Proceedings of the 38th International Conference on Ocean, Offshore & Arctic Engineering
Jun. 9 -14, 2019, Glasgow, Scotland, UK

OMAE2019-96710

LEARNING FROM DYNAMIC POSITIONING EVENTS

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ABSTRACT

Sixteen loss of position incidents on fourteen units are reported to us from the petroleum activity on the Norwegian continental shelf, from 2014 to 2018. The incidents had a mixture of severity, with pollution of 360m^3 mud, damage to drilling and production equipment, falling objects and three autolifts of bridges as the most severe consequences. The incidents are described briefly and the most common causes of the events are found. The cases are discussed in view of several approaches. The barrier concept, and modifications of previous established barrier functions and barrier elements are discussed. I discuss the man-technology-organisation examinations in the investigations. Further the application of the single failure analysis philosophy is reviewed, and I discuss limitations to the method based on our cases. Our cases are compared with previous learning from incidents on shuttle tankers. A discussion is done on the slow reactions to changes in the weather conditions. In the last section I discuss needs for improvement.

Keywords: DP; dynamic positioning; technical errors; reference systems; MTO; procedures; competence; software; barrier functions; barrier elements.

ABREVIATIONS

ATA = Automatic thruster assisted mooring; **DGPS** = Differential Global Positioning Systems: **DP** = Dynamic positioning; **FMEA** = Failure mode and effect analysis; **GPS** = Global positioning system; **HPR** = Hydro acoustic position reference systems; **IMCA** = The International Marine Contractors Association; **MODU** =Mobile offshore drilling unit; MTO = Man, Technology and Organisation; **NMA** = Norwegian Maritime Authority: **NOx** = The most relevant nitrogen oxides for air pollution; **PSA** = Petroleum Safety Authority; **RAO** = Response amplitude operator.

INTRODUCTION

The most critical DP incidents in Norway have previously been on shuttle tankers and on visiting vessels. The collisions were reported by Kvitrud (1994 and 2011), PSA (2011) and by Kvitrud, Kleppestø and Skilbrei (2012). Several research and industry activities were performed, and recommendations were made. Many of the recommendations are implemented by the industry (as in the International Guidelines for Offshore Marine Operations (G-OMO)). No collisions with shuttle tankers or visiting ships in full speed have been reported for several years. PSA have not done any systematic publishing of our other DP incidents. However, some information is available in the IMCA data base. After a period with low number of reported incidents, the number of DP related incidents increased from 2014.

The Norwegian regulatory philosophy is based on the expectation that those who conduct petroleum activities are responsible for complying with the requirements of the acts and regulations. Furthermore, the regulations require a management system that systematically ensures compliance at any time.

DP INCIDENTS

In this review, I have included incidents related to roll and pitch, in addition to the normal surge incidents. DP and ATA systems have also been part of some investigations, not related to loss of position as such, but on how DP systems are used in storm conditions. The DP systems influence the loading on the anchor lines, and in addition wave loading on hulls and wave impacts on decks. These cases are not described in this paper.

All the incidents have been subject to investigations by the owner or the operator. The scope of the investigations and the depth of investigations varied, often dependent of the severity. To get a better understanding of the state of art, I reviewed 16 cases with position related incidents. The platforms are numbered, and I use the numbers for further discussion. There are also reported some minor incidents to us as with a brief

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description of what has happened. They are not included in the list below.

The guidance to our management regulation section 29 specify that notification should be given to PSA in hazard and accident situations, but also in less serious positioning situations. The guidance can be interpreted, but as far as we know, at least the most critical cases are reported to us. The case descriptions below are summaries of the reports. We have not done our own investigations in any of the cases.

