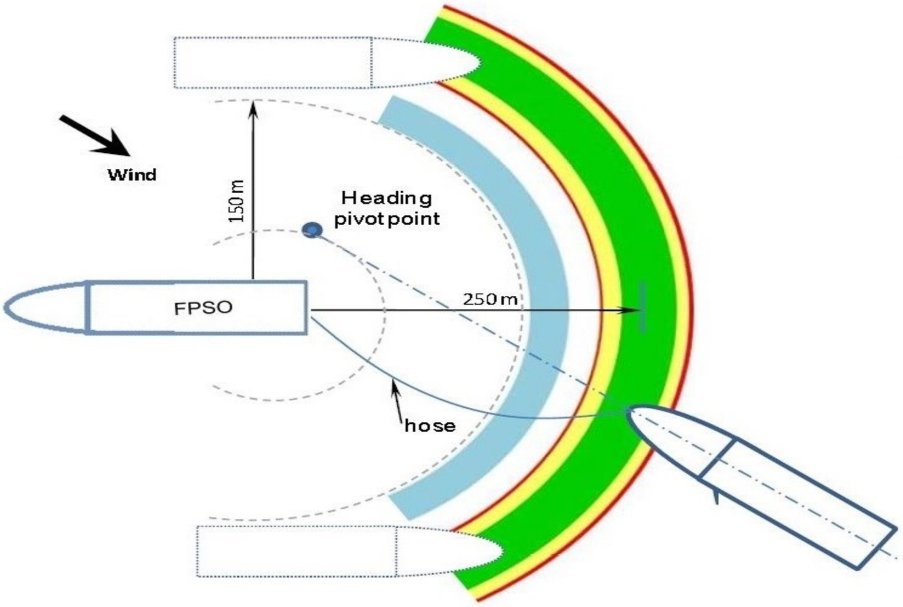

Figure 43: Illustration of offloading between shuttle tanker and ship-shaped FPSO, using direct offloading configuration. Adapted from (Chen and Moan, 2004).

Moreover, as seen from the figure, the concept differs from regular tandem offloading configuration in several ways; the shuttle tanker has a heading pivot point which is positioned sideways of the FPSO; it has a substantially longer separation distance (150-250m vs. 70-100m); and the shuttle tanker will change its heading pivot point when needed. The possibility to change the shuttle tankers heading pivot point when needed enables the shuttle tanker to utilise more of its loading sector. Hence, the disadvantage relating to position keeping, from not being positioned directly behind the FPSO, is offset.

In theory, the direct offloading configuration offers several advantages relative to regular tandem offloading configuration: Firstly, a larger separation distance implies a longer time window to detect and initiate recovery action upon a drive-off forward. (Chen and Moan, 2004) found that by increasing the relative separation distance from 80 to 250m, the time window increases from 53 seconds to 3 minutes. Resultantly, this is found to increase the probability of successful recovery from 2.5E-01 to 9.0E-01, i.e. Pr(collision|drive-off) is reduced to 1.0E-01 (1.0E+00 – 9.0E-01).

Secondly, by moving the heading pivot point away from the FPSO`s stern and to the side, the shuttle tanker is not heading towards the FPSO for the majority of an offloading`s duration. This may have a substantial effect on the collision risk as the vessels are only on a collision course in short time periods, opposed to the entire duration offloading operation. Figure 44 provides an illustration of the collision potential in a drive-off forward scenario, as well as the process of the shuttle tanker changing its heading pivot point. In a drive-off scenario, the shuttle tanker would already have a heading deviation to the FPSO (assuming that the drive-off does not occur whilst changing the heading pivot point). Thus, shuttle tanker could simply steer away from the FPSO. Moreover, if the heading deviation is sufficient, it may not be necessary for the DPO to intervene in order to avoid a collision. Hence, the risk reducing potential from applying direct offloading configuration is seemingly considerable.

The shuttle tanker will only be heading towards the FPSO whilst changing the heading pivot point, an operation which (Chen and Moan, 2004) estimated to last 10 minutes and that would have to be performed one or two times during an offloading operation. The aforementioned information can be applied to estimate the drive-off frequency and collision frequency if using direct offloading configuration instead of tandem configuration.

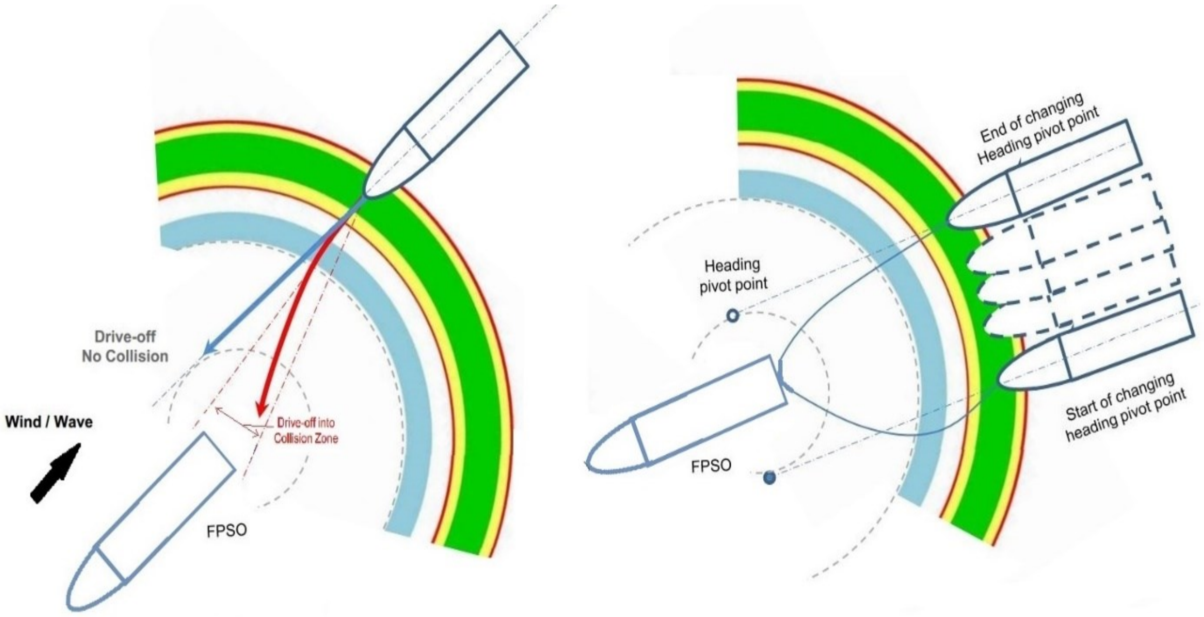

Figure 44: Collision potential in drive-off scenario and illustration of shuttle tanker changing the heading pivot point. Adapted from (Chen and Moan, 2004, Chen, 2013).

In order to provide a conservative estimate of the exposure time, (Chen and Moan, 2004) assumed four changes of heading pivot point per offloading operation when estimating drive-off and collision frequencies. Thus, the shuttle tanker will be heading towards the FPSO for 40 minutes per offloading. The frequencies for the NCS & UKCS aggregated can be estimated by equation (5) and equation (6):

$$\Pr(Drive\ off, direct\ offloading) = \Pr(Drive\ off, tandem) \cdot \frac{2}{3} \tag{5}$$

$$\Pr(Collision, direct\ offloading) = \Pr(Drive\ off, direct) \cdot (1 - 0.9) \tag{6}$$

The new frequency estimates are based on the results from this thesis' incident analysis, as presented in Section 6.1, along with information from (Chen and Moan, 2004). The resulting estimates for the frequencies are presented along with the result of this thesis' analysis, in Table 13.

Table 13: Frequency estimates for tandem and direct offloading configuration, UKCS & NCS aggregated.

	Tandem configuration	**Direct configuration**
Pr(Drive-off)	9.0E-04 to 2.3E-03	6.0E-04 to 1.6E-03
Pr(collision|drive-off)	4.0E-01 to 5.0E-01	1.0E-01
Pr(Collision)	4.5E-04 to 8.0E-04	6.0E-05 to 1.6E-04

Hence, the drive-off frequency is estimated to be reduced by 33% and the collision frequency is estimated to be reduced by nearly 80-87%, if direct configuration is applied instead of tandem configuration. This suggests that there are possibilities for achieving a significant reduction of the collision frequency by applying direct configuration instead of tandem configuration.

However, there may be issues related to applying such a configuration on a ship-shaped FPSO. Firstly, in order to use direct offloading configuration on a ship shaped FPSO, it is necessary that for it to have thrusters. Although all FPSOs on the NCS have such, there are several FPSOs on the UKCS that applies free weather-vaning, and hence they are not equipped with thrusters. Hence, those FPSOs will have to be modified in order for them to apply such a configuration.

Secondly, the heading deviation might be a concern to shuttle tankers performing offloading from ship-shaped FPSOs, since shuttle tankers are very vulnerable to position-loss in situations where there is excessive relative surge and yaw motions between the vessels. In contrast, a geostationary circular FPSO will not experience surge and yaw motions, due to its geometrical shape and it being geostationary, i.e. large fishtailing and surging motions are not possible (Solhaug, 2009). As the studies on the new direct offloading concept has been focusing on geostationary circular FPSOs, more research is needed in order to determine the feasibility of applying the concept on ship-shaped FPSOs.

Thirdly, position-keeping problems may arise because either of the vessels has to maintain a less than optimal heading, i.e. both the FPSO and shuttle cannot select the optimal heading considering the environmental forces and the vessels relative motions, as that would imply tandem configuration. As the operational envelope for tandem offloading in DP mode is already limited by the shuttle tanker`s station-keeping capabilities, i.e. there are maximum limitations for wave heights and wind, the impact on the operational envelope may be a concern. Nonetheless, it is rarely that current, wind and waves are all coming in the same direction.

Hence it may be possible for the shuttle tanker to select a suboptimal heading without it having too much of an effect on the vessel`s motions. Moreover, if the shuttle tanker and FPSO are provided with adequate capabilities for handling the extra environmental forces inflicted, it may be a feasible option to apply the direct offloading configuration in operations between ship-shaped FPSO and shuttle tanker.

6.3 METHODS

As this thesis is intended to provide an update on the current situation of the collision risk in tandem offloading operations between FPSO and DP shuttle tanker in the North Sea, the author found it appropriate to select an analytical approach that is consistent with the previously published research in the field. Hence, the approach was selected with the intention of facilitating comparison and verification of the results. This thesis' analyses the collision risk using both qualitative and quantitative risk analysis methods.

As the scientific area of HOFs is vast, it is thus not possible to cover all HOF aspects of the collision risk within the workload intended for a master thesis. However, by addressing factors found to be the most critical in previous studies, this thesis' should provide insight into core factors which can influence the collision risk. The main changes to tandem offloading operations between FPSO and shuttle tanker, since the JIP project report was published in 2003, are related to developments of new technology and corresponding changes in the education of DPOs, e.g. developments in DP system functionality. However, the field configuration, e.g. relative separation distance between FPSO and shuttle tanker, has not changed radically. Hence, the basis for selecting which HOFs to address should still be relevant.

The theoretical basis for this thesis' analysis of HOFs and technical factors is the socio-technical model, i.e. a system approach. The methodology was selected based on the author finding the system approach to be the better-suited approach for investigating the collision risk, as tandem offloading operations are complex and dependent on numerous human and organisational factors. Moreover, the larger share of those factors are dependent on external conditions (i.e. conditions of the workers surroundings), e.g. education and training of personnel, working environment, procedures. As stated by (Reason, 2000) a personal approach to HOFs more or less isolates the unsafe acts from their system context, often overlooking the reoccurring patterns of unsafe acts. Moreover, recent findings have revealed that the human element`s position in a larger system, is critical for the understanding of accident mechanisms and incident mechanisms (Grech et al., 2008).

The quantitative analysis involved a statistical analysis of reported FPSO-shuttle tanker tandem offloading incidents on the UKCS & NCS from 1995-2013. Overall incident frequencies and collision frequencies were estimated based on the frequency model of (Chen and Moan, 2004). The rationale behind the model as well as the process of obtaining input data for the model was discussed in Section 4.3.4.

Risk analysis is no exact science and thus results will vary depending on numerous factors, e.g. approach, availability of information, etc. Moreover, in relation to risk management, risk analysis should aid in the process of reducing risk levels for the future. Although statistical analysis is based on assessment of historical data, it enables one to quantify historical developments for the risk elements investigated. The last mentioned has off course a limitation in that one must assume that the data is representative for all new installations and vessels. Nevertheless, statistical analysis can be a practical method in making predictions about future risk levels based current risk levels. Furthermore, as statistical analysis enables one to investigate the frequency of events, it may enhance the accuracy when comparing one`s own results against the results from previous studies.

