

Risk Assessment of FPSOs Tandem Offloading Operation

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ABSTRACT

As the offshore oil and gas industry moves into deeper waters, the need for an effective system to offload crude oil from Floating Production Storage and Offloading Vessels (FPSOs) to tankers is progressively increasing. Traditionally, offloading of crude oil from FPSOs to tankers is carried out either in tandem offloading arrangement or by remote Single Point Mooring buoy. Tandem arrangement is carried out through the use of Dynamically Positioned (DP) shuttle tankers or conventional tankers. The operation is associated with high level of uncertainty, because it usually operates in a dynamic environment in which both human and technical interactions might cause possible accidents. This paper analyses the risk of collision associated with tandem offloading of FPSOs and DP shuttle tankers by adopting formal safety assessment methodology. The first part of the analysis estimates the likelihood of collision between the two vessels using fault tree analysis (FTA) techniques. The analysis revealed that human error, environmental force, reference system failure and DP software failure are the significant events that lead to the collision of the vessels.

Key Words: Fault Tree Analysis, Tandem Offloading, Dynamic Position, Base Events.

1. INTRODUCTION

As the price of oil and gas increases, combined with the increase in technology in the oil and gas industry, it has become economical to exploit marginal oil fields that are isolated from existing pipeline infrastructure and also moderate to ultra-deep water oil fields, with the use of FPSOs. FPSOs are the preferred choice of offshore floating production systems because of their crude oil storage capability and the possibility of being disconnected from a depleted oil field and moved to another oil field [1]. The vessels account for more than half of the floating production system in the world [2].

The transfer of crude oil from FPSOs to the refinery market or shore storage facility is carried out through dynamic positioning (DP) tankers, conventional crude oil tankers, or subsea pipeline systems [3]. Offloading of crude oil from FPSOs to shuttle tankers is usually done by different offloading methods. The most common methods of offloading are either from a remote single point mooring, side-by-side offloading, or tandem offloading [4]. In side-by-side offloading, shuttle tankers are positioned parallel to FPSOs. This offloading arrangement can only be used in mild environmental conditions [4]. In severe environmental conditions, tandem offloading arrangement is the most widely used method for offloading crude oil from FPSOs to shuttle tankers. This is due to the fact that tandem offloading systems are designed to withstand severe environmental conditions and are also more advantageous for fast disconnection [4], [5]. In the course of tandem offloading, shuttle tankers' bows are positioned at some distance, usually between 80-150 meters, from the stern of FPSOs and are connected by mooring hawser (a three-segment 'chain-wire-chain' combination) and loading hose. Additionally, shuttle tankers might be assisted with tugs or stand by vessels in taut hawser mode. Shuttle tankers might also be positioned by means of a dynamic positioning system (DPS) [5]. The operational stages of tandem offloading operation are [2]: approach- shuttle tanker approaches the stern of the FPSO, Connection- mooring of shuttle tanker to FPSO by mooring hawser and the connection of loading hose; offloading- offloading of crude oil from the

FPSO to the shuttle tanker; disconnection-connection of loading hose and mooring hawsers and the departure of shuttle tanker from the oil field. Tandem offloading operations usually range from a period of three to five days. This depends on the production rate of an oil field, the storage capacity of FPSOs and the size of shuttle tankers used for crude oil transportation in the oil field [2].

Tandem offloading operation is a complex marine operation with a high level of risk due to the closeness of FPSOs and shuttle tankers, the large masses and subsequently the large impact energy that is involved if collision between the two vessels occurs [6], [5]. In general, it takes an average time of twenty hours to complete the four phases of the operation. This actually depends on the transfer rate of FPSOs [2]. FPSOs and tankers are subjected to motion such as surging, yawing and swaying, as a result of environmental forces (wind, wave and current) acting on the two vessels in areas with harsh environmental conditions [5]. Thus, in order to maintain the separated distance between the two vessels when they are connected during tandem offloading, the shuttle tanker needs to maintain positions such that it changes position along with the FPSO [5].

A major hazard in tandem offloading operations is collision of shuttle tankers and FPSOs. The consequences of collision during this operation are severe damage to FPSOs and shuttle tankers [2]. This might result in flooding of FPSOs' stern and shuttle tankers' forward compartments. In addition, damage to the stern located flare tower might also occur [5]. This could further result in a release of gas, with a potential to cause a chain of explosion and fire on both FPSOs and shuttle tankers [7], [2], [5].

In cases of severe impact energy, damage to FPSOs' internal turret might happen. This could damage the risers and further result in the release of oil and gas from oil wells, with the potential to cause fire and severe pollution of the marine environment [2]. Damage to FPSOs' station-keeping mooring lines might also occur. Similarly, damage to loading hose, which could result in severe pollution of the environment and loss of time, has happened in the past [8]. Therefore, because of these severe consequences, it is essential to prevent or mitigate collision risks during tandem offloading operations.