1. West Venture at Troll in 2014

15 January 2014 the semi West Venture drilled at Troll field in the Northern North Sea for Statoil. She was disconnected from the well. They lost several reference systems and six out of eight thrusters. The DP systems were immediately taken over manually by the DP operator. The incident did not lead to loss of position. Updates of dynamic data on the DP consoles partially stopped. The logs reported a storm of networking events, indicating interference in data traffic on one of the networks. Network channels on nodes detected errors on incoming messages and data collisions with outgoing messages. This resulted in significant increase in network traffic caused by data retransmissions. The DP application consisted of several nodes that exchange data over the networks. The DP application was designed to select away thrusters and reference systems, if relevant data from other nodes was not updated within 15 seconds. The critical data sets did not reach the recipient's node within 15 seconds (ABB, 2016).

2. Floatel Superior on the Kvitebjørn field in 2014

28 January 2014 the flotel (semi) Floatel Superior operated in close vicinity to the Kvitebjørn jacket. The significant wave height was 4.5m. Based on the wave conditions, the gangway was closed, but not disconnected and bridge guards were established. Floatel Superior moved 6,3 meters away from Kvitebjørn caused by a wave, and the DP system started to take her back. Because of the heavy use of the thrusters against the Kvitebjørn facility, the drive off prevention was activated, and the autolift function activated. No one were on the walkway when it lifted. An unsatisfactory evaluation of the wave conditions contributed to the incident (Statoil, 2014a, 2014b and 2014c).

3. Skandi Gamma at the Troll field in 2014

11 September 2014 the vessel Skandi Gamma worked for Stena Drilling at the Troll field. She was next to the semi Stena Don and unloaded deck cargo, when the boat suddenly blacked out and lost machine power for four minutes. The boat drifted slowly towards the platform and touched the platform twice. Local damage occurred on railings and lights (Statoil, 11.9.2014). The significant wave height was 0,8m at Troll A (eKlima.no).

4. West Navigator at the Ivory location in 2014

6 December 2014 the drill ship West Navigator drilled at the Ivory location in the Norwegian Sea for Centrica (Centrica Energi, 2015). The platform waited on weather, connected to the well, and had started to plug. The significant wave height was 3,7m. A sudden significant change in wind direction occurred with an increase in wind velocity. The vessel heading was adjusted to face the wind, but then the vessel was forced off location. She experienced a horizontal position deviation of 46m. As the vessel had passed the maximum allowable distance from the well, the automatic disconnect system activated and the drill pipe was cut, the BOP closed and the riser disconnected from the BOP to prevent damage to the platform and the well. More than 230 m^3 oil based mud in the riser drained out through the bottom of the riser and was deposited on the sea bed. The spill was classified as red chemicals. The control of the vessel's position was regained quickly. The emergency disconnect system worked as it should and the relevant procedures were followed. The investigation highlighted (Centrica Energi, 2015): The DP systems ability to maintain adequate position was exceeded, inadequate location specific station keeping guidelines and planning tools, the vessel did not perform as anticipated in the conditions encountered and lack of containment devices to prevent loss of mud from the riser when disconnected.

5. Transocean Barents at Ormen Lange field in 2015

12 March 2015 the semi Transocean Barents drilled at the Ormen Lange field in the Norwegian Sea (Transocean, 2015a and 2015b) for Shell. Several alarms came on high consumption on the thrusters, while the weather was steadily increasing in line with weather forecasts. The significant wave height was 6,8m. Immediately prior to the incident, a series of large waves hit the platform. The bridge got several alarms. Then the DP system rejected all the reference systems, and started the automatic emergency shut down function, according to design, as the platform had exceeded the set "prediction error rejection limit". This indicated that there had been more than five meters difference in the position estimated by the mathematical model and the position given by the reference systems. The maximum excursion from the wellhead position was 35m. The lower marine riser package separated from the BOP stack, and the well was secured. 66m^3 mud was released to sea, as 36m^3 oil based mud, 20m^3 soap and 10m^3 base oil. Transocean (2015a) concluded that the DP system navigated only on mathematical models and were therefore unable to find setpoint fast enough to avoid disconnection. They had two DGPS, one hydro acoustic reference system and one DGPS in monitoring mode.

