On the need for online decision support in FPSO – Shuttle Tanker collision risk reduction

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Abstract

More than 100 Floating Production Storage & Off-loading (FPSO) concepts are in operation at the moment worldwide, and due to increasing demand many are currently under construction or being converted from commercial tankers. Still, operational risk is an issue that is not considered thoroughly in the initial feed stage, especially when compared to fixed installations. Floating installations are more dependent on manual control of some of the marine systems during normal operations, as well as during critical situations. Accidents can be initiated by errors induced by human and organizational factors (HOF), technical (design) failures, environmental conditions, or a combination of all three. Therefore, effective means are extremely important to prevent or mitigate the effects of potential operational accidents that can result in serious accidents. Updated statistics in 2013 revealed that the frequency of operational accidents during the last ten years was significantly above the target value that has been aimed for, in fact it was concluded that the frequency was around one order of magnitude higher. Hence, the objective of this article is to assess the hazards, the existing barriers, the risk level, and the risk reduction potentials more thoroughly.

Keywords

Floating Production Storage & Offloading (FPSO), operational risk, collision frequency

1. Introduction

Floating Production Storage & Off-loading (FPSO) concepts in principle add mobility to the conventional fixed or floating production platforms. They were traditionally ship-shaped vessels and are involved in oil production and off-loading activities. FPSO concepts were used for the first time in the North Sea and Norwegian Sea in 1986, with the construction of Petrojarl 1 (Teekay, 2012) for extended well testing and pilot production. It was not until 10 years later that several FPSO vessels were installed in the British sector and subsequently in the Norwegian sector of the North Sea, including West of Shetland (North Atlantic) and the Norwegian Sea. These FPSOs were used for regular production of oil and gas resources in the North Sea.

The use of such large vessels has been successful in many ways, without serious accidents to personnel or the environment. More than 100 FPSOs are in operation at the moment worldwide, and due to increasing demand many are currently under construction or being converted from commercial tankers. The use of such vessels is relatively higher in less hostile environmental locations, such as in part of Africa and South-East Asia. Converted tankers (i.e., formally engineered as ships, but later converted into production and storage vessels) appear to be much more dominating in these waters. The vessels that are in operation in fields in the North Sea, the North Atlantic, and/or the Norwegian Sea traditionally have been designed for considerably higher environmental loads, and often have higher throughput compared to those in more benign waters. Without exception, those vessels that are in operation or under construction for these non-benign areas have what is termed an 'internal' turret, that is, a turret integrated into the hull structure in order to transfer environmental loads. The location of the turret implies that those FPSOs that have thruster-power may use this to adjust and fine tune its heading. Such adjustments may ease the navigational burdens on the shuttle tanker and its crew.

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Although FPSOs have become more common, operational risk is an issue that still is not considered thoroughly in the initial feed stage, especially when compared to fixed installations. Floating installations are more dependent on manual control of some of the marine systems during normal operations, as well as during critical situations. Accidents can often be initiated by errors induced by human and organizational factors (HOF), technical (design) failures, environmental conditions or a combination of all three. Therefore, effective means and fail-safe interfaces are extremely important in order to prevent or mitigate the effects of potential operational accidents that can result in loss of life, serious commercial losses and even major environmental damage in the event of damage to the hull.

Most FPSO/ Floating Storage Unit (FSU(s)) in the North Sea rely on shuttle tankers (ST) for cargo oil offloading. The off-loading operation is carried out in what is termed “tandem configuration”. This means that the tanker is positioned at some distance behind the FPSO. A mooring hawser and a loading hose, through which the cargo is off-loaded, physically connect the two vessels. Figure 1 shows the analysis envelope for collision risk, including both FPSO and ST in a tandem off-loading operation, with a [non-taut] hawser connection. Station-keeping and heading-keeping are important capabilities of the FPSO and the ST in the tandem off-loading operation, in order to conduct the operation safely and efficiently. Station-keeping and heading-keeping are dependent on several important systems on each of the vessels. The capabilities of these essential systems are quite variable, because there is a mix of purpose built and converted vessels.

Accidents and incidents started to occur quite rapidly in the mid 1990s, especially collisions between the ST (for off-loading purposes) and the FPSO vessels during off-loading operations. Five collision accidents occurred during the five year period, 1996 – 2000 (Vinnem, 2003), four in the British sector and one in the Norwegian sector, of which the first occurred with a Floating Storage Unit (FSU). Until recently, FPSO and FSU have been understood as tanker shaped vessels, the only difference being that the FSU is lacking the process equipment and is limited to storage of crude oil. Off-take by shuttle tankers is a common feature. The Goliat Sevan-concept´s circular floating structure with storage tanks (Chen, 2014) is under construction to be installed in the near future. This is also referred to as an ‘FPSO’ according to the field operator ENI, and has a similar off-loading concept involving shuttle tankers. But there are also very distinct differences with respect to the concept design, as well as operations, not the least related to absence of weather vaning.

Vinnem (2003) presents the list of accidents and incidents involving FPSO/FSU and ST during the initial period 1996–2003. The unwanted events were so frequent that both authorities and the companies started to worry, and saw a common interest in contributing to a reduction of the incident/accident frequencies. A Joint Industry Project (JIP) was launched as collaboration between UK and Norway, with oil company, shuttle tanker operator, and authority participation (Vinnem, 2003) to analyze the ST collision risk in detail as a basis for proposing risk-reducing measures (Vinnem et al., 2002 & 2003).

The JIP project was partly based on historical reports and incident investigations. Interviews were also conducted with operational personnel for further clarification of specific issues of interests. It helped to compile a good basis of experience data. During the analysis and resolution process, the emphasis was mainly placed on generic influencing factors and feasible solutions from human and human interface perspectives.

Several risk-reducing proposals were made, mainly in the organizational and operational fields. Increased competence and training in simulators were among the main actions taken by the industry, and the frequency of incidents and accidents dropped in the following years (Chen & Moan, 2005; Chen, Moan & Vinnem, 2007; Vinnem, 2013; Lundborg 2014). The industry concluded almost 10 years ago, on the basis of the results presented by Vinnem et al. (2003) and Chen (2002), that the frequency of such accidents were reduced to below 10^{-4} per installation year, which is the cut-off limit for scenarios that offshore installations have to be designed for (PSA, 2014).