Previously, several impacts had occurred between FPSOs and DP shuttle tankers in the North Sea. An example is the impact between *Norne* FPSO and shuttle tanker *Knock Sallie*. This incident resulted in damage to the members and bracing of the FPSO flare tower. Also, a 1.8m long crack was found between the aft and the tank deck of the FPSO [9]. Another instance is the collision between DP shuttle tanker *Loch Rannoch* and *Schiehallion* FPSO. This incident resulted in severe damage to the offloading reel of *Schiehallion* FPSO and subsequently prevented offloading operations for about three months [10].

Despite the fact that severe consequences such as loss of life or loss of FPSOs and shuttle tankers during tandem offloading operations have not happened, the impact between *Norne* FPSO and *Knock Sallie* shuttle tanker might be viewed as a serious incident, which could have resulted in the collapse of the FPSO's flare tower, subsequently causing fire and explosions.

2. LITERATURE REVIEW

FPSOs are offshore floating structures that are used to produce, store and transfer processed crude oil, through shuttle tankers to the refinery market. The first known application of FPSOs in the offshore industry is in 1977. It was installed in a water depth of 117m in the Spanish Mediterranean Shell Castellon oil field [1], [11]. Subsequently, the concept of using FPSOs in the offshore industry became widely accepted and the number increased over the years. The early concepts about FPSOs are centred on the conversion of barges or existing trading tankers [1]. However, with the increase in the number of FPSOs, purpose-built FPSOs are being developed and designed with consideration to cope with harsh weather conditions, in areas with high environmental loads [12].

Traditionally, FPSOs are ship-shaped vessels. They are usually fixed at place with the aid of turret mooring systems or spread mooring systems. Similarly, they are built with production and processing equipment, found on other oil and gas production platforms [13], [3]. This equipment enables them to receive crude oil from subsea wellheads, to process the received oil and to store and discharge oil through subsea pipelines or offloading systems [2], [13], [14]. The general features of FPSOs summarised by [3] are presented as follows: Hull- built in accordance with rules provided by the ship classification society. They are mainly designed to remain in position for a period of 10 to 20 years without docking; Topside- topside oil and gas processing equipment is designed and constructed in accordance with fixed offshore platform and refinery standards. These features are usually

preassembled into skids and are mounted on frameworks which are about three meters above the main deck of the vessel; Turret- the turret consists of a large diameter (16-32 meters) cylinder that sits within the hull of the vessel, mounted on heavy-duty roller bearings. Mooring wires and flexible subsea risers are attached to the turret. The vessel is free to weather vane (rotate through an angle of 270 degrees) around the fixed turret under the action of wind, wave and current; Mooring- a spread of 8-14 anchors ensures that FPSOs remain in location while producing oil. The anchor spread consists of a combination of wires and chains that are tensioned by winches located within the turret; Risers- connection of FPSOs to subsea oil wells is through flexible steel reinforced risers. Risers are designed to absorb wave-induced motion that might affect the position of FPSOs. In addition, FPSOs are also designed with equipment that enables them to discharge processed crude oil to oil tanker ships, for transportation to the refinery market [5]. In general, two types of oil tankers are used for offshore loading operations. They are crude oil ships and DP shuttle tankers [3]. Crude oil ships transport crude oil (cargo) over a long distance while DP shuttle tankers transfer cargo over a short distance and therefore spend a large proportion of their service life in loading and discharging. DP shuttle tankers are usually within a range of 70,000- 120,000 deadweight, approximately half the size of a crude oil ship [3].

A DP shuttle tanker is a ship that automatically maintains position by means of DPS [3]. The first application of DP shuttle tanker in the North Sea was in 1981 by Statoil. This was carried out by using *MT Wilnora* to load crude oil from a single point loading facility at *Statfjord* oil field [15]. Initially, the intention of Statoil was to use the tanker as a stop-gap measure to transfer oil ashore and later in the long run, to construct a pipeline from *Statfjord* oil field to the refinery. However, the result of the experiment was sufficiently encouraging for Statoil and the offshore oil industry as a whole to consider the use of DP shuttle tankers as a lifetime solution for the export of crude oil from offshore oil fields to refineries [15].

In practice, DP shuttle tankers use DPS to maintain position when loading crude oil from FPSOs. DPS comprises three main areas, specifically known as power, control and references [15], [16]. The system operates by taking information from the shuttle tanker sensors (i.e. gyro compasses and wind speed sensors) and position reference sensors (i.e. hydro-acoustic transponders, artemis and satellite position reference systems such as DGPS). It analyses this information and adjusts the propeller thrust to maintain a position within defined limits [15]. The manoeuvrability of DP shuttle tankers is very significant because of the long period spent in maintaining position while loading crude oil [15], [3].

During the period of 2001-2010, as shown in Figure 1, it is seen that reference system failure had about 23% occurrence followed by DP computer failure with 17% occurrence. Thruster failure and power generation failure had equal percentage of occurrence, while environmental condition had the lowest percentage of occurrence. Furthermore, in Figure 2, it can be seen that the number of occurrences of reference system failure, DP computer failure and thruster failure increased sharply to a significant amount between 2007 and 2008. The upsurge might be as a result of increase in the number of DP vessels operating during these years or probably because there was an improvement in the means of reporting data during this period. However, gradual declines in the occurrence of these failures occurred in 2009 and 2010. The decline in occurrence might be as a result of under-reporting during these years or because improvements in the operation and maintenance of these systems were instigated.