6. Safe Boreas at Edvard Grieg field in 2015 (two cases)

5 October 2015 the flotel (semi) Safe Boreas operated for Lundin close to the Edvard Grieg production platform (jacket), when she was hit by a wave. The significant wave height was 4m and the wind speed 16m/s. The roll was 3 degrees and pitch 2,5 degrees. The gangway telescope extended 5m in 15 seconds,

it triggered an autolift of the walkway. The autolift was caused by a combination of the vessel being astern of the set point and the list and trim of the vessel causing further extension of the bridge. The activation of the gangway alarms was late, and allowed too little time for reaction by the DP operators. No personnel were on the walkway, and cables and hoses had been removed in preparation for a scheduled disconnection (Prosafe Offshore, 2015).

4 December 2015 the telescopic gangway autolift function was activated due to compression beyond the autolift limits. The weather at the time of the incident was wind 16 m/s and 3,9 meters significant wave height. Prior to the autolift, and the maximum excursion of the gangway telescope had been three metres. The vessel was slightly off position (2,5 meters) towards the platform. Immediately prior to the autolift the vessel began to pitch forward approximately three degrees, causing compression of the gangway. The roll reached about 4,2 degrees just prior to the autolift. The first stage alarm for compression was passed, followed quickly by the second stage alarm, and compressed further to the autolift limits. It caused the autolift, as it was designed to do. At the time of the second stage alarm, a person crossed the bridge, but returned on hearing the alarm. No one was on the gangway when the actual autolift occurred (Prosafe Offshore, 8.1.2016 and 28.1.2016).

7. Songa Equinox at the Troll field in 2015 (two cases)

24 December 2015 the semi Songa Equinox drilled at the Troll field in the Northern North Sea for Statoil (Songa Offshore, 2016). Due to increasing weather, it was decided to secure the well. The platform was hit by a wave train with Hs at 6,7m, that pushed the platform 38m out of position. The platform was pushed off at a rate that the DP system did not recognize as possible, and rejected all the position reference systems. A manual emergency shut down was initiated. The DP system used 11 seconds to recalculate the reference systems input to the DP position computing model. During the 11 seconds of recalculating, the DP system operated in a mode where the DP model used input based on the last position, velocity and heading to calculate where it should be. The rejection of the reference systems was according to the design of the system, and did not affect the position recovery, since the thrusters worked towards bringing the platform back to the original well location for the period in which the reference systems were rejected. The lower marine riser package was disconnected. Approximately 73 m^3 of water based mud were lost to sea. Songa Offshore (2016) concluded that the systems and personnel did what they were supposed to do during the incident.

30 December 2015 Songa Equinox drilled at the Troll field in the northern North Sea for Statoil. She lost position due to lack of thrust to keep position in the actual weather conditions. The riser and the lower marine riser package hang under the platform at a depth 320m. It drifted in survival draft about 0,5 m/s. All the technical systems were operational (Statoil, 2015). The significant wave height was 6,6 meters and the wind velocity 24m/s at Troll A (eKlima.no).

8. Transocean Spitsbergen on the Wisting field in 2016

16 March 2016 Transocean Spitsbergen drilled at the Wisting field in the northern Norwegian Sea for OMV. She waited on weather. The significant wave height was 7m. The platform got a rapid movement of 19 meters, causing the reference systems to be rejected. The DP system recalibrated within six seconds and green status was restored with a stable position. The circle for "red zone" was set to 20 meters. The riser angle was two degrees, and within the riser disconnection criterion (OMV, 2016).