Determining which FPSOs that should be included in analysis of the incident frequencies was a challenging task. As this thesis investigates the collision risk between FPSO and DP shuttle tanker in tandem offloading, it was necessary to identify the fields that apply such a offloading configuration. This was a simple task for the NCS as the information is readily available. However, for the UKCS the information had to be retrieved through extensive research in several online databases. This involved identifying which FPSOs that applies tandem offloading, and then try to identify the associated shuttle tankers performing offloading. The author did his outmost to verify that only fields applying DP shuttle tankers are included in the analysis.

The statistical data analysis of the incidents presented a major challenge, as the quantity and quality of data, i.e. the amount of detailed and publically available information on incidents involving FPSO-shuttle tanker performing offloading operations, is limited for recent years. In this relation, the reporting bias is highly important. In the context of this thesis' empirical research, reporting bias refers to a tendency for underreporting of incidents, which was discussed in Section 4.1.

The author of this thesis has done his outmost to ensure that the results presented are representable, which has included researching and comparing incident data of multiple statistical sources. It would have been desirable to have direct access to incident databases, e.g. the IMCA database on DP vessels or DNV`s WOAD database, in order to be able to verify that all reported incidents have been included in the analysis. Several requests for access to such databases were made; however, the attempts were unsuccessful. Nevertheless, through extensive investigation of incident reports published by UK and Norwegian governmental bodies, it was possible to present a list of all publicly disclosed incidents. It should however be noted that the number of incidents identified for the UKCS in the period from 2004-2013, is very limited (only one reported incident). Thus, there is uncertainty associated with the data basis for the statistical analysis.

The uncertainty relating to the completeness of the incident database has further implications for the estimated collision and incident probabilities. The probabilities relating to the frequency of drive-off incidents and likelihood of successful recovery, i.e. $Pr(UPFM)$ and $Pr(FOR|UPFM)$ respectively, may be influenced by the aforementioned uncertainty. It is however difficult to quantify the exact magnitude of the resulting error for the probabilities. However, if there had been reported five more drive-off incidents on the UKCS from 1995-2013, $Pr(UPFM)$ would increase by 24.8% (2.9E-03 vs. 2.3E-03) and $Pr(FOR|UPFM)$ would decrease by 20% (2.8E-01 vs. 3.5E-01). Thus, these estimated probabilities should be only be treated as indicative estimates for the order of size for factual probabilities.

Conversely, in the case of collision incidents, it would not be so easy to hide the fact that an incident has occurred, as a collision is likely to result in visible damage to the vessels. Thus, it is the author`s opinion, that the uncertainty of the estimated collision probability, $Pr(collision)$, is less than for the other probability estimates, as $Pr(collision)$ also can be calculated independently[8] of $Pr(UPFM)$ and $Pr(FOR|UPFM)$.

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[8] See section 4.3.4.

7. CONCLUSIONS & RECOMMENDATIONS

This thesis has provided an assessment of the collision risk in tandem offloading operations between FPSO and shuttle tanker in the North Sea. The risk has been analysed using both quantitative and qualitative methods, and the results from the analysis have been discussed. Moreover, measures for reducing the collision frequency have been proposed. This chapter presents this thesis' conclusions and recommendations for further work.

7.1 CONCLUSIONS

Has the collision frequency been reduced since the conclusion of the JIP project 'Operational Safety of FPSOs' in 2003? Moreover, is it possible to reduce the frequency of such incidents significantly? The findings of this thesis suggest that the answer to both questions is *yes*.

Several studies relating to the collision risk in FPSO-shuttle tanker offloading operations have been performed post the conclusion of the JIP project. The research is seemingly mainly concerned with further work regarding the risk elements that were identified in the JIP project and the PhD thesis of Dr. Ing. Haibo Chen, as well as providing updated statistics on incidents and risk levels.

The risks involved in FPSO-DP shuttle tanker tandem offloading operations in the North Sea, are mainly related to failures of technical equipment applied onboard shuttle tankers for position-keeping purposes, as well as HOFs concerning the shuttle tanker DPO. Moreover, the barriers employed to mitigate the collision risk, are also mainly targeted at the aforementioned risks. Such barriers include among other alarms, DP system auto modes specifically designed for avoiding excessive motions between shuttle tanker and FPSO, as well as formal competence requirements for DPOs/station-keeping operators.

Results from this thesis' risk analysis revealed a decrease in the frequency (both absolute and per offloading) of incidents and collisions, during FPSO-shuttle tanker offloading operations on the UKCS & NCS, when comparing 1995-2003 versus 2004-2013. It was however not possible to observe any statistically significant reduction for neither the incident frequency, nor the collision frequency. Moreover, the collision frequency per year on the NCS is found to be more than two decades higher than the cut-off criterion for design loads, applicable to offshore installations on the NCS.

In terms of failure causes, there are found notable differences between the periods 1995-2003 and 2004-2013. Although the evidence is inconclusive, the reduction in the failure causes ‘DP failure’ and ‘operator error’ indicates that there have been improvements to the DP system and/or DPO competence level. Furthermore, the results confirm earlier findings and contribute supplementary evidence that suggest that the loading phase is the most vulnerable part of the offloading operation.

Several measures for reducing the collision frequency have been discussed, which addresses DPO competence level, time available for initiating recovery action, cooperation between the shuttle tanker and FPSO, and alternative field configurations. The collision frequency can be significantly reduced by applying direct offloading configuration instead of tandem offloading configuration. However, there are technical and operational issues that have to be resolved, before applying such a configuration to ship-shaped FPSOs.

The work of this thesis contributes to existing knowledge about the collision risk in tandem offloading operations, in the North Sea, by providing updated incident and collision frequencies for the UKCS & NCS. Whilst this thesis did not demonstrate any statistically significant reduction for neither the incident frequency, nor the collision frequency, it provides an indication of the general direction for the frequency developments. Moreover, it suggests several measures for reducing the collision frequency, which can have a significant impact on the overall collision risk. The methods used in this thesis, to investigate the collision frequency in tandem offloading operations between DP shuttle tanker and FPSO in the North Sea, can be applied to investigate collision risk in similar operations elsewhere in the world.

The findings of this thesis have some limitations. Firstly, the incident data only include DP shuttle tankers performing tandem offloading in the North Sea. Hence, the resulting frequencies are not directly applicable to similar operations elsewhere in the world. Secondly, the risk assessment did not consider consequences, nor the acceptability of current risk levels. Thirdly, the thesis’ investigation of incidents was limited by not having direct access to major incident databases; hence, it has not been possible to confirm if there are recorded incidents that have not been reported to governmental databases.

7.2 RECOMMENDATIONS FOR FURTHER WORK

In the course of working with this thesis, there have been identified issues that needs further work.

The estimated frequencies for the UKCS, the NCS, as well as the UKCS & NCS aggregated, all indicate an increase for Pr(failure of recovery|drive-off) in the period 2004-2013, compared to the period 1995-2003. In the thesis' discussion, it is suggested that this could imply that *the reduction in the collision frequency is due to an improved robustness in relation to the initiation of drive-off events, and that the issues relating to recovery actions remain unresolved*. This hypothesis ought to be further investigated, as it is highly important to determine whether there is a need for addressing the recovery phase more strongly.

This thesis has shown that the collision frequency has been reduced over the course of the last 10 years. However, it has not been able to observe a statistically significant reduction for the frequency. As the estimated collision frequencies indicate that FPSO-DP shuttle tanker tandem offloading operations on the NCS do not meet the requirements of the Norwegian PSA, further work towards risk mitigation is necessary. This thesis proposed several measures for reducing the collision frequency, which should be considered implemented in operations. The topic of applying direct offloading configuration for ship-shaped FPSO, is found especially promising and should be explored in further research.

BIBLIOGRAPHY

AANESLAND, V., KAALSTAD, J. P., ARILD BECH, A. & HOLM, A. 2007. Disconnectable FPSO—Technology To Reduce Risk in GoM. *Offshore Technology Conference.* Offshore Technology Conference.

ABF. 2014. *List Of Floating Production Storage And Offloading Vessels* [Online]. A Barrel Full. Available: http://abarrelfull.wikidot.com/list-of-floating-production-storage-and-offloading-vessels-f [Accessed 20.03. 2014].

APL 2010. Alvheim FPSO with disconnectable STP system. www.tu.no: Teknisk Ukeblad.

AVEN, T. & RENN, O. 2010. *Risk management and governance: concepts, guidelines and applications,* Berlin, Springer-Verlag.

AVEN, T. & VINNEM, J. E. 2005. On the use of risk acceptance criteria in the offshore oil and gas industry. *Reliability Engineering & System Safety,* 90**,** 15-24.

BAINBRIDGE, L. 1983. Ironies of automation. *Automatica,* 19**,** 775-779.

BELL, R. & REINERT, D. 1992. Risk and system integrity concepts for safety-related control systems. *Safety Science,* 15**,** 283-308.

BRADBURY, J. 2009. *Schiehallion FPSO out of action after collision* [Online]. www.offshore.no: Offshore Media Group. Available: http://www.offshore.no/international/article/Schiehallion_FPSO_out_of_action_after_collision [Accessed 20.03. 2014].

CGE. n.d. *The Bowtie Method* [Online]. CGE Risk Management Solutions. Available: http://www.cgerisk.com/support-a-downloads/support/bowtie-method-support/56-the-bowtie-method [Accessed 17.04. 2014].

CHEN, H. 2003. *Probablistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation.* PhD thesis, Norwegian University of Science and Technology.

CHEN, H. Risks in DP Shuttle Tanker Offloading Operations. CeSOS Highlights and AMOS Visions, 27.05-29.05. 2013 Trondheim, Norway.

CHEN, H., LERSTAD, A. & MOAN, T. Probabilistic Evaluation of Collision between DP Shuttle Tanker and Geostationary FPSO in Direct Offloading. *In:* ASME, ed. 29th International Conference on Ocean, Offshore and Arctic Engineering,, June 6-11, 2010 Shanghai, China. American Society of Mechanical Engineers.

CHEN, H. & MOAN, T. Collision risk analysis of FPSO-tanker offloading operation. *In:* ASME, ed. 21st International Conference on Offshore Mechanics and Arctic Engineering, 2002 Oslo, Norway. American Society of Mechanical Engineers, 101-112.

CHEN, H. & MOAN, T. 2004. Probabilistic modeling and evaluation of collision between shuttle tanker and FPSO in tandem offloading. *Reliability Engineering & System Safety,* 84**,** 169-186.

CHEN, H. & MOAN, T. 2005. FPSO-Shuttle Tanker Collision Risk Reduction. *Journal of Offshore Mechanics and Arctic Engineering,* 127**,** 345-352.

CHEN, S.-T., WALL, A., DAVIES, P., YANG, Z., WANG, J. & CHOU, Y.-H. 2013. A Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA). *Safety Science,* 60**,** 105-114.

CLARKSON 2013. *The Mobile offshore production units register 2013,* London, Clarkson Research Services Ltd.

DAUGHDRILL, W. H. & CLARK, T. A. Considerations in Reducing Risks in FPSO and Shuttle Vessel Lightering Operations. Offshore Technology Conference, 6–9 May 2002 Houston, Texas. Offshore Technology Conference.

DECC 2014. UK Annual Oil & Gas Production (1975-present). 01.04 ed.: Department of Energy & Climate Change (DECC) UK Gov. .

DNV 2007. Accident Statistics for Mobile Offshore Units on the UK Continental Shelf, 1980-2005. *In:* VERITAS, D. N. (ed.). London, UK: UK Health and Safety Executive.

FUNNEMARK, E. 2001. Accident Statistics for Mobile Offshore Units on the UK Continental Shelf, 1980-1998. *In:* VERITAS, D. N. (ed.). London, UK: UK Health and Safety Executive.

GOODWIN, S. 2007. Human Factors in QRA. Report for International Association of Oil and Gas Producers. *In:* VERITAS, D. N. (ed.). The International Association of Oil and Gas Producers.

GRECH, M., HORBERRY, T. & KOESTER, T. 2008. *Human factors in the maritime domain*, CRC Press.

HELGØY, K. 2003. State of DP Development and potential in Shuttle Tankers. *Dynamic positioning conference.* Houston, Texas: The Marine Technology Society - Dynamic Positioning Committee.