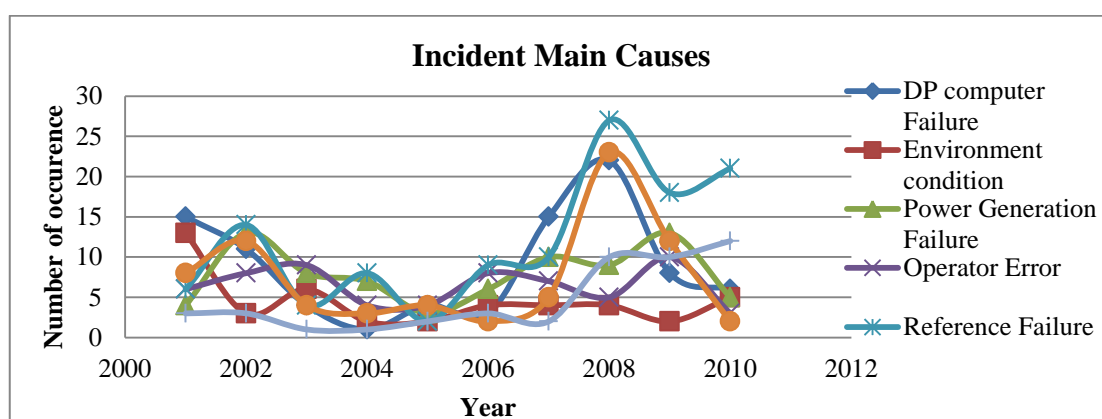


Figure 1: Showing Incident Main Causes from 2001-2010. [16]

From Figure 1 and Figure 2, it can be seen that reference system failure, thruster failure and DP computer (hardware and software) failure tend to be the most frequent causes of incidents. Reference system failure is the most frequent cause of incidents in 2006, 2008, 2009 and 2010. Thruster failure, power generation failure and DP computer failure are the least frequent events in 2006. In 2007, DP computer failure is the main causes of incidents. DP computer and thruster failure are also frequent in 2008. The data used in developing Figure 1-3 are obtained from [16] station-keeping reports.

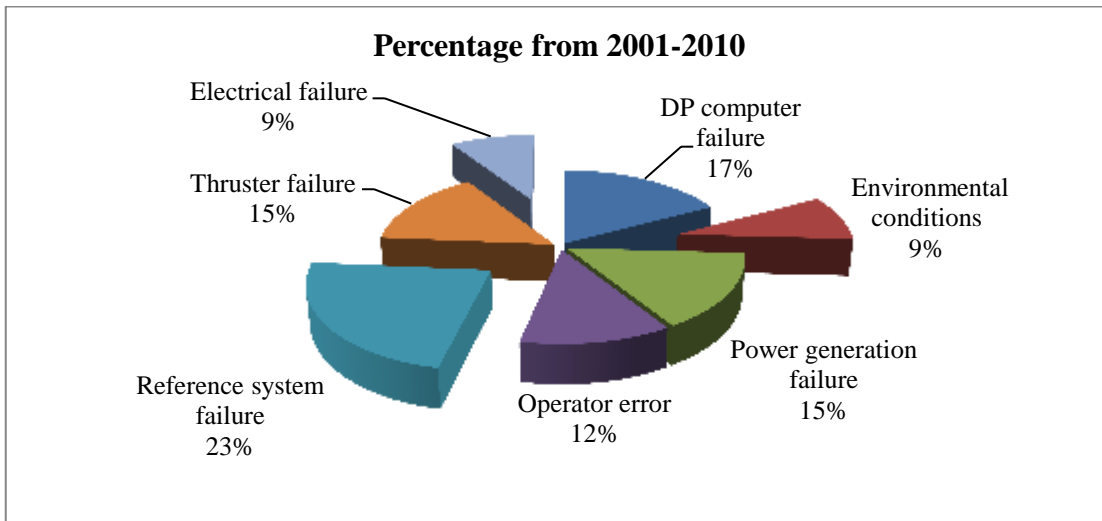


Figure 0: Percentage of Occurrence of the Main Causes of Collision from 2001-2010[16]