Updated statistics in 2013 (Vinnem, 2013; Lundborg, 2014) revealed that the frequency of such scenarios during the last ten years was significantly above the 10^{-4} per installation year limit, in fact, it was concluded that the frequency was around 10^{-3} per installation year. Hence, the objective of this article is to assess the hazards, the existing barriers, the risk level and the risk reduction potentials more thoroughly. The approach adopted in the article is to use statistics from events in the past to calculate the risk level of the future. Two of the crucial conditions for such an approach is that (i) the volume of previous incidents is so high that uncertainties are limited, and (ii) future systems and operations are comparable to past conditions. Both (i) and (ii) are considered to be reasonably well covered to the extent that the assessments should have reasonable validity.

The structure of this article is as follows: section 2 discusses the hazards that are involved in the off-loading operations from FPSO/FSU to shuttle tankers with the tandem configuration of these vessels. The risk levels and the contributing factors are discussed in section 3, including the possibilities for risk reduction. One particular concept for risk reduction is the introduction of on-line risk management system in order to assist the DP operators on the shuttle tankers in their decision-making if serious precursor events occur. The concept is introduced in section 4, followed by discussion and conclusions in section 5.

2. FPSO – Shuttle Tanker tandem off-loading concept main characteristics and hazards

2.1.Regulations, Standards and Industry Practice

There are no specific regulations neither in UK nor in Norway that pertains specifically to FPSOs and/or ST, with the exception that dynamic positioning (DP) class 2 is required for off-loading from an FPSO to a shuttle tanker in the Norwegian sector.

Oil and gas UK, together with Health and Safety Executive (HSE) and the ‘Step Change in Safety’ programme developed some years ago design and construction guidelines for FPSO and recommendations for off-loading by tankers: Tandem off-loading guidelines[2]. These guidelines have also been adopted by the operators in the Norwegian sector, on a voluntary basis. There are, however, some differences between UK and Norwegian operations, when it comes to configurations and technical solutions, as shown in Table 1.

The separation distances during off-loading are usually somewhat longer in the Norwegian fields compared to UK fields, implying that hawser and hose are longer in Norwegian fields. DP1 tankers are also somewhat more extensively used in the UK sector and both these two aspects have implications for the collision hazard. Also the heading control capability of the FPSO has implications for the collision risk, because turning the FPSO will be more controlled, and thus it is possible to plan for the ST. This aspect is therefore also included in Table 2.

In the Norwegian sector, there is only one FPSO, which off-loads to a shuttle tanker in ‘taut hawser’ mode (Petrojarl 1), with approx. 0.5 knots speed astern in order to keep a minimum tension in the hawser. In UK, there are several fields that use or have used the ‘taut hawser’ mode.

Operational procedures are fairly standardized, with main focus on arrival and departure procedures, such as distance (where manual control shall be taken over by tanker (say 500 m)) and maximum speed limit during approach. Connection distance is governed by the possibility to transfer and connect the hawser.
When it comes to the stable off-loading phase, the procedures and relatively general, and some shuttle tanker captains have their own more detailed procedures. The same applies to emergency procedures; some procedures provide very general guidance on what to do in an emergency, whereas others contain more details.

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[2] , http://www.ukooa.co.uk/issues/fpso

2.2.Hazards for tandem off-loading

The main hazard during tandem off-loading is collision between the ST and the FPSO. Structural damage and possible need for repair of one or both vessels would be the typical outcome of such events, but severe consequences could occur in extreme situations. This could involve extensive environmental spill and/or major fire. Escalation to storage tanks could occur in adverse circumstances, especially if a flare tower located in the stern of the FPSO topples over due to the impact.

The entire off-loading cycle consists of three main phases. A collision may occur in any of the phases of off-loading operations:

- Approach and connection
- Off-loading
- Disconnection

It should be noted that the durations of these phases are quite different; the first and last typically last for up to one hour, whereas the actual off-loading typically goes on for 20 hours, or even more. The distance between the vessels is the shortest (the order of 30 m) during connection and disconnection. The distance during off-loading is usually in the 50 – 80 m range, but two recent cases (including Skarv FPSO) have increased the distance to at least 150 m (Chen, 2014).

Experience with DP systems has demonstrated that incidents and accidents may occur in the following circumstances:

- Drive-off (by shuttle tanker)
- Drift-off (by shuttle tanker)
- Surging (by FPSO)
- Fishtailing (by FPSO)

Surging and fishtailing were involved in the collisions in 1997 and 1998, but have since then not caused accidents. It may thus appear that the crew competence has increased relating to how to operate in a safe manner in these circumstances.

Standby vessels and/or tugs are not used actively for DP tankers in relation to FPSOs, because they have sufficient maneuverability, and the tanker will, due to the upwind heading, drift away from the FPSO, in the case of power loss. There is also a very long drifting distance to shore.

The main hazard scenario is drive-off, particularly during the off-loading phase, which has a long duration as noted above. Drive-off implies a powered, yet uncontrolled forward movement of the ST causing a collision, regardless of the underlying cause. The main attention in the following discussions in this article is therefore on the drive-off scenario. Section 3 is limited to the drive-off scenario only.

Environmental load has a direct effect on the dynamic nature of operations involving FPSOs and STs in a tandem configuration. Subsequent responses can take place in the form of auto-guided rapid positioning and/or manual human intervention tasks. Notably, rough weather conditions are often a challenge in the North Sea, increasing the collision risk between vessels. Technologies, such as global positioning systems (GPS), are used as reference input to the dynamic positioning system, but human interventions in monitoring and control activities have never been completely designed-out because of the inherent risk of vessel-to-vessel collisions, due to malfunctions or delayed/unwanted responses of the technical monitoring-and-response system. In this dynamic setting, harmony between human, technological, and organizational components of the operational setting is extremely critical in terms of operational risk exposure.