HENNINGSGÅRD, S. 2013. *Operational Risk in the Norwegian Barents Sea.* MSc. thesis, Norwegian University of Science and Technology.

HSE 2005. Report on UKCS DP Shuttle Tanker Incidents 1998-August 2004. *RR348.* London, UK: Health & Safety Executive UK.

HSE 2006. The Offshore Installations (Safety Case) Regulations 2005 (SCR05). London, UK: HSE Books.

IMCA 1999. Quantified frequency of shuttle tanker collision during offtake operations. The International Marine Contractors Association.

IMCA 2007. *Guidelines for the Design and Operation of Dynamically Positioned Vessels*, International Marine Contractors Association.

IMO, M. 1994. Circ. 645 - Guidelines for Vessels with Dynamic Positioning Systems. International Maritime Organization.

ISO, I. 2009. *31000: 2009 Risk management–Principles and Guidelines,* Geneva, Switzerland, International Organization for Standardization.

ISO/IEC 2002. Risk management - Vocabulary - Guidelines for use in standards. British Standards Institution.

KAPLAN, S. 1991. Risk assessment and risk management–basic concepts and terminology. *Risk management: Expanding horizons in nuclear power and other industries*, 11-28.

KHAKZAD, N., KHAN, F. & AMYOTTE, P. 2012. Dynamic risk analysis using bow-tie approach. *Reliability Engineering & System Safety,* 104**,** 36-44.

KM. n.d. *IMO DP Classification* [Online]. www.km.kongsberg.com: Kongsberg Maritime. Available: http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/D9479D5DB35FCA01C1256A4C004A876E?OpenDocument [Accessed 02.04 2014].

KVITRUD, A., KLEPPESTØ, H. & SKILBREI, O. R. Position Incidents during Offshore Loading with Shuttle Tankers on the Norwegian Continental Shelf 2000. The twenty-second International Offshore and Polar Engineering Conference, June 17–22, 2012 Rhodes, Greece. International Society of Offshore and Polar Engineers.

LEONHARDSEN, R. L., ERSDAL, G. & KVITRUD, A. Experience and Risk assessment of FPSOs in use on the Norwegian Continental Shelf Descriptions of Events. The eleventh International Offshore and Polar Engineering Conference, June 17-22, 2001 Stavanger, Norway. Tile International Society of Offshore and Polar Engineers.

NORDGÅRD, D. E., GJERDE, O., SAND, K., CATRINU, M. D., LASSILA, J., PARTANEN, J., BONNOIT, S. & AUPIED, J. A risk based approach to distribution system asset management and a survey of perceived risk exposure among distribution companies. CIRED-19th International conference on electricity distribution, 2007 Vienna, Austria. CIRED.

NOROG. 2011. *FPSO LESSONS OVERVIEW* [Online]. norskoljeoggass.no: The Norwegian Oil and Gas Association. Available: http://www.norskoljeoggass.no/no/FPSO-Experience-Transfer/FPSO-Lessons-overview/ [Accessed 16.03 2014].

NPD 1980. Guidelines for conceptual evaluation of platform design. Stavanger, Norway: Norwegian Petroleum Directorate.

NPD 2014. Fields on the Norwegian continental shelf, Production - net figures. 02.04 ed. http://factpages.npd.no/: The Norwegian Petroleum Directorate (NPD).

NTS 2010. NORSOK Standard Z-013. *Risk and emergency preparedness analysis.* Oslo, Norway: Standards Norway.

NTS 2013. NORSOK Standard N-004. *Design of steel structures.* Oslo, Norway: Standards Norway.

OET 2014. FPSO and shuttle tanker in tandem offloading. www.offshoreenergytoday.com: Offshore Energy Today.

OGUK 2009. Accident Statistics for Offshore Units on the UKCS 1990-2007. *In:* UK, O. G. (ed.). Oil & Gas UK.

OLF 2004. A summary Report on FPSO - shuttle tanker interface. A follow-up review of lessons reported in 2003 with two major North Sea shuttle tanker operators. Stavanger, Norway: Norwegian Oil Industry Association.

PAIK, J. K. & THAYAMBALLI, A. K. 2007. *Ship-shaped offshore installations: design, building, and operation,* Cambrigde, UK, Cambridge University Press.

PSA 2014a. Trends in risk level in Norwegian petroleum activity (RNNP), Main report 2013. *Available in Norwegian only.* Stavanger, Norway: Petroleum Safety Authority Norway (PSA).

PSA 2014b. Trends in risk level in Norwegian petroleum activity (RNNP), Methods report 2013. *Available in Norwegian only.* Stavanger, Norway: Petroleum Safety Authority Norway (PSA).

RAUSAND, M. 2013. *Risk assessment: theory, methods, and applications,* New York, John Wiley & Sons.

REASON, J. 2000. Human error: models and management. *BMJ,* 320**,** 768-770.

RENN, O. 2005. *white paper no. 1 RISK GOVERNANCE TOWARDS AN INTEGRATIVE APPROACH,* Geneva, Switzerland, International Risk Governance Council.

RIGZONE. 2014. *How do Shuttle Tankers Work?* [Online]. RIGZONE. Available: http://www.rigzone.com/training/insight.asp?insight_id=357&c_id=12 [Accessed 10.03 2014].

ROBSON, J. & BRITAIN, G. 2003. *Ship/platform Collision Incident Database (2001),* London, UK, HSE Books.

SKLET, S. 2006a. *Safety barriers on oil and gas platforms. means to prevent hydrocarbon releases.* PhD thesis, Norwegian University of Science and Technology.

SKLET, S. 2006b. Safety barriers: Definition, classification, and performance. *Journal of Loss Prevention in the Process Industries,* 19**,** 494-506.

SKOGDALEN, J. E., HAUGEN, S., HELDAL, F., HOLO, B., OKSTAD, E., STEEN, S. A. & VINNEM, J. E. Analysis of Barriers in Marine Operations on Offshore Oil Installations. ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, 2009. American Society of Mechanical Engineers, 239-248.

SKOGDALEN, J. E. & VINNEM, J. E. 2011. Quantitative risk analysis offshore—Human and organizational factors. *Reliability Engineering & System Safety,* 96**,** 468-479.

SMSC. Meeting with instructors and administrative personnel at SMSC. 11.04. 2014 SMSC headquarter, Trondheim, Norway. Magne Erik K. Lundborg.

SMSC. n.d. *Offshore Loading* [Online]. Ship Modelling & Simulation Centre AS. Available: http://smsc.no/courses/offshore-loading [Accessed 11.04 2014].

SOLHAUG, T. The Sevan Marine concept - Safety solutions for the future! , March 2009. Sevan Marine ASA.

STRANKS, J. 2005. *The Manager's Guide to Health and Safety at Work,* London, UK, Kogan Page Publishers.

TANNURI, E. A., PESCE, C. P. & KUBOTA, L. K. 2006. Adaptive control strategy for the dynamic positioning of a shuttle tanker during offloading operations. *Journal of offshore mechanics and Arctic engineering,* 128**,** 203-210.

VINNEM, J. E. 2000. Operational safety of FPSOs: Initial summary report, OTO 2000/86. *Offshore Technology Report.* London, UK: Health & Safety Executive UK.

VINNEM, J. E. 2013a. *Offshore Risk Assessment - Principles, Modelling and Applications of QRA Studies,* London, UK, Springer-Verlag.

VINNEM, J. E. 2013b. TMR4555 Subject 4: Analysis of FPSO - shuttle tanker collision risk. *In:* TECHNOLOGY, N.-D. O. M. (ed.). It's learning.

VINNEM, J. E., HOKSTAD, P., DAMMEN, T., SAELE, H., CHEN, H., HAVER, S., KIERAN, O., KLEPPESTOE, H., THOMAS, J. J. & TOENNESSEN, L. L. 2003a. Operational safety analysis of FPSO - Shuttle Tanker collision risk reveals areas of improvement. *The 2003 Offshore Technology Conference.* Houston, Texas: Offshore Technology Conference.

VINNEM, J. E., UK, H. & TECHNOLOGY, N. U. O. S. A. 2003b. Operational safety of FPSOs shuttle tanker collision risk summary report. *In:* TECHNOLOGY, N. U. O. S. A. (ed.). London, UK: Health and Safety Executive UK.

WALPOLE, R. E., MYERS, R. H., MYERS, S. L. & YE, K. 2007. *Probability & statistics for engineers & scientists,* London, Pearson Prentice Hall.

WILKERSON, S. M. & NAGARAJAIAH, S. 2009. Optimal Offloading Configuration of Spread-Moored FPSOs. *Journal of Offshore Mechanics and Arctic Engineering,* 131.

XUE, L., FAN, J., RAUSAND, M. & ZHANG, L. 2013. A safety barrier-based accident model for offshore drilling blowouts. *Journal of Loss Prevention in the Process Industries,* 26**,** 164-171.

ØIEN, K. 2001. A framework for the establishment of organizational risk indicators. *Reliability Engineering & System Safety,* 74**,** 147-167.

APPENDIXES

A1 – DEFINITIONS

Table 14 shows selected risk terms and the associated definitions applied in this thesis, which are extracted from (Rausand, 2013) and (Vinnem et al., 2003b).

Table 14: Risk terminology

Term	Description
'*Accident*'	An incurred event whose outcome is undesirable.
'*Accident scenario*'	A specific chain of events, leading from the initiating event to the undesirable outcome. If no barriers[9] are in place, this can be a single event.
'*Event*'	Generally, an incidence that has a related outcome. An initial event may have numerous potential outcomes, whose severity also may vary.
'*Frequency*'	The rate of occurrence of an undesirable event. It is expressed as number of events per unit time, commonly per year.
'*Harm*'	Damage or physical injury to environment, property or health.
'*Hazard*'	Existing conditions that have the potential for resulting in an undesirable event.
'*Hazardous event*'	An event whose occurrence in turn initiates a sequence of events that ultimately leads to unwanted consequences to assets. Sometimes also termed accident initiating event, critical event, undesired event, or TOP event.
'*Near-miss*'	An incurred event whose outcome had potential for causing harm to assets, but did in fact not. The term may also be denoted as 'precursors' since such events are commonly hazardous events where safety barriers have prevented an accident.
'*Resilience*'	A system`s capability to absorb disturbances or shocks without suffering a catastrophic failure.
'*Risk-influencing factor*' (RIF)	A comparatively steady set of conditions that has an effect on the risk. RIFs can be classified as either consequence influencing or frequency influencing.
'*Vulnerability*'	A system`s incapability to withstand impacts of an undesirable event and restore its original state or function after the event.

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[9] See section 3.2.4.

A2 – SHUTTLE TANKER BRIDGE LAYOUT

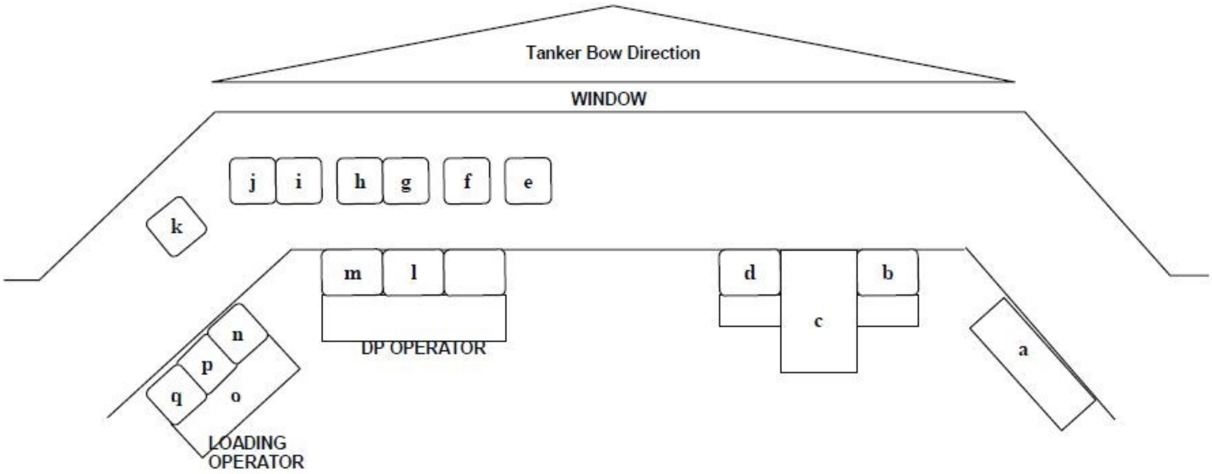

Figure 45: Shuttle tanker bridge layout. (Chen, 2003)

Table 15: Explanation to Figure 45 (Chen, 2003).

a.	Emergency key (engine and controller)	j. Video screen of hawser winch
b.	Radar	k. Video screen of tanker bow and FSU stern.
c.	Navigation board	l. DP II console (Slave)
d.	Radar	m. DP I console (Master)
e.	Artemis screen	n. BLS console
f.	Blom PMS monitor	o. ESD buttons
g.	DARPS I screen	p. Loading/ballast console I
h.	DARPS II screen	p. Loading/ballast console II
i.	Video screen of loading hose	

A3 – EXAMPLE OF THE PROCESS FOR A TANDEM OFFLOADING OPERATION IN THE NORTH SEA

Table 16 presents an example of the process for a tandem offloading operation in the North Sea, adopted from (Chen, 2003, pp. 130-132). It is included to enlighten the reader on how tandem offloading operations are performed in practice.