9. Songa Endurance on the Troll field in 2018

7 January 2018 Songa Endurance was on the Troll field in the northern North Sea for Statoil. She waited on weather before anchor handling. A DP box test (change of position set points) was performed in survival draft. The platform got a roll movement of 8,5 degrees. Two risers and one landing joint moved unintentionally, and hit the aft deckhouse bulkhead. No personnel were exposed to the moving risers. The incident occurred as a combination of several factors (Songa Offshore, 2018), such as:

- Increased platform motions in survival draught,
- The DP controller created a variable DP current during the testing, that indicates that the DP model was affected by the testing (station keeping performance and thruster usage). The excessive use of thrusters increased the pitch and roll motions.
- An unfavourable platform heading with swell. The forecasted swell was a significant wave height of 1,9m and Tp of 10,5 seconds.
- Effects from free surfaces in liquid tanks,
- The effects from environmental loads.

The root causes were missing guidelines for when to perform DP tests, unclear requirements for slack tanks, and competence related to operational decisions (Songa Offshore, 2018).

10. Island Wellserver on the Åsgard field in 2017

20 October 2017 the vessel Island Wellserver did well stimulation on the Åsgard field in the Norwegian Sea for Statoil. She got an unintended stop of an azipull thruster, and drifted off. The drifting resulted in an emergency quick disconnect. The umbilical termination head was disconnected, and the valves on the BOP closed. The thruster failed due to short circuit on an electric motor. An error in the thruster control software was the direct reason that the device failed to hold position. The thruster control software limited the power take-off when propel water was directed towards close-up thruster. This was done to avoid loads on the thrusters and power loss. This restriction could not be repaired when the thruster stopped. The software was updated after upgrading of the electrical motor. The root cause was lack of quality of testing of the DP systems in a degraded situation (Island Offshore, 2017).

11. Bucentaur on Valhall Flanke West in 2017

12 June 2017 the vessel Bucentaur was doing soil sampling at Valhall Flanke West in the North Sea for Aker BP. She experienced a thruster pitch alarm, followed by a drive off, and lost position. The main events leading up to loss of position happened in 17 minutes. The DP system was operating in auto position (surge, sway, yaw locked). The consequences were a broken drill pipe. Aker BP (2017) concluded on six potential critical factors:

1) Fault in the pitch control loop - thruster pitch command signal. There was a difference between the pitch commands and feedback for port azimuth thruster at the time of incident.
2) The emergency stop of the port azimuth thruster was not activated when the first alarm was received.
3-6) Faults in the pitch control loop. Several errors were registered from the port azimuth pitch control. Contact errors were detected on a terminal block for a card in the azimuth thruster cabinet.

12. Island Patriot at Valhall field in 2018

14 April 2018 the vessel Island Patriot did well stimulation at Valhall IP in the North Sea for Aker BP. The significant wave height was 2-3m. She was connected to the platform with a signal cable and a high-pressure hose. The vessel then moved unintentionally. The DP system was inadvertently instructed to move the vessel to its previous set point. The vessel moved of its current position in a forward direction at a speed of 0,14 m/s. The movement caused tension in the cable, and the junction box fell into the sea. The cable was cut and the high-pressure hose were rolled into the vessel. The cable and the junction box ended on the seabed (Aker BP and StimWell, 2018).

13. Deepsea Stavanger at the Skarv field in 2018

21 April 2018 the semi Deepsea Stavanger drilled at the Skarv field for Aker BP. She drifted out of position and came marginally outside the red circle set to 11 meters. The weather in the field was 15 m/s wind and 5,2m significant wave height. The automatic emergency disconnection was aborted by operator when he saw that the platform was about to stop close to the red limit. The platform moved automatically back to position and maintained position. The root causes (Odfjell, 2018) were lack of training, and that other users had reserved electric power for their own use, and not enough power was available for the thrusters.