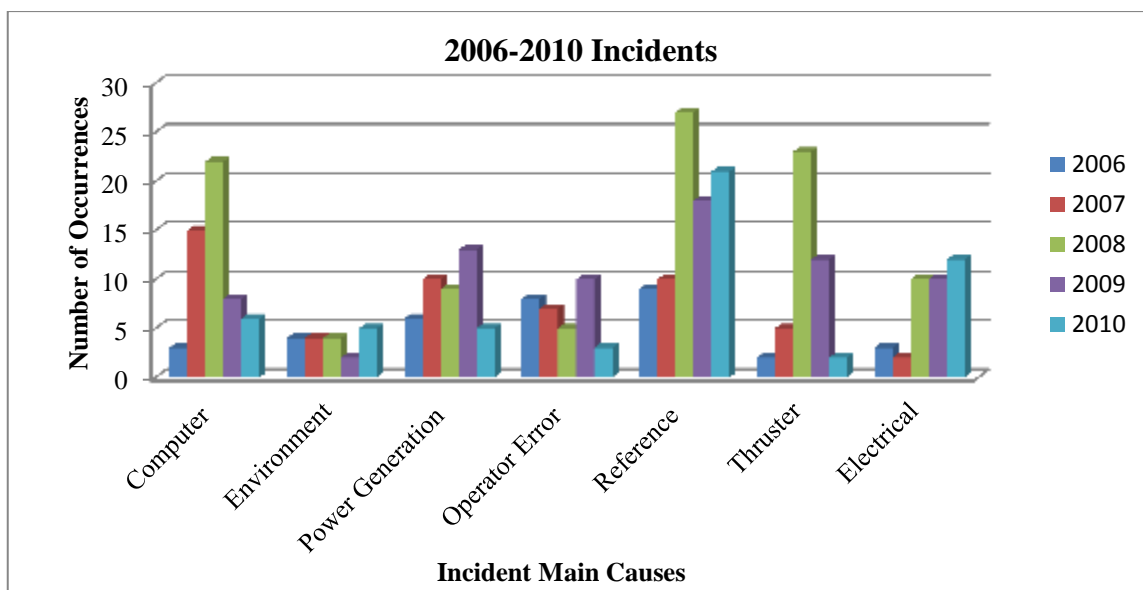


Figure 3: Trend of Main Causes of Incidents from 2006 to 2010[16]

Fault tree analysis technique applied by [8] and [17] is a deductive risk assessment technique that clearly models the logical relationships among equipment failures, human errors and external events, and how they combine to cause a particular undesired (top) event [18]. Fault tree risk analysis technique was first introduced in 1962 by Bell Telephone Laboratories [19], [20], [21]. Subsequently, the technique was improved and used to predict complex system reliability in fields such as the chemical industry, nuclear industry, marine industry and offshore industry [22]. Fault tree risk analysis method is the most widely applied safety analysis technique in the afore-mentioned industries. Particularly, it is suitable for the risk analysis of large marine and offshore engineering systems [23]. The undesired (top) events can be identified from experience or previous incidents' reports [23]. The top events in fault tree analysis are events with a severe consequence. These events are placed at the top of a fault tree diagram, and intermediate failure events that lead to the top event are located immediately below in sequential level [23]. The development of fault trees terminates when component failure events known as basic events are encountered [24].

The strength of fault tree analysis lies in its ability to analyse complex systems. It also provides a clear picture of the relationship between hardware failures, software failures and human errors while considering influences from external events [18], [25], [23]. Additionally, fault tree techniques can be used for either qualitative or quantitative risk analysis. Qualitatively it is used to identify the individual scenarios (called cut-sets) that lead to the top event while quantitatively it is used to estimate the likelihood of occurrence of the top event [24], [18], [25]. However, the process of developing a fault tree for complex systems might be time consuming and expensive. Also, considerable effort might be required in order to identify all the events that could lead to the top event [25]. For a further description of fault tree analysis and its application in risk assessment, the researcher refers the reader to the following references: [24], [18], [25] and [23].

A study examining the safety of roll-on roll-off passenger ferries was carried out by [26] by using fault tree analysis to build a risk model for collision, grounding and fire accident scenarios. The study highlights human factors, navigation aids, manoeuvrability and mechanical systems failure as significant initiating events that could cause collision and fire hazards on a roll-on roll-off passenger ferry. Additionally, a quantitative analysis of collision and grounding accident is presented. Based on the quantitative analysis, a sensitivity analysis is carried out by increasing the failure data of basic events by 10%. Figure 4 show a diagrammatic view of fault tree construction.

The study concludes that human factor basic events are the most sensitive basic events. This is because the likelihood of collision increased by approximately 90% and that of grounding increased by approximately 80% when the failure data of human factor basic events was increased by 10%. However, as a result of lack of historical failure data, assumptions are made when determining the failure rate for human error and mechanical system basic events. These obviously affect the degree of uncertainty in the results of the sensitivity analysis presented by the study.