Table 16: The process for a tandem offloading operations in the North Sea (Chen, 2003).

Time/Distance	Operational Activities	Phase
3:30 am / 3 nm	Due to dense fog, approach is postponed	
5:30 am / 4800 m	ST begins approach towards FPSO FPSO heading 175° ST heading 272°, speed 15 kn Wind 18 kn, 280°, wave Hs 1,2 m	Approach phase starts
2400 m	ST speed 12 kn Contact from FPSO to ST	
1900 m	ST speed 10 kn	
5:53 am / 1870 m	Start DP manual ST speed 8,35 kn	
1718 m	ST speed 3,2 kn	
1500 m	ST 2,4 kn, heading 170°	Total duration 1 h 20 min
1000 m	ST speed 2,5 kn, heading 166°	
6:18 am / 500 m	ST speed 1,36 kn, heading 168° Contact from FPSO to ST	
350 m	ST speed 0,56 kn, heading 172°	
294 m	ST speed 0,39 kn, heading 176°	
233 m	ST speed 0,34 kn, heading 172°	
200 m	ST asking FPSO to change heading to 180°	
6:33 am / 165 m	Start DP Approach mode	
6:43 am / 118 m	DP drop-out test	
6:50 am / 75 m	Distance alarm setting, 3 m warning, 5 m alarm	Connection phase starts
75 m	ST contacts FPSO Ready for shooting messenger line	
7:00 am / 75 m	FPSO shoots messenger line on ST	
7:15 am / 75 m	Mooring connection, messenger line rolling	
7:20 am / 75 m	Chain stopper is locked	
7:21 am / 75 m	Start DP Weather vane mode. Take hawser tension input in DP reference input.	
7:30 am / 75 m	DP Weather vane mode with ‘operator selected heading’. FPSO heading 182°, ST heading 193°. This is in order to facilitate hose connection operation.	Duration 1 h 46 min
7:35 AM	Hose connection completed. ST asks FPSO to change heading to 195°.	
7:45 AM	Pump test, shutdown test. FPSO has initial problems with pump, problems are fixed	
8:05 AM	ST gets no signal of receiving oil. New pump test initiated. Chief Officer takes over for the 1st Officer on the bridge.	

Time/Distance	Operational Activities	Phase
8:36 AM	ST commences loading FPSO 194°, ST 198°. <u>Environmental condition</u>: Hs: 1,1 m, Current 2,5 m/s, Wind 9 kn.	Loading phase starts Duration 11 h 24 min
9:00 AM	2nd DARPS back to normal The position reference used: Artemis – position origin 1st & 2nd DARPS – relative distance	
9:10 AM	ST in loading FPSO 194°, ST 204°	
9:25 AM	Captain leaves bridge. Chief Officer on DP watch. 2nd Officer on the loading operation.	
12:45 PM	FPSO 239°, ST 243°	
3:30 PM	FPSO 314°, ST 315°	
4:00 PM	Dense fog, unable to FPSO stern. Wind 16 kn. Loading continues.	
6:00 PM	FSU 1°, ST 5°	
7:00 PM	Loading stopped. Start to flush hose from FPSO.	
7:50 pm / 75 m	Finish flushing hose. Close coupler valve. Close crude valve.	Disconnection phase starts Duration 21 min
8:00 PM	Hose is dropped. Send back hose messenger line.	
8:11 PM	Chain stopper is opened. Send back hawser, chain and messenger line.	
8:14 PM	Begin DP Approach mode. 100 m set as point distance.	Departure phase starts Duration 11 min
97,6 m	FSU 11°, ST 35°.	
200 m	Start DP manual	
8:25 PM	All messenger line is sent back ST sails away.	
TOTAL		**15 h 2 min**

A4 – GOVERNMENTAL REGULATIONS FOR TANDEM OFFLOADING OPERATIONS ON THE NCS

The PSA are responsible for HSE regulations concerning petroleum activities on the NCS. Overall, the regulations are divided into five categories, framework regulations, management regulations, information duty regulations, facilities regulations, and activity regulations. Most of the regulations' provisions are formulated as functional requirements, i.e. requirements to different characteristics, aspects or qualities, of the product, process or service. Along with the regulations, there is a set of guidelines providing recommendations for solutions to the requirements (Skogdalen and Vinnem, 2011).

In 2004, the PSA introduced the first regulations specifically targeted at preventing position incidents and collisions in shuttle tanker offloading operations on the NCS. However, definitions in the Petroleum Activities Act section 2 have implications for the regulations' validity, i.e. 'petroleum activity' does not include transport of petroleum in bulk by ship, 'facility' does not include ships transporting petroleum in bulk, but 'production' does include shipment of petroleum for ship transport. Subsequently, the aforementioned definitions make the PSA regulations only applicable for a shuttle tanker while it is inside the safety zone of the FPSO/FSU.

The abovementioned PSA regulations were modified in 2010. Based on experience from shuttle tanker operations, the 2010 edition of the activity and facilities regulations contains several clarifications of the recommendations on issues ranging from equipment classes to various offloading systems (Kvitrud et al., 2012).

Relevant to FPSO shuttle tanker tandem offloading operations:

- The regulations require the shuttle tanker to be equipped with DP class 2. However although the guideline recommends the FPSO/FSU to be equipped with a DP system, there is no formal requirement for such.
- Ship-shaped FPSOs/FSUs are required to know their own direction and position, as well as the direction and position of surrounding vessels and facilities, at all times. (Kvitrud et al., 2012) states that the text sounding in the guidance was made to ensure that the shuttle tanker`s position and movements can be monitored simultaneously by both the FPSO/FSU crew and the shuttle tanker crew, alerting both parties if the shuttle tanker has lost control of its position.

- If doing offloading operations without the use of mooring hawser, the shuttle tanker must have the capability of automatic offloading process shutdown if directional -or distance limits are exceeded, and there must be emergency shutdown valves installed on both shuttle tanker and FPSO/FSU. (Kvitrud et al., 2012) states that the text sounding was chosen to achieve the same level of safety in offloading operations, regardless of whether a mooring hawser is applied or not.
- The FPSO/FSU must be able to withstand any load, accidental or natural, with a likelihood equal to or exceeding 1.0E-04 per year, without loss of its main safety functions.
- If following the framework regulation Section 3, the FPSO/FSU must fulfil the Norwegian Maritime Directorate (NMD) regulations as well as any complementary classification rules issued by Det Norske Veritas (DNV). E.g. in relation to collision impact energy and installation energy absorption capacity, Norwegian offshore structures must meet the collision design minimum criteria, which corresponds to an impact energy of 11 MJ for head-on collisions and 14 MJ for sideways collisions (Vinnem, 2013a).
- NORSOK N-001 recommends for the shape of the FPSO/FSU stern to be rounded or partly rounded as it has been found that the collision energy absorbed by the FPSO, as well as the collision potential, is greatly reduced for slender stern designs (OLF, 2004).
- During FPSO/FSU – shuttle tanker offloading operations, all other ship activities should be halted for the duration of the hydrocarbon transfer. (Kvitrud et al., 2012) states that the text is projected to mitigate the crew risk if a position incident should occur.

A5 – INFLUENCE DIAGRAM FOR COLLISION RISK BETWEEN ST AND FPSO

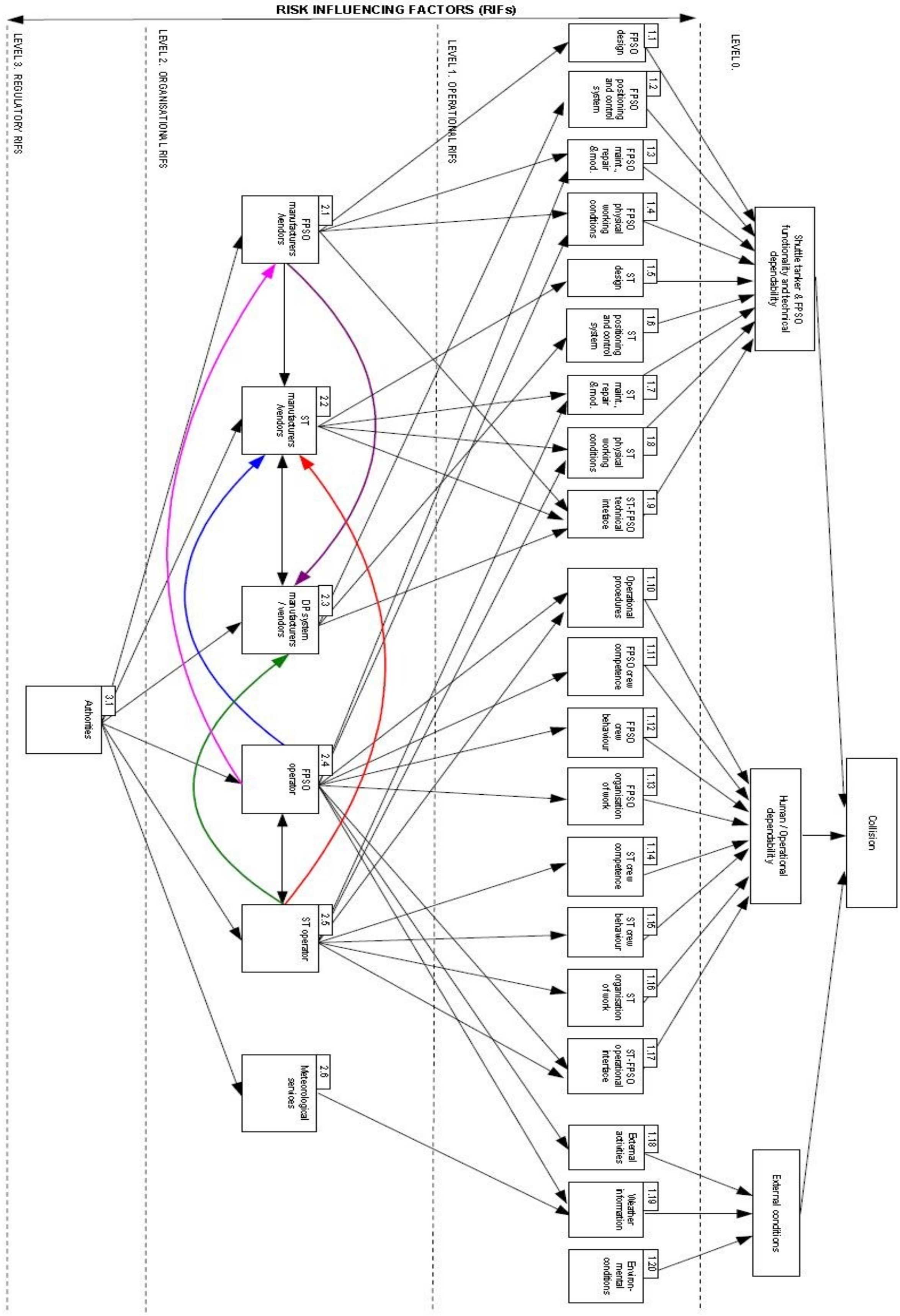

Figure 46: Influence diagram for collision risk between shuttle tanker and FPSO (Vinnem et al., 2003b).

A6 – PRODUCTION AND OFFLOADING STATISTICS FOR FPSOS/FSUS ON THE UKCS & NCS

Table 17: Annual and accumulated number of offloadings from FPSO/FSU, on the UKCS and the NCS, 1995-2013.