14. West Phoenix at the Kristin field in 2018

4 November 2018 the semi West Phoenix drilled for Equinor on the Kristin field in the Norwegian Sea (Equinor, 2018 and Seadrill, 2018). The platform had eight anchors in a thruster assisted mooring. It got salt water leakage in one of its generators cooling system. It again led to a short-circuited generator. The power of four of eight side propellers were out of service until the ATA system was reconfigured, with six of eight side propellers operative. All eight side propellers were operational 25 minutes later. Throughout the incident, the platform went up to seven meters of location, and was in green status (up to eight meters).

REQUIREMENTS IN THE REGULATIONS

Our first regulations related to DP in the petroleum activities came in 1.1.2002, and were modified 1.1.2010. Our regulations on DP are applied to facilities, well stimulation vessels, diving vessels and vessel operations near the platforms, mainly inside the safety zones. We also apply our regulation on shuttle tankers doing offloading outside the safety zones. Our facility regulation (PSA, 2004) section 63 on anchoring and positioning requires that "*floating facilities shall have systems designed to hold their position at all times and, if necessary, be able to move from their position in the event of a hazard and accident situation. Dynamic positioning systems shall be designed so that the position can be maintained during defined failures and damage to the system, as well as during accidents. Components and equipment shall be designed so that the total system satisfies the requirements for a certain equipment class*...". Further our activity regulation (PSA; 2004) section 90 on positioning requires that "*when carrying out maritime operations, the responsible party shall implement necessary measures so that those who participate in the operations, are not injured, and so that the likelihood of hazard and accident situations is reduced. Requirements shall be set for maintaining the position of vessels and facilities when conducting such operations, and criteria shall be set for start-up and interruption*". With our 16 cases in five years, it is difficult to concluded that the industry acted completely in accordance with the regulations!

To fulfil the requirements, we recommend a set on equipment classes is in the guidance to the activity regulation section 90. They refer to IMO/MSC (1994) circ. 645 guidelines. A clarification to the recommendations to equipment classes were done in 2010. The changes limited some creative unsafe solutions. The high number of events on units with valid certificates of compliance both with the IMO/MSC (1994) circ. 645, the rules of flag states and classification societies, may also rise questions if our references is sufficient, and if the standards are sufficient.

COMMON CAUSES

Incident statistics

Based on my reading of the 16 cases on 14 units described above, I have summarized the causes of the cases in a cross-reference table (Table 1). In several of the cases I have ticket off in more than one box. It may be questioned if I should include failure in the reference systems as an error cause. In some of our cases, the underlying reason for failures of reference systems was lack of thruster power.

Table 1: CROSS-REFERENCE TABLE OF REPORTED DP CASES. THE NUMBERS ARE THE CASE NUMBER, AS DESCRIBED ABOVE. X" REFER TO THE MAIN CAUSES AS I READ THEM IN THE INVESTIGATION REPORTS. WHERE TWO SITUATIONS ARE REPORTED ON THE SAME PLATFORM, I HAVE USED "XA" AND "XB", ON THE FIRST AND SECOND EVENT DESCRIBED ABOVE. I HAVE CLASSIFIED THEM AS:

- SOFTWARE AND HARDWARE COMPUTER ERRORS ("SOFTWARE")
- LOSS OF ELECTRICAL POWER ("POWER")
- LACK OF THRUSTER CAPACITY (THRUSTER")
- WRONG UNDERSTANDING OF POSITION ("POSITION")
- OPERATIONAL OR PROCEDURE FAILURES ("OPERATION")

	Software	Power	Thruster	Position	Operation
1	x			x	
2	x				x
3		x			
4	x		x		
5	x			x	
6	xa xb			xa	xb
7			xb	xa	
8	x			x	
9					x
10	x	x			x
11	x				
12	x				
13					x
14		x			
Sum	10	3	2	5	5