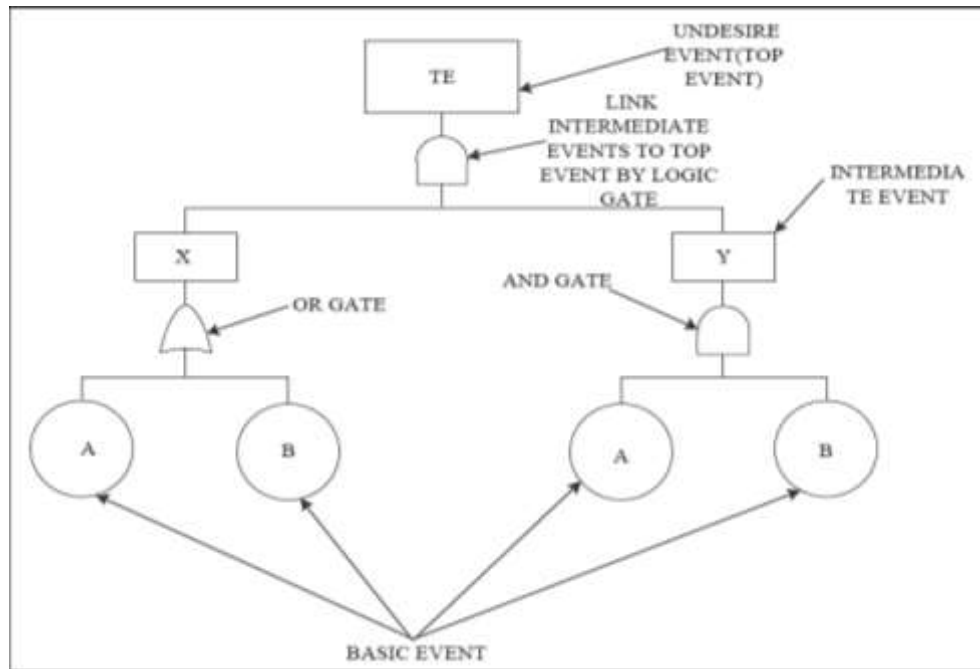


Figure 4: Diagrammatic View of Fault Tree Construction [18]

Similarly, [27] uses fault tree analysis to assess the risk of collision between two ships navigating in an open sea area. A risk model is developed to show the interaction of failure events that might result in collision between the ships. Based on the risk model, the study is able to identify human error and machinery failure as the main causes of collision between ships navigating in open sea areas. Ways of preventing the occurrence of collision between two ships navigating in open sea areas are proposed.

Furthermore, [28] use fault tree analysis to develop a risk model for human error activities that might contribute to the collision and grounding of oil tanker ships. The failure data of fault tree basic events are calculated with reference to nuclear plant human error data. The likelihood of collision and grounding as a result of human error activities are calculated with the failure data. Additionally, sensitivity analysis of basic events are carried out, in order to determine the types of human activity that significantly contribute to collision and grounding of oil tankers. Activities such as command failures and communication failures are identified as the most significant human activities.

3. OBJECTIVES AND METHODOLOGY

The following methodology is adopted;

- Hazard identification
- Development and description of risk model
- Qualitative estimation of risk model
- Ranking of base event

4. CASE STUDY

The Risk of Collision of DP Shuttle Tankers and FPSOS

4.1 Hazard Identification

The identification of hazards is carried out through a flow diagram. The flow diagram developed for the operation is shown in Figure 5. Additionally, the tasks carried out during the phases of the operation are listed. These assist to give a broad picture of tandem offloading operation and aid in the identification of hazards during the phases of the operation.

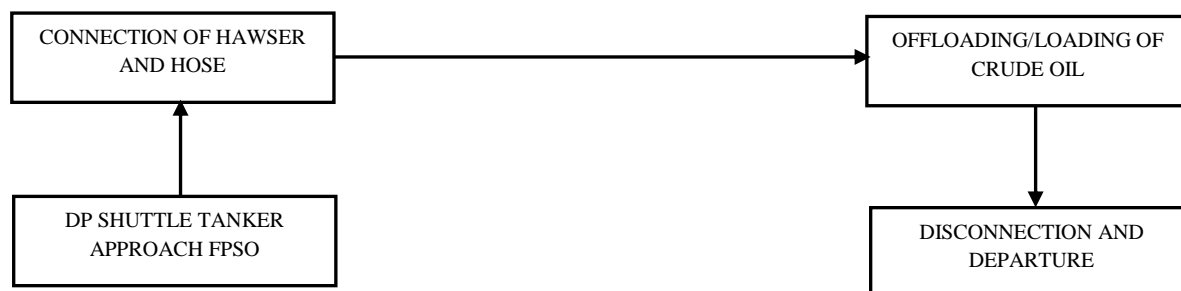


Figure 5: Tandem Offloading Operation Flow Diagram

The tasks carried out during tandem offloading operation are the following: (a) Approach: Arrival of shuttle tanker in the oil field. Shuttle tanker communicates with the FPSO and requests to proceed for loading. Pre-mooring preparation is carried out. Shuttle tanker requests to enter FPSO 500m zone. Shuttle tanker reduces speed to minimum. Shuttle tanker manoeuvres using thrusters and main engine to position at the stern of the FPSO [29], [5]. FPSO adjusts heading with thruster to assist in the positioning. Shuttle tanker maintains a distance of about 80m-150m to the stern of the FPSO. Shuttle tanker maintains position at the stern of the FPSO with its thruster and DP system. (b) Hawser and hose connection: Messenger line for mooring hawser is sent from the FPSO to the shuttle tanker. Shuttle tanker connects mooring hawser to its bow mooring system. Cargo loading hose is connected to shuttle tanker loading manifold. Shuttle tanker and FPSOs line up pipeline by opening the required valves to prepare for offloading. (c) Offloading/Loading operation: A pre-transfer discussion is carried out between shuttle tanker and FPSO operators [29], [5]. Crude oil cargo transfer pump is started. Transfer begins at a minimum pumping rate to ascertain that there are no leakages and systems are correctly lined up.