	UKCS		*NCS*	
Year	**Annual number of offloadings**	**Accumulated number of offloadings**	**Annual number of offloadings**	**Accumulated number of offloadings**
1995	72	72	0	0
1996	98	170	8	8
1997	164	335	19	27
1998	290	625	83	110
1999	394	1019	188	298
2000	406	1425	355	654
2001	430	1855	328	982
2002	444	2299	278	1260
2003	416	2715	273	1533
2004	362	3077	277	1810
2005	302	3379	267	2077
2006	266	3644	246	2323
2007	272	3916	203	2526
2008	211	4127	209	2735
2009	190	4317	225	2960
2010	189	4507	218	3179
2011	158	4665	188	3367
2012	171	4836	169	3536
2013	165	5001	165	3701

Table 18: Production and offloading statistics for FPSOs/FSUs on the NCS, 1995-2013.

FPSO	*Field*	*Total Field production [Sm3*10^3]*	*Total Field production [Tonnes*10^3]*	*FPSO storage capacity [tonnes]*	*Total number of loading operations*
Åsgard A FPSO	Åsgard (oil)	84961	71349	121495	587
Norne FPSO	Norne	87761	73700	96128	767
Alvheim FPSO	Alvheim	23202	19485	74766	261
	Vilje	8709	7314	74766	98
	Voulund	6508	5465	74766	73
Jotun A FPSO	Jotun	22868	19204	78024	246
Skrav FPSO	Skarv	2140	1797	116822	15
Balder FPSO	Balder	57674	48433	50734	955
Petrojarl Varg	Varg	15511	13026	62750	208
Njord B FSU	Njord	25815	21679	92123	235
Navion Saga FSU	Volve	8205	6890	133511	52
	Yme (No longer producing)	7906	6639	133511	50
Åsgard C FSU	Åsgard (condensate)	17113	14371	115888	124
	Mikkel (condensate)	2229	1872	115888	16
	Kristin (condensate)	2097	1761	115888	15
Total	-	372699	312988	-	3701

Table 19: Production and offloading statistics for FPSOs/FSUs on the UKCS, 1995-2013.

FPSO	*Field*	*Total Field production [Tonnes*10^3]*	*FPSO storage capacity [tonnes]*	*Total number of loading operations*
Schiehallion FPSO	SCHIEHALLION	46328	126836	365
Petrojarl Foinaven	FOINAVEN	49388	40053	1233
ALBA FSU	ALBA	57675	110147	524
Emerald FSU	Emerald	464	120160	4
Liverpool Bay Osi	LENNOX	13241	116155	114
	DOUGLAS	11706	116155	101
Glas Dowr (OOP)	DURWARD	907	88117	10
	DAUNTLESS	543	88117	6
	DONAN	833	88117	9
Triton FPSO	BITTERN	18122	84112	215
	GUILLEMOT W	3198	84112	38
	GUILLEMOT NW	945	84112	11
Bleo Holm	BLAKE	13115	117200	112
	ROSS	4327	117200	37
Global Producer III	BALLOCH	196	66756	3
	DUMBARTON	5167	66756	77
	LOCHRANZA	1376	66756	21
	LEADON (OOP)	2568	66756	38
Petrojarl Banff	BANFF	6714	16021	419
North Sea Producer	MACCULLOCH	15398	74766	206
Haewene Brim	PIERCE	14217	80107	177
Anasuria	TEAL	7522	113485	66
	TEAL SOUTH	967	113485	9
	GUILLEMOT A	5379	113485	47
Captain FPSO	CAPTAIN	41152	73431	560
Gryphon A	GRYPHON	16187	72096	225
	MACLURE	3941	72096	55
	TULLICH	3575	72096	50
Maersk Curlew	CURLEW	5796	74766	78
	CURLEW C	362	74766	5
	KYLE	2891	74766	39
Aoka Mizu	ETTRICK	2993	82642	36
BW Athena	ATHENA	737	6676	110
Total	-	357930	-	5001

A7 – INCIDENT DATA 1995-2003

Table 20: Number of incidents per operations phase, UKCS & NCS, 1995-2003.

#No. incidents in each phase UKCS and NCS		**#No. incidents in each phase UKCS**		**#No. incidents in each phase NCS**	
Loading	14	Loading	10	Loading	4
Disconnection	2	Disconnection	1	Disconnection	1
Connection	2	Connection	1	Connection	1
Approach	2	Approach	1	Approach	1
Sum	20	Sum	13	Sum	7

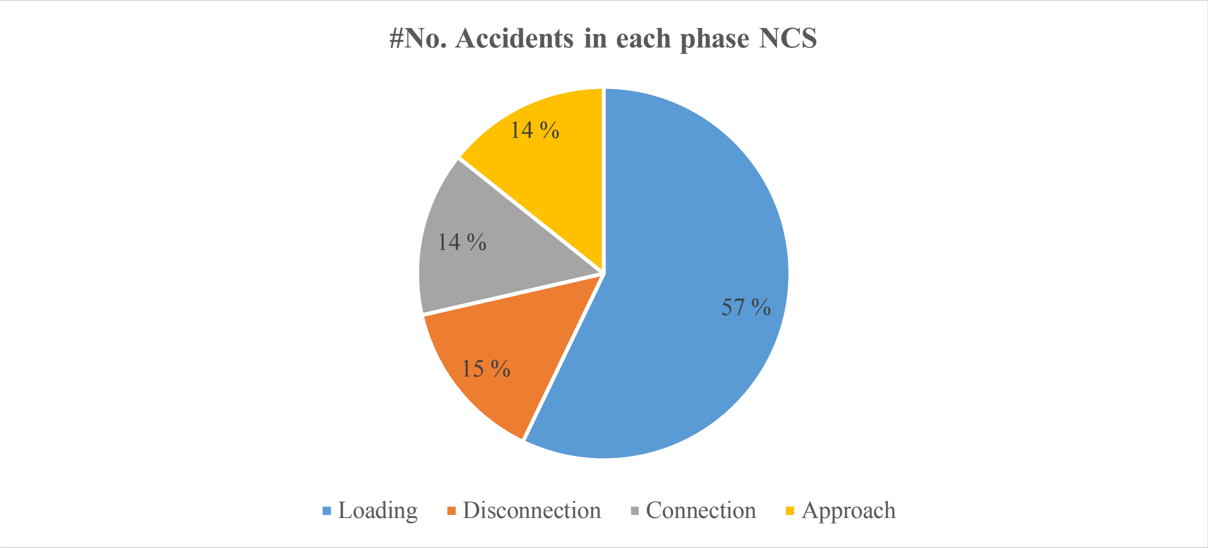

Figure 47: Number of accidents per operation phase, NCS 1995-2003.

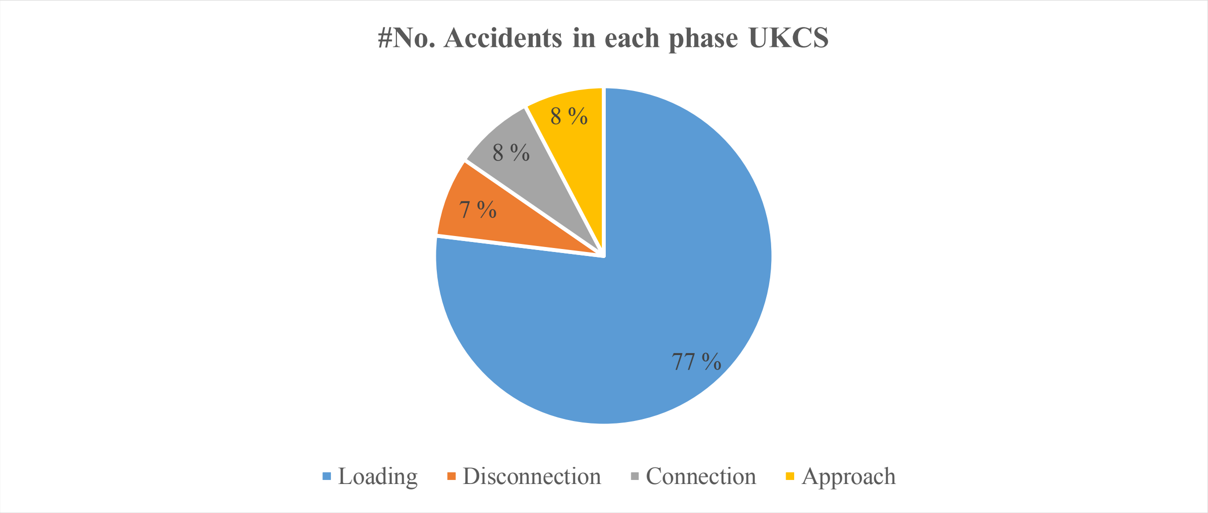

Figure 48: Number of accidents per operation phase, UKCS 1995-2003.

Table 21: Number of incidents per failure cause UKCS & NCS, 1995-2003.

Failure cause UKCS and NCS		**Failure cause UKCS**		**Failure cause NCS**	
Black-out	0	Black-out	0	Black-out	0
CPP failure	1	CPP failure	1	CPP failure	0
DP failure	5	DP failure	2	DP failure	3
Engine failure	1	Engine failure	1	Engine failure	0
FPSO thrusters tripped	1	FPSO thrusters tripped	1	FPSO thrusters tripped	0
Manually initiated drive off	1	Manually initiated drive off	0	Manually initiated drive off	1
Operator error	4	Operator error	3	Operator error	1
PRS failure	3	PRS failure	2	PRS failure	1
Rapid wind change	1	Rapid wind change	1	Rapid wind change	0
Technically initiated drive off	3	Technically initiated drive off	2	Technically initiated drive off	1
Sum	20	Sum	13	Sum	7

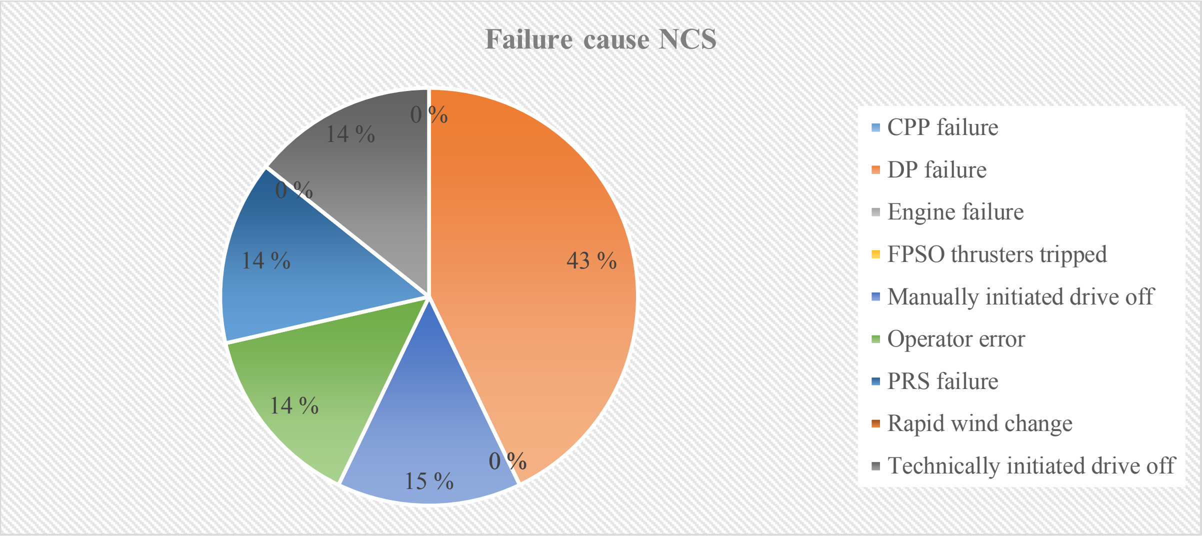

Figure 49: Distribution of incidents per failure cause, NCS 1995-2003.