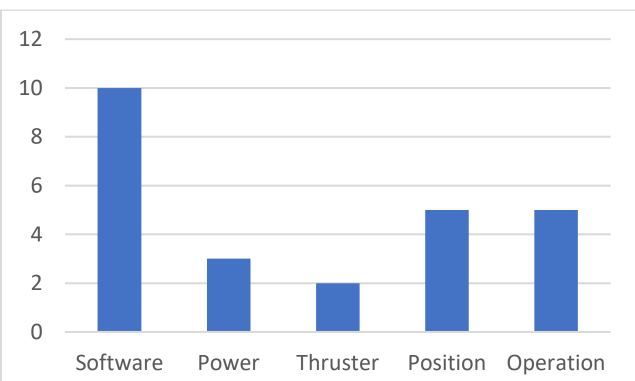

Figure 1: THE NUMBER OF EVENTS IN TABLE 1 RELATED TO THE MAIN CAUSES OF INCIDENTS. AS DESCRIBED IN TABLE 1, SEVERAL CASES HAVE MORE THAN ONE MAJOR CAUSE.

Table 1 and figure 1 are to a large extent the picture given by the platform or vessel owners in their investigation reports. They are explaining many of the cases as software problems. If the system or software suppliers had done the investigations, they may have questioned more if the use of the software had been according to their expectations, or if the thrusters' capacity were optimal.

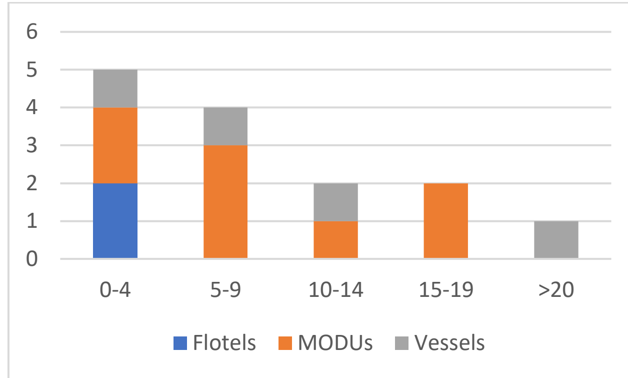

FIGURE 2: THE AGES OF THE UNITS (14X) WITH POSITION INCIDENTS REPORTED IN THE PERIOD 2014-2018. THE AGE IS AT THE TIME OF THE INCIDENTS, IN YEARS.

The ages of units show a normal age decay function, where most problems are observed early. Two of the units were less than one year old when the incidents occurred. Reviewing the most critical cases, the pollution cases happened on one unit that were less than one year old, one was six years and one was 16 years. The autolift cases occurred on units with ages less than five years. It is fair to say, that the youngest units had a higher occurrence of severe cases than the others. This behaviour is usually explained as deficiencies in design, fabrication and commissioning, together with unsatisfactory quality control or verifications. Since known errors usually are corrected, the number of faults are reduced over time, and so are the number of incidents. Important contributors to errors on new vessels are also new crews, new complex facilities, lack of vessel specific training and knowledge of the vessels, and how it behaves under the prevailing conditions. This is the same as our experiences on shuttle tanker incidents (Kvitrud et al, 2012).

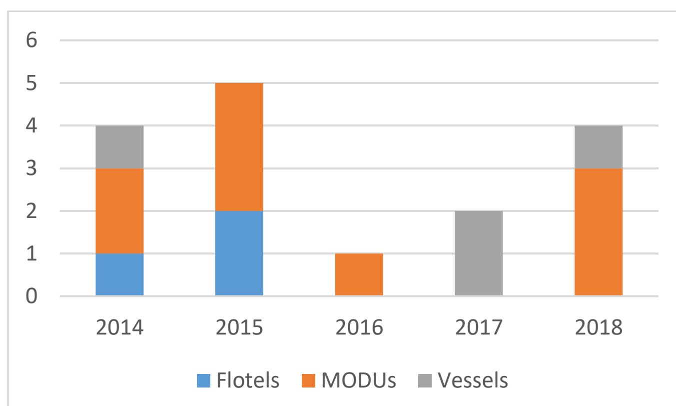

FIGURE 3: POSITION INCIDENTS (16X) REPORTED IN THE PERIOD 2014-2018, AS FUNCTION OF THE INCIDENT YEARS.