All FPSOs have a conventional mooring system without variation. There is, however, an extensive variation in terms of propulsion. Some vessels do not have any propulsion power at all, neither main propulsion (for forward movement) nor thruster power (for sideways movement). The other extreme side of the case is having an FPSO with main propulsion (as for a conventional tanker), in addition to extensive thruster power. Thruster power is particularly important for heading-keeping, that is, to maintain a particular heading of the vessel. The FPSOs without any propulsion do not have any heading-keeping ability, and is subjected to weather vaning passively in response to the forces of wind, waves, and current. The STs have main propulsion, either as single or twin screw (main propellers), but there is an extensive variation in thruster power from none to the redundant dynamic positioning (DP) system.

The most basic DP system is the DP1 concept, where there are no requirements to redundancy. DP2 implies that no single fault in an active system will cause the system to fail, implying that virtually all active components of the DP system have to be redundant, except the main engines. Other components of the DP system, such as reference systems, computers, thrusters, and control systems, shall be redundant in order to achieve the 'DP2 classes´; The DP2 tankers have relatively slim chances for DP system failure. DP3 vessels have even lower probability, as also main engines are redundant. DP3 is used, for instance, for diving vessels. The normal off-loading mode for the ST is in DP mode, assuming that the tanker is at least a DP1 tanker. In some areas, a minimum of DP2 is required, either by regulation or as industry practice. ST may operate in 'non-DP' mode in some cases with 'taut hawser', that is, by pulling with a limited force (by main propulsion) on the hawser to keep it tensioned in order to control the distance. This is a simple way to control the distance, but has more limitations with respect to the conditions of the sea compared to the DP mode. The off-loading distance between the FPSO and the ST varies from 50 meters up to some 150 meters. This has particular importance for the time window available for the operator to respond in the case of abnormal occurrences. This is discussed in detail below. Table 2 illustrates some of the major configuration variations that have important impact on the potential for collision risk between the ST and the FPSO.

During vessel-to-vessel operations, the main focus is on the off-loading phase, which can typically take up to 20 hours (more in some cases). In addition, other phases may be just as critical, but all with limited durations. These phases involve:

- ST approach (up to 500 meter distance to the FPSO)
- ST connection to FPSO (from 500 meter distance to physical connection between the vessels)
- Disconnection of ST (from connected until 500 meter distance between the vessels) ST sail away (from 500 meter distance)

One of the main hazards relating to these operations is the threat of collision between the two vessels. Obviously, such a potential collision situation arises due to the close proximity of the vessels, that is, when the ST for some reason moves closer to the FPSO than the normal distance during off-loading. The likelihood is highest for this to occur during the long off-loading phase. The important issue is that proximity is a variable that is largely affected by the condition of the sea and the wind patterns, and regulation of the level of proximity is usually under the control of the fully-automated DP system under the surveillance of human operators. Alarm limits are defined in the DP system, but if the system or its inputs fail, alarm may not be given or may not be sufficient to prevent collision. In this particular case, different collision scenarios can be considered in relation to:

- Different loading phases (as mentioned above)
- Possible initiating events (drive-off, drift-off, etc., see discussion below)

Table 2 gives an overview of 28 reported incidents in tandem off-loading mode in the North Sea during the years 1996–2013. ‘Near-miss’ and ‘Collision’ are obvious classifications. ‘Other’ implies incidents that are less severe than ‘near-miss’, such as failure of a vital system, but without further consequences.

Data on FPSO-ST incidents are not fully available in the public domain (Chen, 2014), and thus the opportunity for lack of reporting exists. There are two main sources; Petroleum Safety Authority (PSA) for incidents and accidents in the Norwegian sector (in the public domain), and International Marine Contractors Association (IMCA) for worldwide occurrences. The IMCA source is based on membership and is therefore not accessible in the public domain. This also implies that validity completeness is unknown. Underreporting in the IMCA database is not unlikely, due to membership restrictions.

3. Review of FPSO – Shuttle Tanker tandem off-loading collision risk

3.1. Collision risk scenario

The most feared collision scenario is called 'drive-off'. The primary cause of such a failure is a flaw in the DP system itself, and there is usually no automatic recovery possible in these situations (the recent drive-off preventer is outlined in Section 3.4). Manual intervention by the DP operator on the bridge is usually the only way left to control the situation, described in detail in the following. Other collision scenarios include surging and extensive heading deviations (Chen, 2002). These scenarios are not included in the discussions in this article.

The drive-off scenario is particularly critical due to the movement of the ST towards the FPSO and the lack of recovery options. The fact that the ST often will accelerate towards the FPSO implies that it increases the impact speed of a collision. Hence, the role of the timing of operator responses is a very critical issue. This can be illustrated briefly through some accidents and incidents that have occurred in the past, with particular emphasis on the time windows that were available for operator response and recovery action.

Vinnem and Liyanage (2008) present five cases, of which recovery action initiation was completed within 40–45 seconds in two of the cases, i.e., those without collision. In the three remaining cases the recovery action initiation took 60 seconds or more, and they all resulted in collision. This illustrates the criticality of response times[3] in the handling of abnormal situations.

The five cases shown in Vinnem and Liyanage (2008) have approximately the same distances between FPSO and ST; 70–80 m. The times used by DP operators to initiate recovery action were 100; 80; 50; 40 and 30 seconds, of with the two last cases avoided collision. The challenges for the DP operator in a Human-Machine-Interface (HMI) context are discussed more in depth in Vinnem and Liyanage (2008).

3.2. Causes to ‘drive-off’

Vessels and rigs are becoming more technologically advanced and operate in more challenging environments. Complexity is increasing, particularly in terms of integration and dependencies between sub-systems and components. Operation and system status may be so complex that operators onboard do not have the full overview of the potential behavior of all systems, and may not be able to handle all arising situations in a safe and effective manner. The number of signals and failure modes to be considered may be many thousands where proper response actions must be taken in few seconds. Intuitive alarm systems with operator support prioritizing actions and guiding the operator to critical situations are missing for complex systems and operations.