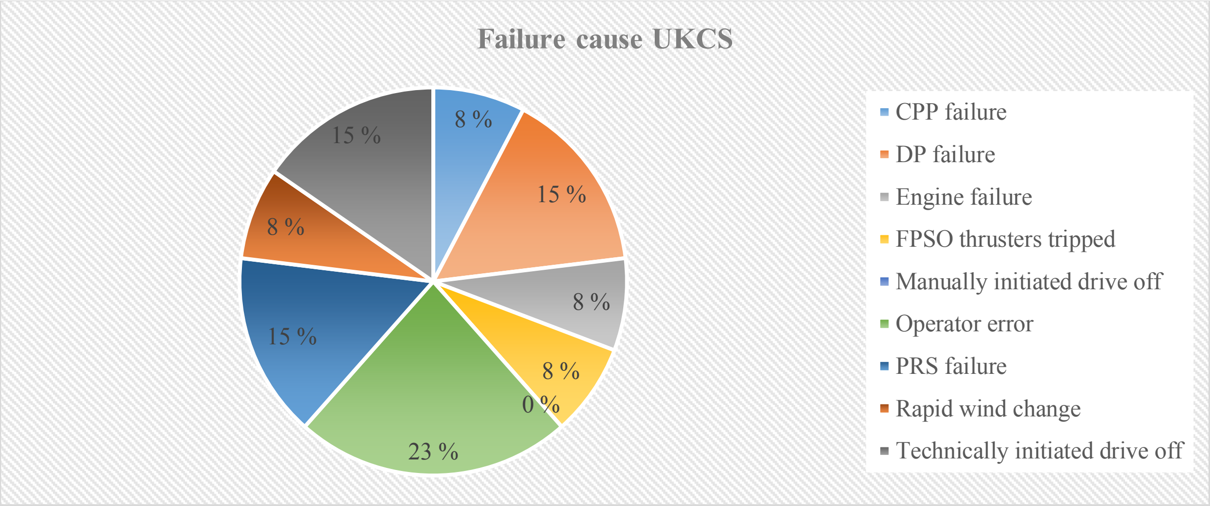

Figure 50: Distribution of incidents per failure cause, UKCS 1995-2003.

A8 – INCIDENT DATA 2004-2013

Table 22: Number of incidents per operations phase, UKCS & NCS, 2004-2013.

#No. incidents in each phase UKCS and NCS		**#No. incidents in each phase UKCS**		**#No. incidents in each phase NCS**	
Loading	5	Loading	0	Loading	5
Disconnection	0	Disconnection	0	Disconnection	0
Connection	2	Connection	0	Connection	2
Approach	1	Approach	1	Approach	0
Sum	8	Sum	1	Sum	7

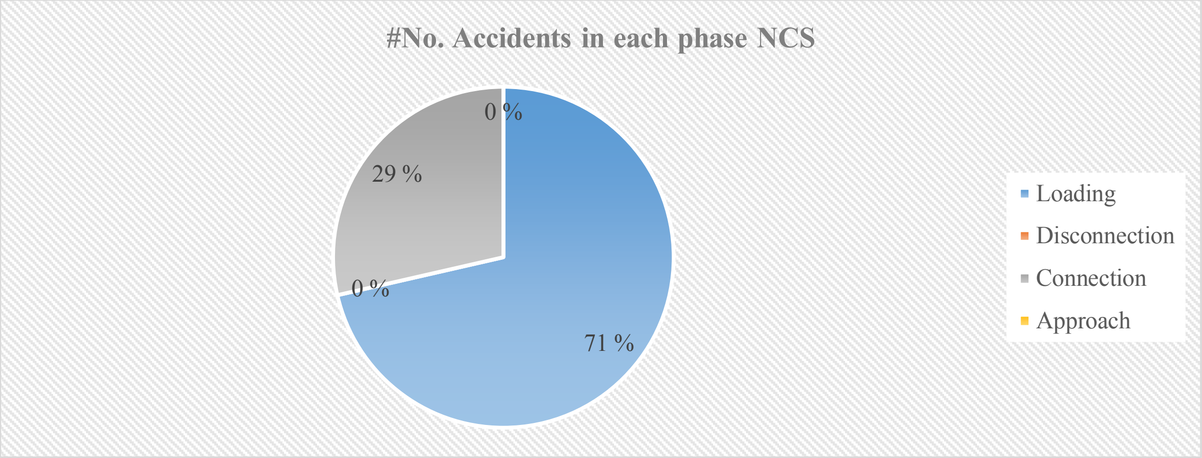

Figure 51: Distribution of incidents per operation phase, NCS 2004-2013.

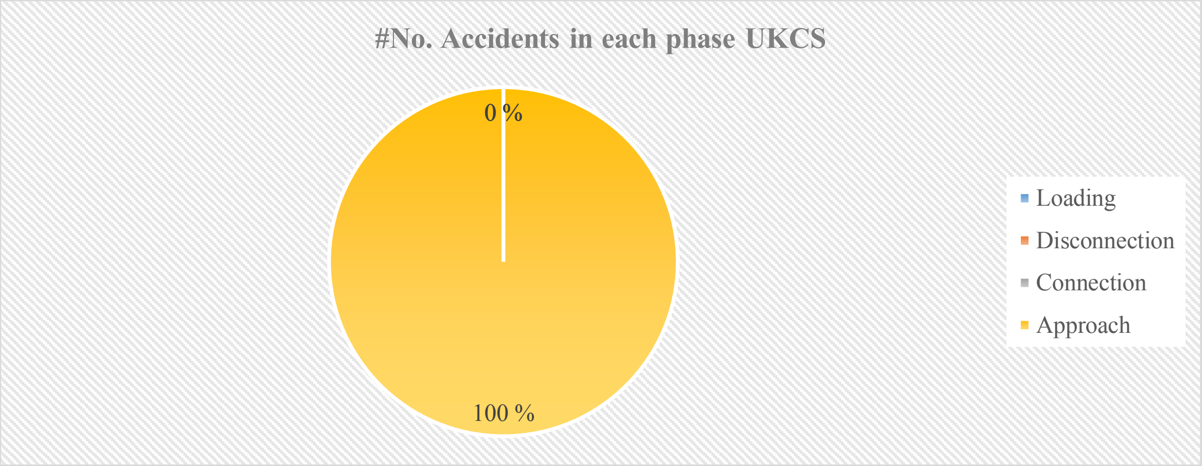

Figure 52: Distribution of incidents per operation phase, UKCS 2004-2013.

Table 23: Number of incidents per failure cause UKCS & NCS, 2004-2013..

Failure cause UKCS and NCS		**Failure cause UKCS**		**Failure cause NCS**	
Black-out	1	Black-out	0	Black-out	1
CPP failure	1	CPP failure	0	CPP failure	1
DP failure	1	DP failure	0	DP failure	1
Engine failure	1	Engine failure	0	Engine failure	1
FPSO thrusters tripped	0	FPSO thrusters tripped	0	FPSO thrusters tripped	0
Manually initiated drive off	0	Manually initiated drive off	0	Manually initiated drive off	0
Operator error	1	Operator error	0	Operator error	1
PRS failure	2	PRS failure	1	PRS failure	1
Rapid wind change	1	Rapid wind change	0	Rapid wind change	1
Technically initiated drive off	0	Technically initiated drive off	0	Technically initiated drive off	0
Sum	8	Sum	1	Sum	7

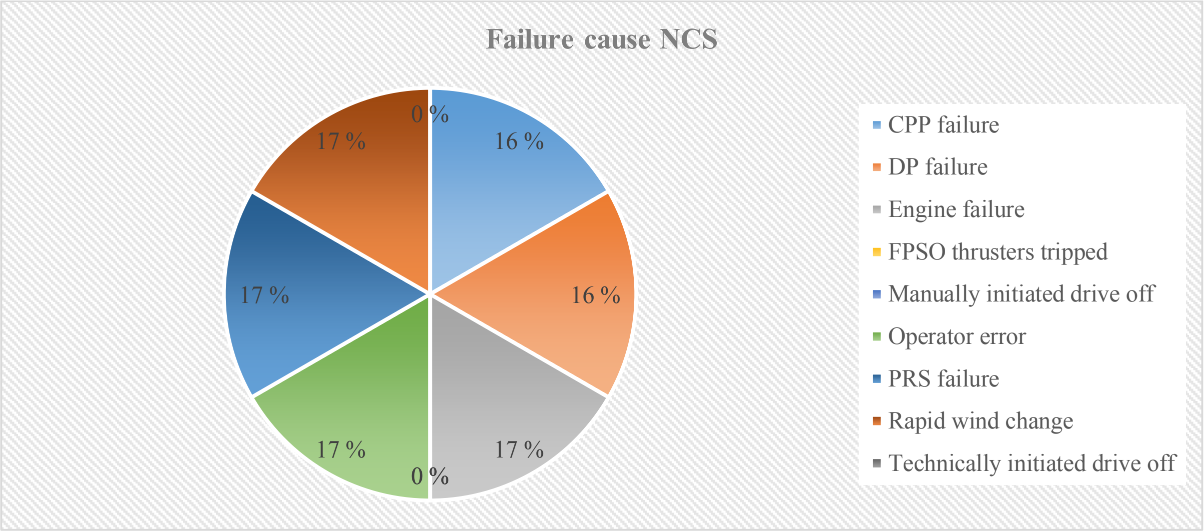

Figure 53: Distribution of incidents per failure cause, NCS 2004-2013.

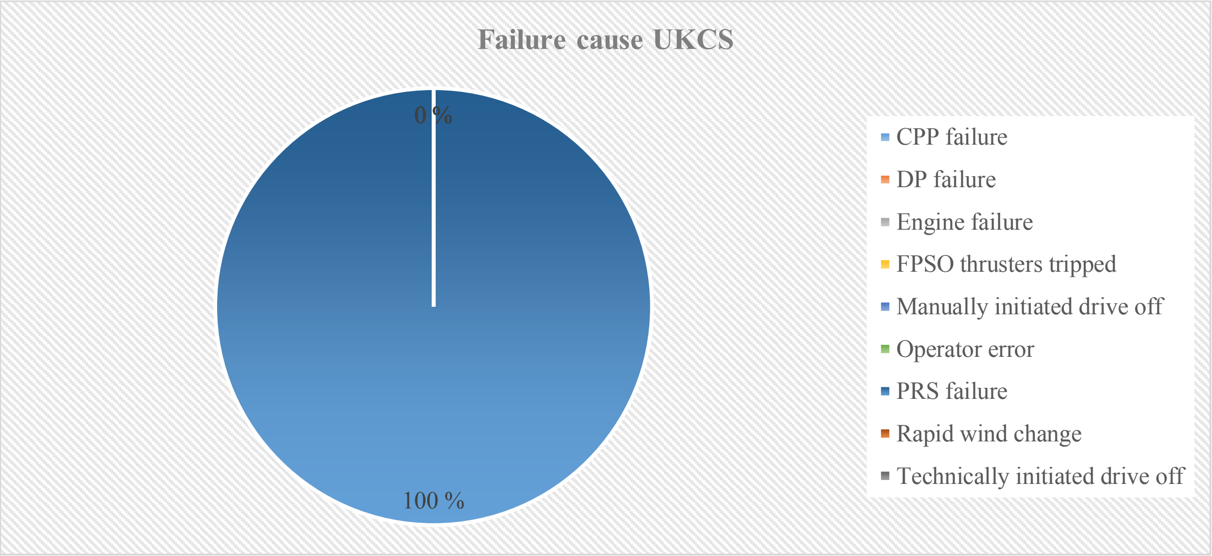

Figure 54: Distribution of incidents per failure cause, UKCS 2004-2013.

A9 – INCIDENT DATA 1995-2013

Table 24: Number of incidents per operations phase, UKCS & NCS, 1995-2013

#No. incidents in each phase UKCS and NCS		**#No. incidents in each phase UKCS**		**#No. incidents in each phase NCS**	
Loading	19	Loading	10	Loading	9
Disconnection	2	Disconnection	1	Disconnection	1
Connection	4	Connection	1	Connection	3
Approach	3	Approach	2	Approach	1
Sum	28	Sum	14	Sum	14

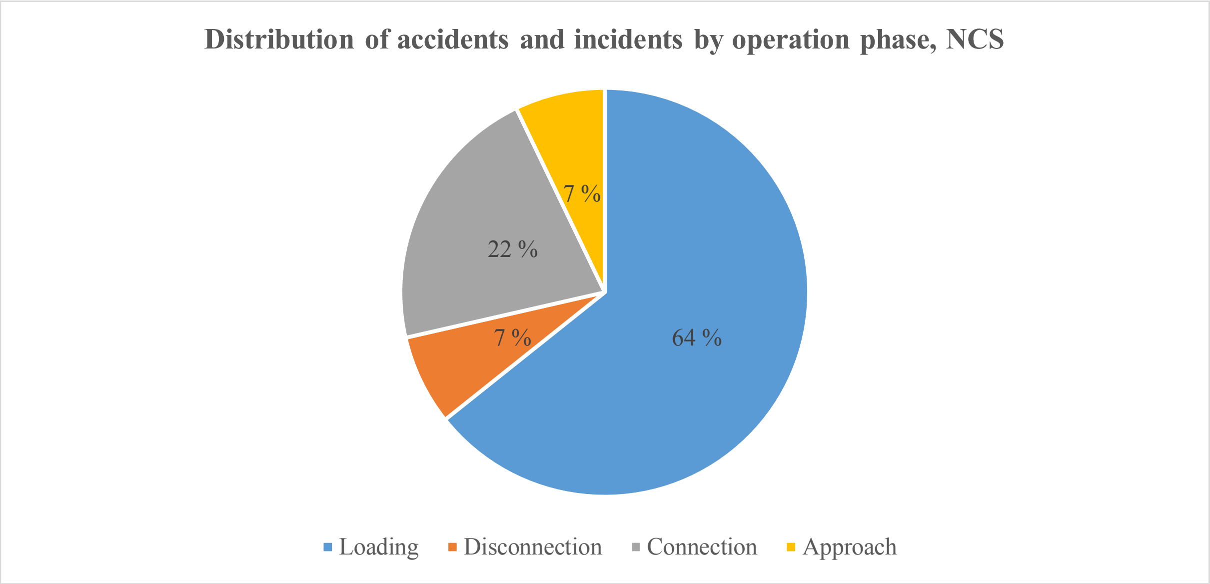

Figure 55: Distribution of incidents per operation phase, NCS 1995-2013.