A temporary drop in number of in incidents occurred in 2016, but no clear trend is visible. A correlation between the drop of oil prices and reduced activities versus the changes in incidents do exist, but the tables and figures are not normalized for changes in the activities and the number of DP units in use.

Many incidents and failure modes are reported world-wide on DP systems. *Chong-Ju Chae* and *Yun-Chul Jung* (2015). analysed the IMCA data for 612 DP loss of position incidents from 2001 to 2010, and found the main causes of incidents were on the position reference systems, followed by DP computers, power systems, human errors and thruster systems. My cause distribution in figure 1, is not significantly differently.

The barrier concepts

Our management regulations section 5 (PSA, 2002) states that barriers shall be established that can identify conditions that can lead to failures, hazard and accident situations, reduce the possibility of failures, hazard and accident situations occurring and developing, limit possible harm and inconveniences. Barriers are measures intended either to prevent a chain of events from occurring or to affect a chain of events in a way that limits harm and/or losses. The two basic building blocks associated with the barriers are barrier function and barrier element. A barrier function can stop the accident evolution, so that the next event in the chain is not realized or reduce the accident consequences. Barrier elements contributes to achieve the required barrier function.

Haibo Chen (2006) and Haibo Chen et al (2008) described a set of DP barrier functions and a set of barrier elements for each barrier function for MODUs. They had a special focus on the reference systems. I compared our data set with their conclusions, to review its relevance. Their conclusions on barrier functions and barrier elements were briefly:

- Barrier function 1 - prevent loss of position, separated into three groups:
- Barrier function 1.1 - prevent DGPS generating erroneous position data. Three barrier elements were identified as independence between DGPS's, appropriate antenna locations and DGPS QC function
- Barrier function 1.2 - prevent erroneous DGPS position data being used by DP software. Two barrier elements were identified as DGPS input validation function and position reference error testing function.
- Barrier function 1.3 - arrest vessel movement before she passes the yellow limit. Barrier function 1.3 was analysed together with the barrier function 2.
- Barrier function 2 - arrest vessel movement. The DP operator was identified as the only barrier element.
- Barrier function 3 - prevent loss of well integrity. Three barrier elements were identified as EQD (Emergency Quick Disconnection system), SDS (Safe Disconnection System) and well shut-in function.

In addition to MODUs, as Chen et al (2006 and 2008) discussed, my data also include data from flotels and vessels. In their barrier function 1 loss of position is the basic failure mode, but unintended pitch or roll should also be included. In our data, we have two cases in this category:

- Case 6 when the facility pitched caused an autolift.
- Case 9 where DP testing probably initiated heavy roll movements.

A new barrier function can be followed by barrier functions 2. However, the barrier elements to barrier functions 2, should also include other personnel groups than the DP operator. A new barrier function (in addition or included in number 3), should prevent autolift of bridges and moving objects. Barrier elements can be pitch and roll predictions based on local wave data, thruster forces and RAOs for roll and pitch.

On barrier function 1.1, Chae and Jung (2015) described the most common cases world-wide. The barrier element on quality control will probably cover these cases. Our case 1 with a storm of networking events, that gave a to slow position updates will probably fit in here.

For barrier function 1.2 two barrier elements were identified as DGPS input validation function and position reference error testing function. We had the following cases:

- Case 5 when a large wave, or series of large waves forced the platform out. Then the DP system rejected all the reference systems. The system was unable to find setpoint fast enough to avoid disconnection.
- Case 7 when a wave train pushed the platform out of position. The platform was pushed off at a higher rate that the DP system recognize as possible, and therefore rejected all the position reference systems. The DP system used too long time to recalculate the reference systems to avoid disconnection.
- Case 8 when the platform got rapid movement, causing the reference systems to be rejected. The DP system became recalibrated within six seconds, but the riser angle came outside the riser disconnection criterion.