Constant communication is maintained between FPSO mooring master and shuttle tanker operators. Shuttle tanker communicates and or confirms the receiving of crude oil from the FPSO. Transfer rate is increased to the maximum. Heading deviation is monitored and adjustments are made by shuttle tanker operators and or FPSO operators. Effective communication is maintained during the average time of about 20 hours that transfer of crude is carried out. Hawser tension and other DP systems are monitored. Limiting sectors are monitored [29], [5]. FPSO weight decreases while that of the shuttle tanker increases and power to weight ratio is monitored. Offloading is completed, and preparation is made for disconnecting. (d) Disconnection and Departure; Flushing of manifold and offloading hose is carried out by using hose flushing arrangement provided on the FPSO. Offloading hose is disconnected with a consideration to prevent spills [29], [5]. Hose is secured to hose reel on the FPSO. Mooring hawser is disconnected. Shuttle tanker moves astern continuously with the use of main engine connected to controllable pitch propeller and messenger line is sent back. Shuttle tanker changes heading with the use of rudder and or controllable pitch propeller and navigates away from the oil field [29], [5]. The major hazards associated with above-listed tasks are collision between shuttle tankers and FPSOs, hawser damage and offloading hose damage. From the review of literature, collision between shuttle tankers and FPSOs during tandem operations is estimated as medium frequency and high consequences. Hawser damage and offloading hose damage are estimated as low frequency and low consequences [7]; [2] . [29], [5].

The causes of collision incidents between DP shuttle tankers and FPSOs during tandem offloading operation are identified based on the review of literature in Section 2. The identified causes and their descriptions are listed below [16], [25]. Thruster failure- denotes bow thruster failures, stern thruster failures, controllable pitch propeller failures, main engine failures, and rudder failures. Power generation failure- means generator failures, generator synchronisation failures, and alternator failures. Electrical failure- signifies circuit breaker failures, automatic voltage regulator failures, power supply failures and other electrical switchboard failures. Reference system failure- symbolises gyro failures, wind sensor failures, hawser tension failures, and other position

reference system failures. Excessive environmental force- denotes excessive wind, excessive wave and excessive current. DP shuttle tankers operator error- represents human error, DP computer failure- symbolises DP software failures or DP hardware failures.

4.2 Development and Description of Risk Model

The development of a risk model for the research is based on the obtained copy of Failure Mode and Effect Analysis (FMEA) report from DP vessels [30], [31], [32] and the review of literature. A risk model for collision between DP shuttle tankers and FPSOs during tandem offloading operations is constructed, using Isograph Fault Tree Analysis 11+ software [33]. The typical constructed model is shown in Figures 6.