The DP system on a shuttle tanker is a very advanced automation system with complex human-machine interaction. It is documented in Vinnem et al. (2003) how the majority of incidents and accidents are caused by a combination of technical, environmental and human and organizational factors.

Figure 2 presents the distribution of the primary initiating causes for FPSO-ST collisions and near-misses, for UK and Norwegian sectors in the period 1996–2013, based on statistics presented by Vinnem (2013) and Lundborg (2014). Only collisions (7 cases) and near-misses (13 cases) are included in the diagram, whereas

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[3] The times referred to cover the following phases: Time to detect an abnormal behaviour of the DP system ('drive off'); Time to interpret the information and warnings; Time to decide what is the best evasive action to take; Time to implement the decisions made; Time for the vessel to respond to actions taken by operator.

the less severe ('other') incidents are disregarded in the diagram. Each incident is classified into only one category of initiating causes, and some of the categories have been split between DP1 and DP2 tankers.

First of all it may be noted that there is no single dominating causal factor. Operator error contributed to three collisions, referred to as "too late recovery action". Operator error (or too late recovery action) account for 25%, if accidents and incidents are combined. DP software and engine/propulsion failures account for 50%, whereas reference system (PRS) failure accounts for 20%.

DP software with DP2 class system has never caused an actual collision, only near-misses. There are, on the other hand, aspects of the collision in year 2000, which are related to DP software of a DP2 tanker. DP1 class has been involved in one collision and two near-misses. Loss of engine or power failure has not resulted in any collision, irrespective of DP class.

The seven collisions have been caused by DP software (1), engine failure (1), error in reference system (2), and operator late recovery action (3). Vinnem (2013) mentions an FPSO-ST collision in Brazil in May 2012, involving a DP2 tanker; indications are that this also was a DP software problem with too late recovery action.

It is worth noting that in the case of DP software errors and reference system errors only manual control of thrusters and propulsion is a possible way to control the situation.

It is also worth noting that although some causes may be expected, they are not found in the statistical reporting. One such cause, for example, may be failure of wind sensor, which may have happened in the past. There are several reasons why such causes may not be visible; one of which is related to possible underreporting, as discussed in Section 2.2. Another possible explanation is that an event may have been classified under an alternative primary cause. This further emphasizes the weakness of such an approach, where each incident or accident is only given one cause. There will often be a combination of a causes.

3.3.Collision risk level

Vinnem (2013) presents a 10-year rolling average frequency of slightly less than 0.5 collisions per 1000 ST visits. This corresponds to 0.025 collisions per year for an FPSO with 50 visits per year (thus corresponding to an 'installation year'). The trend is falling, but it has only decreased by a factor of 3 since the peak around year 2000. The statistics cannot support an anticipated reduction by a factor of 10 (or more), i.e., from 10^{-3} to 10^{-4}per installation year. The volume of accidents and incidents is too low to allow a formal trend analysis to be carried out, and the observation of a falling trend is purely a subjective evaluation, and thus relatively weak.

The latest statistics is presented by Lundborg (2014) in a MSc thesis, based on statistics from British and Norwegian sectors. For UK and Norwegian sectors, the following is the average collision frequency for the period 1995–2013, when it is assumed 30 off-loading cycles per installation per year (Lundborg, 2014):

FPSO – ST collision frequency: $2.4 \cdot 10^{-2}$ per installation year

The average UK and Norway collision frequency for the period 1995–2003, when it is assumed 50 off-loading cycles per installation per year (Lundborg, 2014):

FPSO – ST collision frequency: $3.6 \cdot 10^{-2}$ per installation year

The average UK and Norway collision frequency for the period 2004–2013, when it is assumed 50 off-loading cycles per installation per year (Lundborg, 2014):

FPSO – ST collision frequency: $1.35 \cdot 10^{-2}$ per installation year

The average collision frequency for the Norwegian sector alone for the period 2004–2013 is virtually the same as the average for the UK and Norwegian sectors (Lundborg, 2014).

Lundborg (2014) has presented average frequencies for the UK and Norwegian sectors combined, whereas Vinnem (2013) has presented different historical frequencies for UK and Norwegian sectors. None of these sources have taken any allowance for possible underreporting. Table 1 also shows that there are significant technical differences between the two sectors. These differences may have caused different frequencies in the early phase, i.e., before 2004/5. It would still be expected that the risk level is lower in the Norwegian sector due to the differences in Table 1, but this cannot be substantiated based on statistics.

3.4. Need for improvement of tandem off-loading concept

The preceding sections have shown that there is a substantial need to reduce the frequency of collision, if the aim is to bring the frequency below 10^{-4} per installation year. The collision frequency needs to be reduced by more than one order of magnitude. 10^{-4} is the accepted risk level in the Norwegian oil and gas industry. A variety of causes that may lead to drive-off scenarios have been presented in this article in Section 3. The DP system in a failed state is found in the majority of the cases, thus it cannot provide additional barrier functions. Hence, the DP operator is often the only barrier element left. The available time for response by the DP operator is mainly a function of the distance between the FPSO and the ST.

The need for bringing the frequency down below 10^{-4} per installation year stems from the cut-off criterion for design accidental loads (PSA, 2014), in relation to main safety functions. Although it may be questionable if a shuttle tanker collision would impair a safety function, it is still customary to consider this limit to be applicable, because it cannot be ruled out that such impairment may occur. But there are additional requirements (PSA, 2014b) for further risk reduction (ALARP), as well as the precautionary principle, etc. Therefore, reducing the frequency to below 10^{-4} per installation year should be followed by emphasis on further risk reduction. For the time being, however, the challenge to bring the frequency below 10^{-4} per installation year is hard enough to overcome.

Two recent FPSO installations have off-loading operation with distance to the ST about 150 m, in order to increase the available time for recovery. It is unlikely that such an increase of distance will lead to a reduction of the collision frequency by more than one order of magnitude; in fact, the likely reduction is perhaps by a factor of 3–4 (half an order of magnitude). It is impossible to visualize that any type and extent of improvement of present barriers (including DP operator performance) are capable of reducing the collision frequency with one order of magnitude. More fundamental improvements, such as implementation of additional, independent barriers, will therefore be required to achieve a reduction of the collision frequency by more than one order of magnitude.