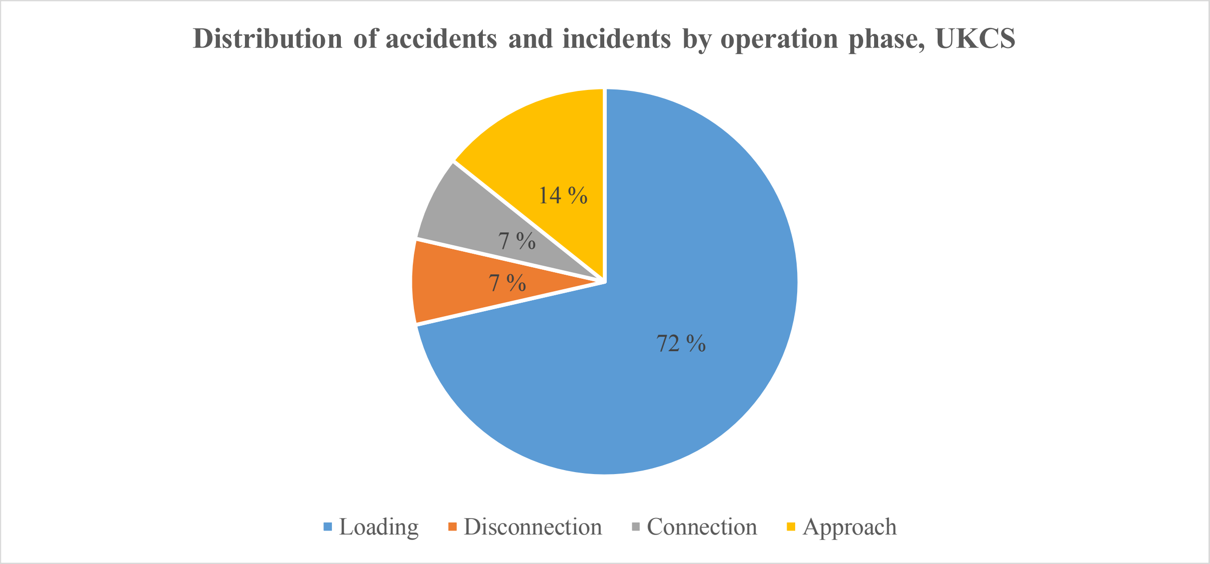

Figure 56: Distribution of incidents per operation phase, UKCS 1995-2013.

Table 25: Number of incidents per failure cause UKCS & NCS, 1995-2013.

Failure cause UKCS and NCS		**Failure cause UKCS**		**Failure cause NCS**	
Black-out	1	Black-out	0	Black-out	1
CPP failure	2	CPP failure	1	CPP failure	1
DP failure	6	DP failure	2	DP failure	4
Engine failure	2	Engine failure	1	Engine failure	1
FPSO thrusters tripped	1	FPSO thrusters tripped	1	FPSO thrusters tripped	0
Manually initiated drive off	1	Manually initiated drive off	0	Manually initiated drive off	1
Operator error	5	Operator error	3	Operator error	2
PRS failure	5	PRS failure	3	PRS failure	2
Rapid wind change	2	Rapid wind change	1	Rapid wind change	1
Technically initiated drive off	3	Technically initiated drive off	2	Technically initiated drive off	1
Sum	28	Sum	14	Sum	14

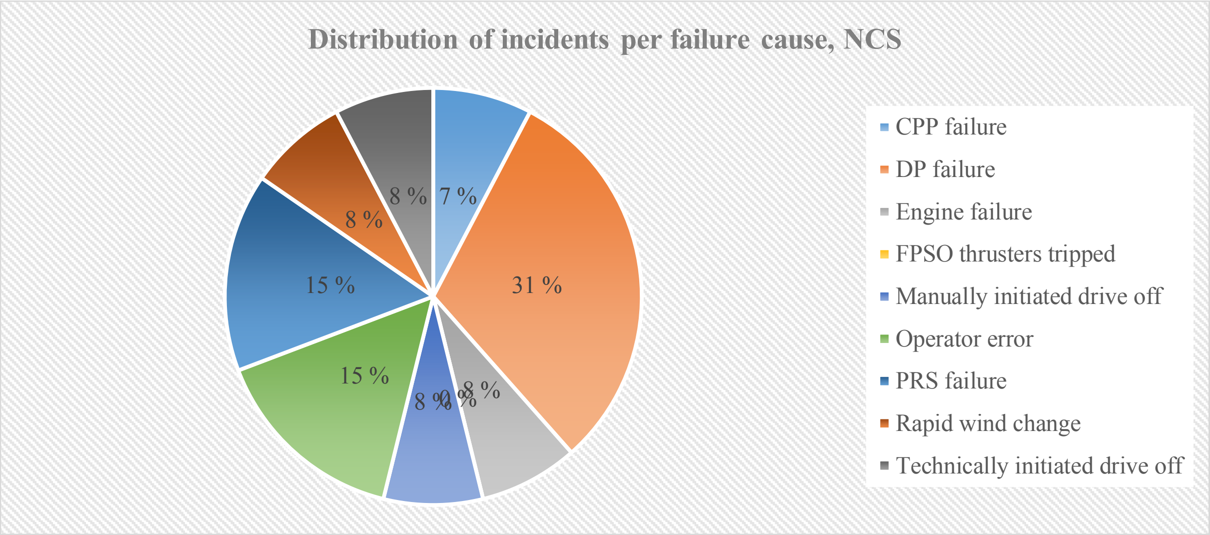

Figure 57: Distribution of incidents per failure cause, NCS 1995-2013.

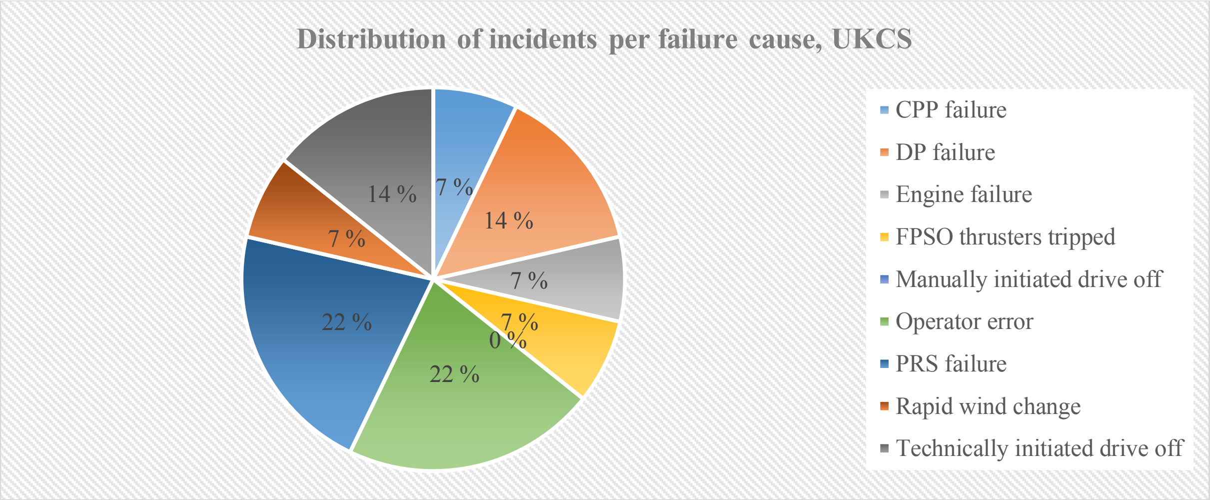

Figure 58: Distribution of incidents per failure cause, UKCS 1995-2013.

A10 – PROBABILITY CALCULATIONS

Table 26: Probability calculations for selected time periods, UKCS & NCS.

UKCS & NCS			
Period	1995-2013	1995-2003	2004-2013
Number of years	19	9	10
Total number of incidents	28	20	8
Total number of drive-offs	20	16	4
Total number of collisions	7	5	2
Incidents per year	1.47	2.22	0.80
Collisions per year	0.37	0.56	0.20
Total number of offloadings	8702	4248	4455
Pr(Drive off)	0.00230	0.00377	0.00090
Pr(failure of recovery|drive-off)	0.35000	0.31250	0.50000
Pr(collision)	0.00080	0.00118	0.00045

Table 27: Probability calculations for selected time periods, UKCS.

UKCS			
Period	1995-2013	1995-2003	2004-2013
Number of years	19	9	10
Total number of incidents	14	13	1
Total number of drive-offs	11	10	1
Total number of collisions	5	4	1
Incidents per year	0.74	1.44	0.10
Collisions per year	0.26	0.44	0.10
Total number of offloadings	5001	2715	2286
Pr(Drive off)	0.00220	0.00368	0.00044
Pr(failure of recovery|drive-off)	0.45455	0.40000	1.00000
Pr(collision)	0.00100	0.00147	0.00044

Table 28: Probability calculations for selected time periods, NCS.

NCS			
Period	1995-2013	1995-2003	2004-2013
Number of years	19	9	10
Total number of incidents	14	7	7
Total number of drive-offs	10	6	3
Total number of collisions	2	1	1
Incidents per year	0.74	0.78	0.70
Collisions per year	0.11	0.11	0.10
Total number of offloadings	3701	1533	2168
Pr(Drive off)	0.00270	0.00391	0.00138
Pr(failure of recovery|drive-off)	0.20000	0.16667	0.33333
Pr(collision)	0.00054	0.00065	0.00046

Table 29: Incident probabilities per year for the UKCS & NCS aggregated. Part 1.

Year	1995	1996	1997	1998	1999	2000
Number of years	1	1	1	1	1	1
Total number of incidents	0	1	3	2	4	5
Total number of drive-offs	0	1	2	1	4	4
Total number of collisions	0	1	2	1	0	1
Incidents per year	0	1	3	2	4	5
Collisions per year	0	1	2	1	0	1
Total number of offloadings	72	106	184	373	582	762
Pr(Drive off)	0	0.00948	0.01089	0.00268	0.00687	0.00525
Pr(failure of recovery|drive-off)	0	1	1	1	0	0.25
Pr(collision)	0	0.00948	0.01089	0.00268	0	0.00131

Table 30: Incident probabilities per year for the UKCS & NCS aggregated. Part 2.

Year	2001	2002	2003	2004	2005	2006
Number of years	1	1	1	1	1	1
Total number of incidents	2	2	1	1	0	1
Total number of drive-offs	2	1	1	1	0	1
Total number of collisions	0	0	0	0	0	1
Incidents per year	2	2	1	1	0	1
Collisions per year	0	0	0	0	0	1
Total number of offloadings	759	721	689	639	569	512
Pr(Drive off)	0.00264	0.00139	0.00145	0.00156	0	0.00195
Pr(failure of recovery|drive-off)	0	0	0	0	0	1
Pr(collision)	0	0	0	0	0	0.00195

Table 31: Incident probabilities per year for the UKCS & NCS aggregated. Part 3.