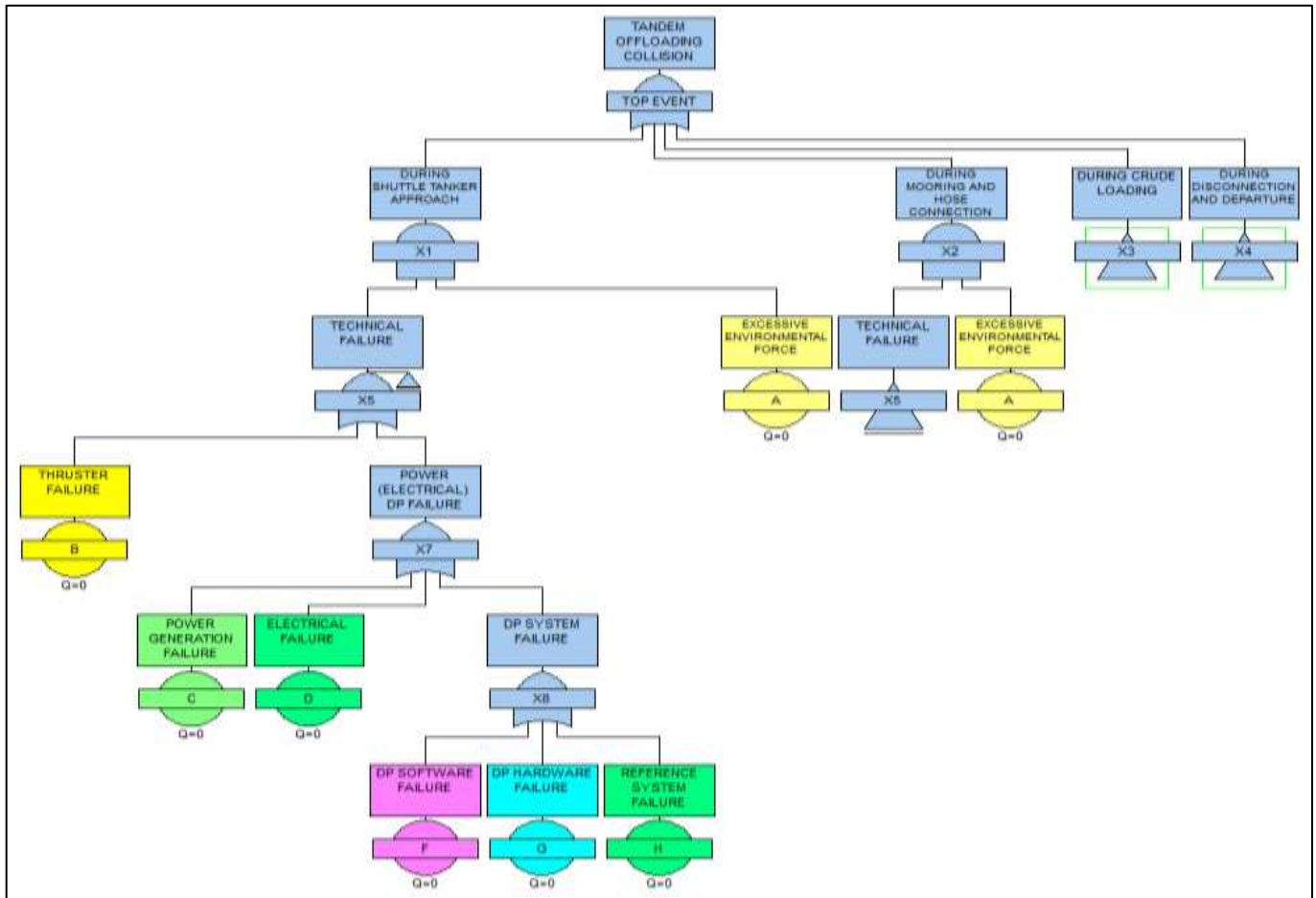


Figure 6: Risk Model for approach, mooring and connection

In constructing the model, the critical hazard (collision) is used as the top event. Collision during tandem offloading operation occurs either during shuttle tanker approach (X1), during the process of connecting mooring hawser and loading hose (X2), during the transfer of crude oil from the FPSO to shuttle tanker (X3), or when disconnecting loading hose and mooring hawser and the shuttle tanker is leaving the oil field (X4).

Collision during tanker approach (X1) and during the connection of mooring hawser and loading hose (X2) happens when both technical failure (X5) and excessive environmental force (A) occur simultaneously. Technical failure happens when thruster failure (B) or power- DP failure (X7) occurs. Additionally, power-DP system (X7) occurs when power generation failure (C), electrical failure (D) or DP system failure (X8) happens. DP system failure (X8) occurs when DP software failure (F), DP hardware failure (G) or reference system failure (H) happens. During the loading of crude oil (offloading operation), collision (X3) occurs when shuttle tanker drive-off (X9) or drift-off (X10) happens. Drift-off occurs when excessive environmental force (A) and power- thruster failure (X23) occur simultaneously. Power- thruster failure (X23) happens when power generation failure (C), electrical failure (D) or thruster failure (B) occurs.

Additionally, drive- off occurs when technical-excessive environmental force (X11) or DP- error occurs (X12). Technical-excessive environmental force (X11) occurs when both technical system failure (X5) and excessive environmental force (A) occur simultaneously. DP-error (X12) happens when both DP software failure (F) and operator error (human error) (E) occurs, or both

DP hardware failure (G) and operator error (E) occur or both reference system failure (H) and operator error (E) happen. Furthermore, during the disconnection of mooring hawser and loading hose and the departure of the shuttle tanker from the field, collision (X4) happens either during the disconnection of loading hose and mooring hawser (X18), or when the shuttle tanker is departing from the oil field (X17). Event X17 happens if excessive environmental force (A) and thruster to power failure happen (X25). Additionally, Event X25 occurs when thruster failure (B), power generation failure (C) or electrical failure happen (D). Further, Event X18 occurs when both technical system failure (X5) and excessive environmental force (A) happen.

4.3 Qualitative Estimation of Risk Model

The qualitative estimation of the constructed risk model is carried out by obtaining the minimum irreducible path (minimum cut-sets) in the risk model. Minimum cut-sets contain a unique set of basic events that lead to the occurrence of the top event (collision). The obtained minimum cut-sets are ;

- E*H**
- E*G**
- B*A**
- H*A**
- G*A**
- F*A**
- E*F**
- D*A**
- C*A**

In order to carry out quantitative analysis, failure data of risk model basic events are required. These data are to determine the likelihood of occurrence of collision during the operation. The failure data for risk model basic events are obtained from the station keeping incident data report [34]. Table 1 shows risk model basic events, their associated abbreviations and failure data.