Recently new functionality has been added in some commercial DP software solutions (called Drive-off Preventer (Chen, 2014)). The details of this function are not available publicly; hence, we have assumed that the system will automatically initiate a full astern movement, if all alarm limits are passed in a drive-off situation without operator response actions. If these assumptions are correct, the next question is to what extent such new functionality will be able to intervene in cases when the DP software is failed or intact, and to what extent the reference and propulsion systems need to be intact. If all these functions need to be intact for the Drive-off preventer to work properly, the only major risk contributor in Figure 1 that could be reduced by this new functionality would be the ‘operator’ category, which then would not result in a dramatic reduction of the collision frequency.

Therefore, it is required to search for more fundamental improvements of the tandem off-loading to reduce the collision frequency to below 10^{-4} per installation year. In principle, a new barrier function is required. Online decision support and alarm systems during critical situations, such as drive-off of DP-systems, may prevent critical unwanted events or provide earlier situational awareness and increased response time to allow for manual intervention in such cases. The following theoretical speculation may indicate the potential: if the new function of online decision support and alarm system has a failure probability of 5% and in theory is applicable to all failure modes, the collision frequency could in principle be reduced by a factor of 20 (1/0.05). An online decision support system shall provide early warning to the operator about possible future deviations from the operating envelope of the system. As such, we claim that in theory it may be possible through such a system to mitigate all failure modes. However, since this is a theoretical speculation, the intention in this article is not to illustrate how it could be achieved in practice. In reality, such a function would probably not apply to all failure modes, and thus never achieve a reduction factor of 20.

4. Online risk management – concept and framework

Development of on-line decision support for safer FPSO/ST operation involves risk assessment and modeling, data models and representation, sensors and communication technology, visual computing, human-machine interface (HMI), and organization theory, as well as system integration. Online decision support systems leads to improved functionality in safety critical software-based systems, better informed operators, less manual operation and intervention, and longer response time if manual intervention becomes necessary. In this section an online risk management framework is proposed providing online decision support and giving DP operators a real-time risk picture and pre-warnings of possible deviations in on-board automatic systems.

Current risk analysis presents a static picture of the average state of the system and operation, based on historical data and expert judgments. Risk analysis techniques for offshore oil and gas systems have been developing for more than 30 years, but methods are mainly developed for the design phase and they are not used regularly. The Quantitative Risk Assessment (QRA) is, for example, updated with typically 5-year intervals. During operation, only safe job analysis (SJA) is carried out regularly (Vinnem et al., 2010). SJA is mainly focused on occupational risk during the execution of work and not major hazard risk. In recent years the need for more dynamic risk assessment approaches has been addressed (Skogdalen et al., 2011), i.e., risk assessment methods that can be used as an operational tool reflecting any rapid changes or incremental increases in the risk level for standard daily operations. Among the very few known attempts on a more dynamic risk analysis in the petroleum industry are developed by Statoil and ConocoPhillips, but these tools are not yet in widespread use.

The application of sensors in online decision support systems capable of monitoring assets covering large areas has been hindered by, e.g., the cost of wired sensor networks, complex installation and space limitations. As a result many sensor technologies are confined to inspection applications. Developments in wireless technology and cheaper, smaller and improved sensor technology opens up for increased use of online measurements in decision support. Assessments for communication technology (e-Com) are well-known, but mostly for the Information and Communication Technology (ICT) system itself. Loss or degradation in e-Com are considered, but their effects on risk management are hardly addressed. DP vessels are exposed to risk due to loss of communication related to the global positioning system (accuracy, availability, and stability), internal communication systems, or the input data accuracy.

The amount of information a person can utilize depends on the available time and the method for data representation. DP operations are characterized by the need for rapidly understanding changes in the state of complex processes from real time sensor data and video.

4.1 Online risk management framework

Online risk management will supply the operators in FPSO/ST operations with a real time risk picture and pre-warnings of possible deviations in the DP system. Even though the focus in this article is on FPSO/ST operations, it is expected that the framework can be applied to on-line decision support in a number of marine operations. The framework is illustrated in Figure 3 and consists of a number of modules, such as risk models, data models, HMI, visualization module as well as decision support module. Input data will be historical data, online sensor data and experience data.

The on-line risk models build on data from different sources (historical data, sensors and measurements, and experience data). The data models may range from empirical models based on historical or online data to physics-based models; and they may be either static models or include dynamics. Without online data, models' effectiveness is quickly lost, thus degrading the risk monitoring precision level. Further, online data interpretation without mathematical models may lead to inappropriate advice to the users since the information content in the online data itself may be inadequate to identify a hazardous situation. There are numerous methods for merging models with online data. These include deterministic, typically optimization based, methods, and stochastic techniques, e.g., Bayesian methods. The choice and tailoring of an algorithm depends on a range of factors, including data stream, uncertainty and computational demand. Moreover, physical-based models are also considered as data generators and as basis for simulations and simulator development. The utilization of data based models could reduce the level of uncertainty and provide means for prediction of information, handling of large data loads, as well as fusing of data from different sources (Foss, 2012).

The risk models are based on current methods, such as quantitative risk assessment (QRA), fault tree analysis (FTA), event tree analysis (ETA), bayesian belief networks (BBN), accident models, such as STAMP (Leverson, 2011) and FRAM (Hollnagel, 2006) etc. Experience data from operator training can be used to improve the risk models through updated data models.

The proposed framework emphasizes the need for exploring the potential for enhanced utilization of existing sensors and instrumentations to improve online decision support, as well as the development of new monitoring solutions, e.g., in marine operations. Improvement of the conditions for sense-making and decision making in complex, information-dense and high-tech environments, requires acknowledgement of both the formal modes of working, characterised by procedures, standardised work flows and models, as well as the informal modes of working with operationalized experience, pragmatic workarounds and case-based reasoning.