Year	2007	2008	2009	2010	2011	2012	2013
Number of years	1	1	1	1	1	1	1
Total number of incidents	1	0	3	0	1	0	0
Total number of drive-offs	0	0	2	0	0	0	0
Total number of collisions	0	0	1	0	0	0	0
Incidents per year	1	0	3	0	1	0	0
Collisions per year	0	0	1	0	0	0	0
Total number of offloadings	475	421	415	408	346	340	330
Pr(Drive off)	0	0	0.00482	0	0	0	0
Pr(failure of recovery|drive-off)	0	0	0.5	0	0	0	0
Pr(collision)	0	0	0.00241	0	0	0	0

A11 – TABLES AND FIGURES FOR COMPARISON OF INCIDENT DATA

Table 32: Number of incidents, in selected time periods.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	28	20	8
UKCS	14	13	1
NCS	14	7	7

Table 33: Incident frequency per offloading, in selected time periods.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.00322	0.00471	0.00180
UKCS	0.00280	0.00479	0.00044
NCS	0.00378	0.00457	0.00323

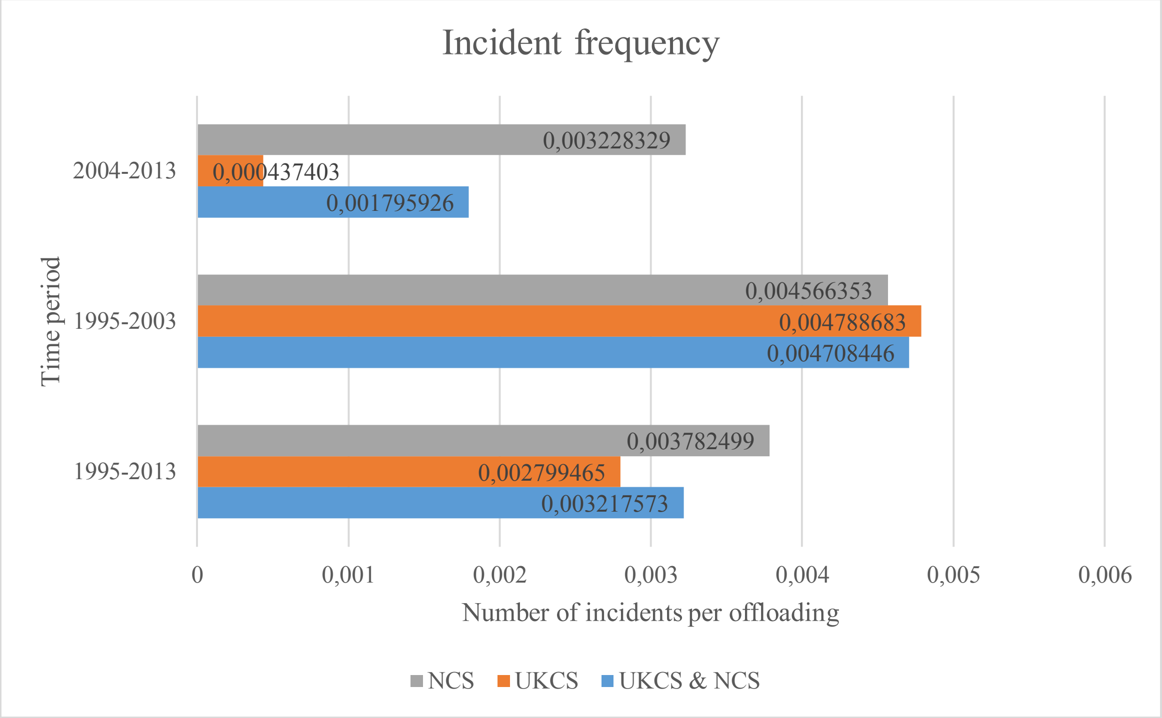

Figure 59: Incident frequency per offloading, comparison chart.

Table 34: Number of collisions, in selected time periods.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	7	5	2
UKCS	5	4	1
NCS	2	1	1

Table 35: Collision frequency per offloading, in selected time periods.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.00080	0.00118	0.00045
UKCS	0.00100	0.00147	0.00044
NCS	0.00054	0.00065	0.00046

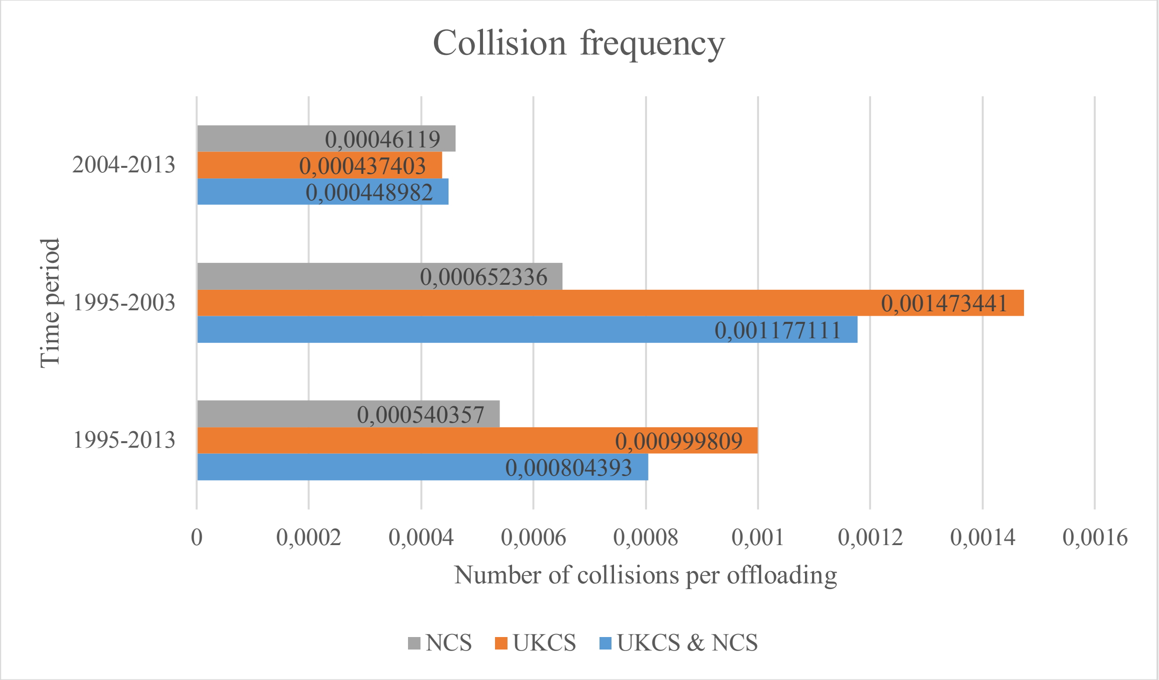

Figure 60: Collision frequency per offloading, comparison chart.

Table 36: Drive-off frequency per offloading, in selected time periods.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.00230	0.00377	0.00090
UKCS	0.00220	0.00368	0.00044
NCS	0.00391	0.00391	0.00138

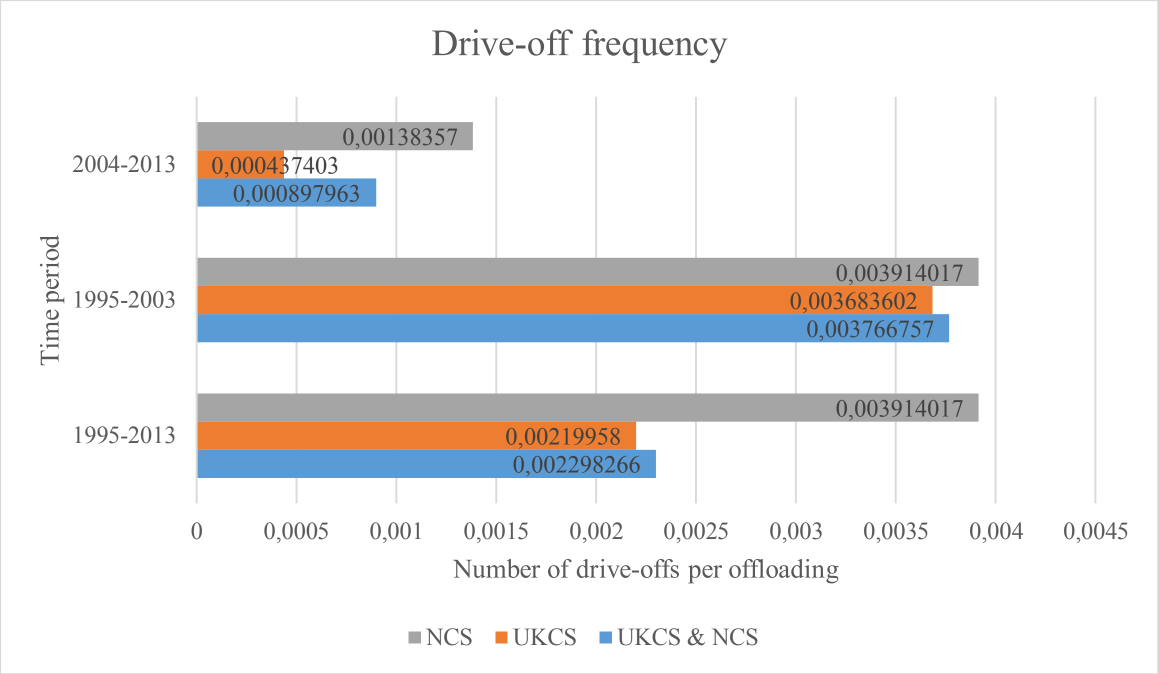

Figure 61: Drive-off frequency, comparison chart.

Table 37: Pr(failure of recovery|drive-off), in selected time periods

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.350	0.313	0.500
UKCS	0.455	0.400	1.000
NCS	0.200	0.167	0.333

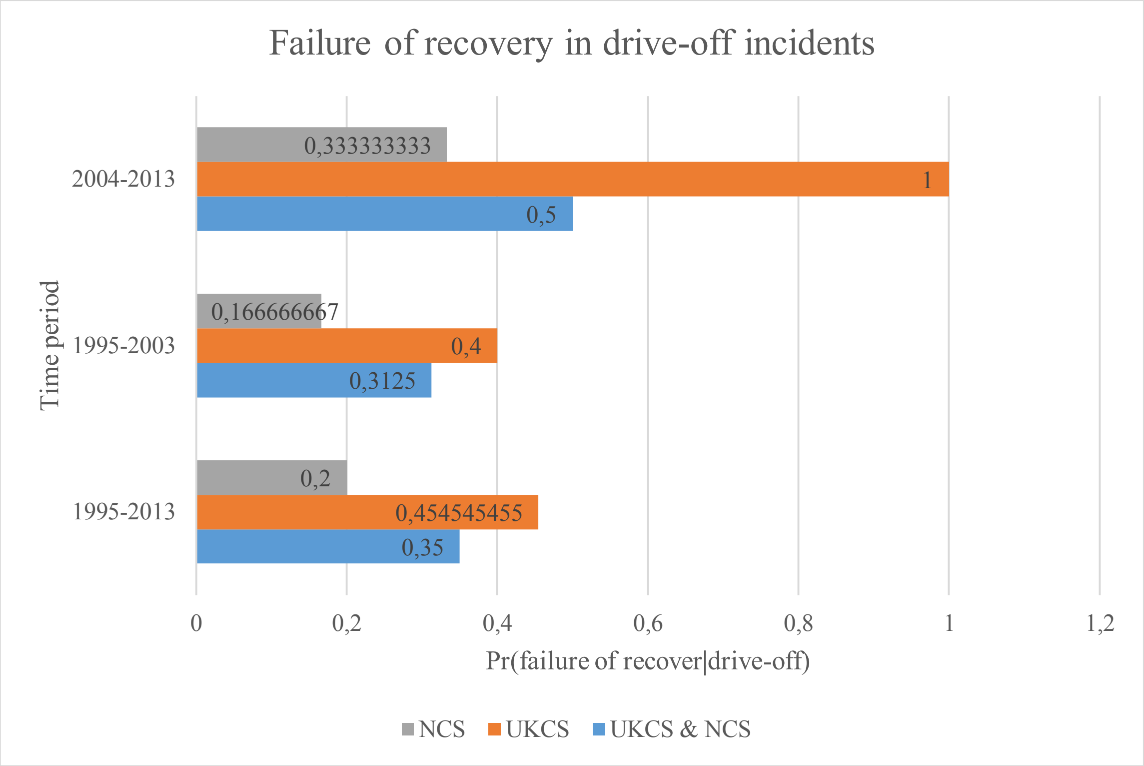

Figure 62: Pr(failure of recovery|drive-off), comparison chart.

Table 38: Drive-off frequency per offloading in direct offloading configuration.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.00153	0.00251	0.00060
UKCS	0.00147	0.00246	0.00029
NCS	0.00261	0.00261	0.00092

Table 39: Collision frequency per offloading, in direct offloading configuration.

Period	*1995-2013*	*1995-2003*	*2004-2013*
UKCS & NCS	0.00015	0.00025	0.00006
UKCS	0.00015	0.00025	0.00003
NCS	0.00026	0.00026	0.00009