Table 1: Basic Event, Symbol and Failure Data

Abbreviation	Basic Event	Failure Data (Likelihood)
A	Environmental force	0.089
B	Thruster failure	0.139
C	Power failure	0.12
D	Electrical failure	0.038
E	Operator error	0.228
F	DP software failure	0.177
G	DP Hardware failure	0.025
H	Reference failure	0.184

It is vital to mention that the failure data obtained from [34] is ten years estimated likelihood of occurrence of the basic events. Thus, estimation of the likelihood of collision, in the research is based on a period of ten years. The risk model constructed in this research is a generic model for tandem offloading operations of DP shuttle tankers and FPSOs. From the generic model, the likelihood of intermediate events might be estimated manually. For instance, to estimate the likelihood of shuttle tanker drift-off, the first step is to obtain the minimum cut-set of drift-off through the use of Boolean algebra. The minimum cut-set of drift off is obtained as follows:

$A(C+D+E) = AC+AD+AE$. Having obtained the minimum cut-set of drift off, the likelihood is calculated as follows:

$$\begin{aligned}
 &L(AC+AD+AE) \\
 &= L(AC) +L(AD+AE) - L(AC(AD+AE)) \\
 &= L(AC) + L(AD) +L(AE) -L(ADAE) - L(ACD+ACE) \\
 &= L(AC) + L(AD) +L(AE) -L(ADE) - L(ACD+ACE) \\
 &= L(AC) + L(AD) +L(AE) -L(ADE) - L(ACD) - L(ACE) +L(ACDACE) \\
 &= L(AC) + L(AD) +L(AE) -L(ADE) - L(ACD) - L(ACE) + L(ACDE) \\
 &= L(A) \times L(C) + L(A) \times L(D) + L(A) \times L(E) - L(A) \times L(D) \times L(E) - L(A) \times L(C) \times L(D) - L(A) \times L(C) \times L(E) + L(A) \times L(C) \times L(D) \\
 &\quad \times L(E) \\
 &= 0.089 \times 0.12 + 0.089 \times 0.038 + 0.089 \times 0.228 - 0.089 \times 0.038 \times 0.228 - 0.089 \times 0.12 \times 0.038 - 0.089 \times 0.12 \times 0.228 + \\
 &0.089 \times 0.12 \times 0.038 \times 0.228 = 0.01068 + 0.00338 + 0.02029 - 0.00077 - 0.00040 - 0.00243 + 0.00009 = 0.031
 \end{aligned}$$

The likelihood of shuttle tanker drift-off during tandem offloading operations is 0.031. The same procedure could be used to estimate the likelihood of the generic model top event (collision). However, as a result of the size of the generic model, it is difficult to use the manual procedure to estimate the likelihood of collision. Therefore, the likelihood of collision is estimated using Isograph Fault Tree Analysis 11+ software. The likelihood of collision between FPSOs and DP shuttle tankers during tandem offloading operation, given a period of ten years, is 1.182×10^{-1} . It is essential to mention that the estimated likelihood of the top event is equivalent to the likelihood of collision during the offloading phase of the operation.

4.4 Ranking of Basic Events

The ranking of basic event is carried out using Fussel-Vesely basic event importance measure. The importance of e^j is represented by $I(e^j)$, where U stands for “union” or “OR” operation and L symbolises the likelihood of occurrence [35].

$$I(e^j) = L(U \text{ cut sets containing } e^j) / L(\text{top event})$$

Fussel-Vesely Importance for thruster failure I(B) and DP software failure I(F) are calculated as follows:

$$\begin{aligned} I(B) &= L(BA) / L(T) \\ &= L(A) \times L(B) / L(T) = 0.139 \times 0.089 / 0.1182 = 0.1047 \\ I(F) &= L(U \text{ cut sets containing } F) / L(T) \\ &= L(FA+EF) / L(T) = (L(FA)+L(EF) -L(FAEF)) / L(T) = (L(FA)+P(EF) -L(AEF)) / L(T) \\ &= (L(F) \times L(A)+L(E) \times L(F) -L(A) \times L(E) \times L(F)) / L(T) \\ &= (0.177 \times 0.089 + 0.0.228 \times 0.177 - 0.089 \times 0.228 \times 0.184) / 0.1182 = 0.4443 \end{aligned}$$

The same procedure is repeated for other basic events and the results are presented in Table 2. The ranking of basic events is as follows: E > A > H > F > B > C > G > D. This means that human error (Basic event E) is the most significant basic event while electrical failure (Basic event D) is the least significant.

Table 2: Fussel-Vesely Basic Event Importance

Symbol	Basic event	Fussel-Vesely Importance
I(A)	Environmental force	0.4757
I(B)	Thruster failure	0.1047
I(C)	Power failure	0.0904
I(D)	Electrical failure	0.0286
I(E)	Operator error	0.5915
I(F)	DP software failure	0.4443
I(G)	DP Hardware failure	0.0629
I(H)	Reference failure	0.4619

5. CONCLUSION

The research aim and objectives have been achieved by reviewing literature and incident reports related to tandem offloading operation. Based on the review of literature and incident reports, collision is identified as the critical hazard during the operation. In assessing the risk of collision of the afore-mentioned vessels during tandem offloading operations, the likelihood of collision given a period of ten years globally is estimated in the order of 10^{-1} and by considering a period of one year, the likelihood is in the order of 10^{-2} . The estimated order in the study is in accordance with the order of collision during tandem offloading operations.

The analysis indicates that the likelihood of collision during the offloading phase of the operation falls within the unacceptable region. Results from the ranking of based events using Fussel-Vesely basic indicates that human error, environmental force, reference system failure, DP software failure and thruster failure are significant events leading to collision during tandem offloading of these vessels compared to power failure, electrical failure and DP hardware failure which are trivial events.

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