An online risk management framework can be applied to marine operations, for example, in terms of an independent software based system installed on a ship´s bridge or in the central control room utilizing data from the propulsion system, the power management system, wind, waves, and currents to analyse the operational performance. The results of the analysis will be presented to the human operator(s) for information about any possible deviations, but the system will also be able to intervene if the operator does not take appropriate action. The previously mentioned "drive-off preventer" can be considered as a very early and limited version of an online risk management system for DP-operations.

4.2 The framework applied to DP systems for FPSO/ST operations

The online risk management framework as outlined above is supposed to provide an additional barrier function to improve the decision support and alarm systems before and during critical situations, such as drive-off. This additional function should provide earlier situational awareness and increased response time to allow for manual intervention of human operators. The need for a new barrier function was outlined in Section 3.4. During development of the online risk management system more knowledge on the potential problems, risk and challenges with current operations are expected, which combined with operational experience from implementation of the system should contribute to inherently safer design of DP-systems.

Before designing and implementing a barrier function in terms of the suggested online risk management system it is necessary to analyze the relevant operations in detail. For DP operation it is necessary to start with a description of operation, task analysis, and consequence analysis of failure (to facilities) due to technical and human errors, for example in drive-off scenario, both for single and multiple vessel operation. The framework can be applied to develop an aggregated risk picture that specific and detailed information that contribute to risk are presented in an easily accessible manner to the operator. Existing qualitative risk models (Chen et al., 2008; Vinnem, 2003) mainly based on influence diagrams, can be expanded on and quantification can be introduced, as well as improving the time representation in the model. Current methods do not take the time aspect into account sufficiently and risk should be modeled as a function of time through early warnings indications of allowable windows or operating envelopes to avoid loss of control.

Figure 4 shows a simplified influence diagram of important risk influencing factors (RIFs) for a drive-off scenario leading to a collision. The grey box illustrates the barrier function of the online risk management system, which contains the functionality in Figure 3. The node "sensors" is included because the independent online risk management system needs separate sensors and instrumentation, for example regarding position and heading of the vessel, to avoid potential cascading failures propagating from other software systems (such as the DP system). The node "condition and process parameters" also includes existing sensors instrumentation.

The risk models used as basis for the online risk management system or decision support system set requirements to data input and information. An advisory system should be developed to handle uncertainty in data and estimation of missing data. Uncertainty in data, for example with respect to any measurement problems, has to be addressed since this is a key to generate probabilistic risk information.

There may be an improvement potential for new sensors and measurements, and there may be opportunities for better state representation and more advanced analysis of existing data. This may be important, for example, for giving early warning and preparing operators for possibility of needs for rapid manual actions. Part of the input may also be based on simulation of possible scenarios.

The risk models will generate information about risk of technical failure and time availability for recovery actions. HMI knowledge and methods will be exploited on how to present this information together with control systems in an optimal manner. This can allow the operators to take manual control before the automation breaks down, and thus invite for more advanced human-automation collaboration. Rule based, naturalistic and discretionary decision-making, including organizational context, perception, sense-making, and interpretation have to be considered.

Decision making in safety critical operations occur in multidisciplinary work environments, where the dependence on sensor data and model support is high. A case study should focus on the challenge for different groups of professionals to put together pieces of information to create a coherent picture and to give meaning to familiar and unfamiliar situations.

5. Conclusions

Although the performance of FPSO ST tandem off-loading systems has improved over the past 10–15 years, the statistics presented in this article still reveal that considerable improvement is needed. A reduction of the collision frequency by one order of magnitude is necessary to reach a value below 10^{-4} per installation year; the limit below which such a scenario need to be designed against. To achieve such extensive reduction, an additional barrier function is required. This barrier needs to be independent of other barriers, including the DP system. The extra barrier function is suggested to be an independent online risk management system, as outlined in Section 4, with advisory functions to enable the operator to make better and timely decisions, but probably also with independent automatic avoidance maneuvering as a last resort.

A number of systems in oil and gas operation, such as marine operations and topside processing, are exposed to unpredictable environmental conditions and operational risk. Complexity in operations, software systems, sub-systems and components is increasing and current decision support systems are insufficient. Risk assessment methods are currently based on statistical data and probability models and to a large extent human judgment. In addition, up till now there has been a large focus on alarms. Alarms are not proactive and often leave short time for operators to react. For the operator to achieve full situation awareness, prediction of incidents, near-misses, and accidents is needed, as well as an improved understanding of the current situation and on how to act. The suggested concept and framework in this article can be installed in parallel with existing systems, such as automatic on-board control systems, to supply systems with independent, early warning of possible accidents or incidents. Advances in estimation and data assimilation are important to bring into online risk management development.

The framework outlined in this article contributes to the development of a best practice framework with respect to barrier management in offshore operations. The framework should be integrated within the overall risk management of the vessel. Important prerequisites are deriving requirements for available data, measurements, data types, format and condition data for equipment and operation, and determine available data and software. In addition, it is necessary to assess the needs for additional sensors and instrumentation.

Further work includes development of a simulator to be integrated in operator training simulators followed by the development of a demonstrator and pilot. This may be extended from the FPSO ST tandem off-loading operations to other DP operations and beyond.

Abbreviations

ALARP	As low as reasonably practicable
BBN	Bayesian belief network
CPP	Controllable pitch propeller
DP	Dynamic positioning
ETA	Event tree analysis
FPSO	Floating production, storage & offloading [system]
FRAM	Functional resonance analysis method
FSU	Floating storage unit
FTA	Fault tree analysis
GPS	Global positioning systems
HMI	Human-machine interface
HSE	Health and Safety Executive
ICT	Information and communication technology
IMCA	International Marine Contractors Association
PRS	Position reference system
PSA	Petroleum Safety Authority [Norway]
QRA	Quantitative risk assessment
SJA	Safe job analysis
ST	shuttle tanker
STAMP	Systems-Theoretic Accident Model and Processes

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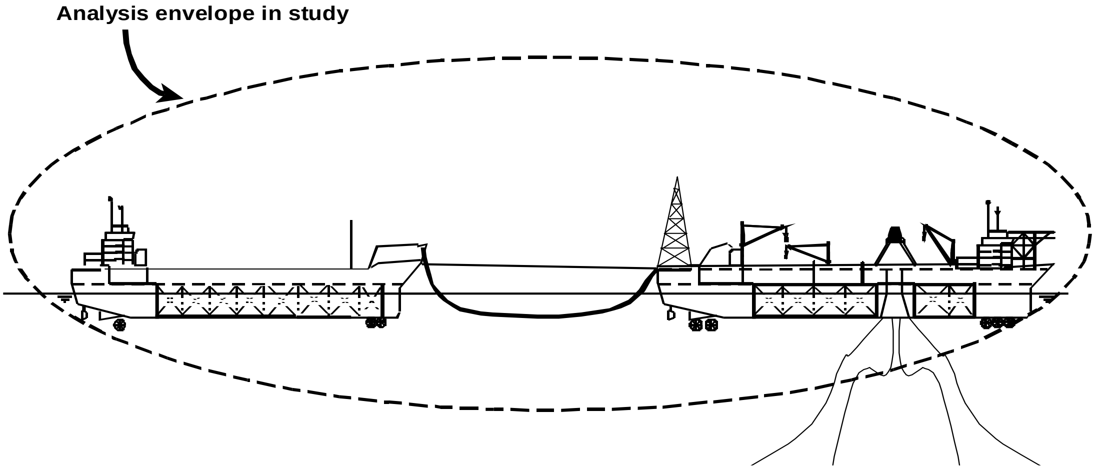


Figure 1 Analysis envelope for FPSO–ST collision risk

Table 1 Overview of Norwegian and UK characteristics for tandem off-loading configurations. (Adapted from Vinnem, 2003)

Configuration/technical/operational aspects	**Typical solutions in Norwegian sector**	**Typical solutions in UK sector**
Distance FPSO and tanker during off-loading	70-80 m, recently extended to 150 m	Around 50 m
DP class, tankers	DP2	DP1 and DP2
Extent of heading control possible from FPSO	Extensive capacity mainly	Few fields have significant capacities
Station-keeping by Shuttle Tanker	DP, with one exception	Mainly DP, but also some cases with taut hawser
Use of hawser between FPSO and Shuttle Tanker	Always	Always

Table 2. FPSO/shuttle tanker collision drive-off incidents and near-misses 1995–2013 (based on Vinnem (2003) and Lundborg (2014)

Year	**Sector**	**Phase**	**Cause**	**Type of incident**			**DP class**
				Near-miss	**Collision**	**Other**	
1996	UK	Loading	DP failure		X		1
1997	UK	Loading	PRS failure		X		1
1997	UK	Loading	Operator error		X		1
1997	UK	Loading	PRS failure			X	1
1998	UK	Loading	Operator error		X		1
1998	UK	Loading	CPP failure			X	1
1999	Norway	Loading	DP failure	X			2
1999	Norway	Loading	DP failure	X			2
1999	UK	Disconnection	FPSO thrusters tripped	X			1
1999	UK	Approach	DP failure	X			1

2000	Norway	Loading	Operator			X	2
2000	Norway	Disconnection	Manually & software error initiated drive off		X		2
2000	Norway	Approach	DP failure	X			2
2000	Norway	Connection	Technically initiated drive off	X			2
2000	UK	Connection	Operator error	X			1
2001	Norway	Loading	PRS/DP failure	X			2
2001	UK	Loading	Technically initiated drive off	X			1
2002	UK	Loading	Rapid wind change	X			1
2002	UK	Loading	Engine failure			X	1
2003	UK	Loading	Technically initiated drive off	X			?
2004	Norway	Loading	DP failure	X			2
2006	Norway	Connection	Loss of all engine power (all but one propellers) due to fuel contamination		X		2
2007	Norway	Loading	PRS failure			X	2
2008	Norway	Loading	Rapid wind change			X	2
2009	Norway	Loading	Engine failure			X	2
2009	Norway	Connection	Operator error	X			2
2009	UK	Approach	PRS failure		X		2
2011	Norway	Loading	CPP failure			X	2

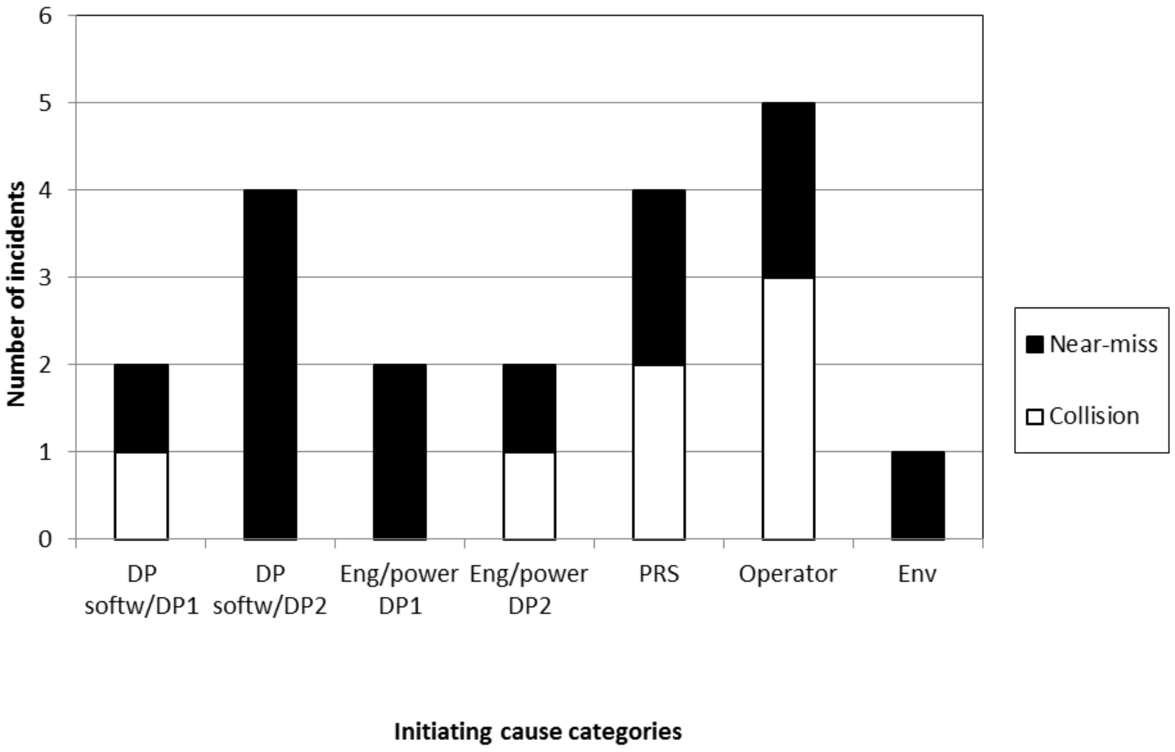
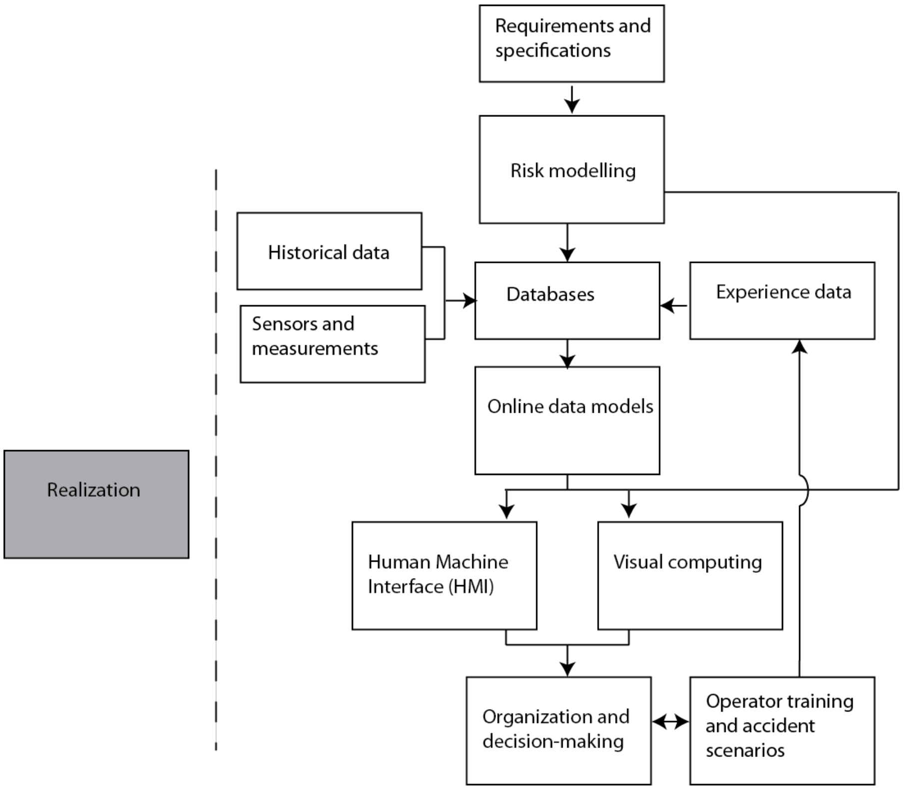


Figure 2 Initiating causes to Drive-off incidents UK and Norwegian sector, 1996-2013. ("Env" implies that rapid major change of environmental loads was the primary cause)



Requirements and specification to operations

Identification of hazards and risk influencing factors. Development of risk models, based on existing methods, such as QRA, HRA, Bayesian networks, STAMP and FRAM.

Sensor platforms, data sources and data fusion provide input to online data models, based on risk models.

Utiliziation of mathematical and empirical models for data transformation.

Visualization tools and graphical user interfaces for present the information to the operator.

Critical accident scenarios can be tested in simulator. Experience data can be gathered as input to online data models.

Figure 3 Overall concept for online risk management.

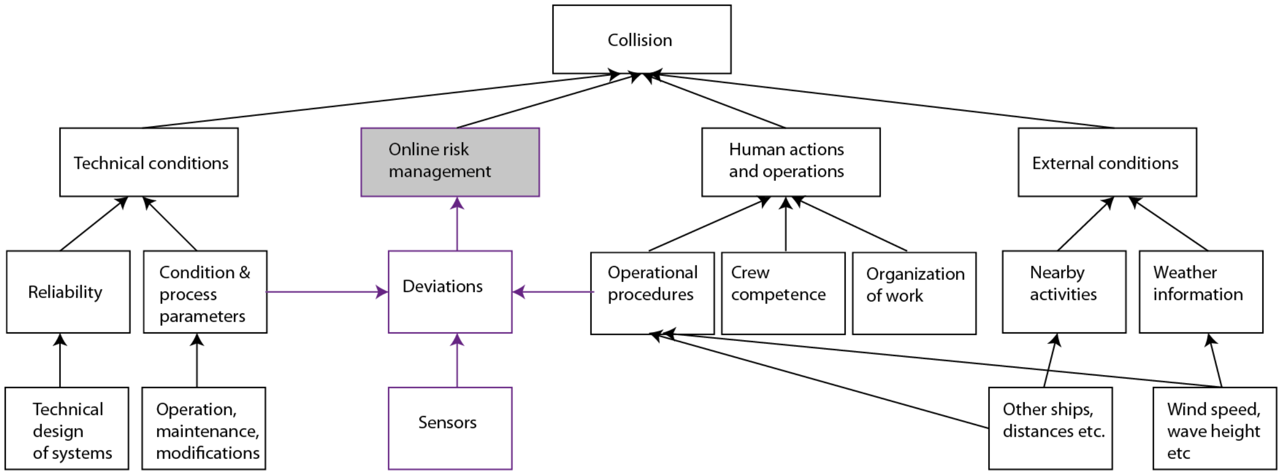


Figure 4 An influence diagram with risk influencing factors (RIFs), which shows the independent barrier function of the online risk management system.