In contrary to the main idea, the reference systems functioned in these cases as they were designed. It was the logic of what is normal changes to the position, that caused trouble. The barrier function 1.2 – "prevent erroneous DGPS position data being used by DP software", should either be reformulated or a new barrier function should be made. A new barrier function could be "prevent rejecting correct position data".

Related to barrier function 1.3 and barrier function 2, our platforms remained in the green zone in three of our cases:

- Case 8 where the recalibration time of the reference systems were sufficient, but a higher DP current could have caused disconnection.
- Cases 9 where DP testing contributed to heavy roll movements.
- Case 14 after a short-circuit of a generator. The thruster assisted mooring may have saved the situation.

In our case 9 the incident occurred even if it was inside the yellow limit. A limit on surge, is an insufficient criterion to avoid unintended incidents. A limit should also be made for other movements than surge. Thruster assisted mooring gives an independent system for station keeping. Not all the present DP systems give sufficient independence to prevent incidents. We also have one collision and three autolifts that should have been avoided. None of them caused major accidents, indicating that other barrier elements may have been in place:

- Case 2 where the walkway was lifted.
- Case 3 with a collision.
- Case 6 with two cases of autolift.

Examples of barrier elements are forecasting the bridge movements, early disconnection, closing of the bridge for traffic at specified weather conditions, and using guards in both ends.

On barrier function 3 we have no cases were the wells were damaged. And this had a 100% success. However, we have several cases with disconnections, and three with pollution:

- Case 1 disconnecting from the well.
- Case 4 when drill pipe was cut causing pollution
- Case 5 with oil based mud released to sea
- Case 7 with mud lost to sea
- Case 10 with an emergency quick disconnect
- Case 11 with a broken drill pipe

Chen et al (2008) had no barrier functions to avoid pollution if an emergency disconnect is actuated. The last ten years, pollution have got a significantly higher public attention. The barrier function lack of confinement should be discussed in barrier analysis.

Man, technology and organisation (MTO)

Our guidance to the management regulation section 20 on registration, review and investigation of hazard and accident situations, requires investigations to clarify human, technical and organisational causes of the hazard and accident situation, as well as in which processes and at what level the causes exist. *Yining Dong* et al (2016) investigated the man-technology-organisation aspects in several Norwegian DP incidents. Almost as a default of the method, the results of the MTO analysis indicated that most cases involve both technical and human and operational factors. Similarly, *Helle Oltedal* (2012) analysed six Norwegian collisions. She identified two groups of direct causes, related to inadequate transfer of command and human deficiency to detect or interpret a technical state or error. Her analysis concluded that underlying factors to ship–platform collisions are related to violations of procedures that drift into normalized operational behaviour. This drift is not addressed in the safety management systems. To improve offshore vessels' safety, she concluded that organizations should strive to identify and understand the nature of the crews' practical drift from the formal guidelines and procedures. The MTO methods are typically applied on the offshore activities, and not on the designer, manufacturer nor on the onshore management.

Our cases involved a few situations where the operator played a role in the incident:

- Case 1 when the reference system failed and the DP operator took over manually.
- In case 2 an unsatisfactory evaluation of the wave conditions contributed to the incident.
- Case 12 when personnel on the vessels cut the cable.
- Case 13 when the automatic emergency disconnection was aborted by the DP operator.

It is also possible to discuss if the DP operator could have or should have intervened, in some of the cases. In case 7 and 13 the investigations concluded that the personnel did what they were supposed to do during the incident. The role of the operator is not discussed in detail in any of the investigations. It is fair to say that the roles could have better investigated, and can be a point of improvement in future incident investigations with reference to the guidance to the management regulation section 20.

Several research activities on human aspects related to DP incidents are performed in Norway. Among them, *Linda Sørensen* et al (2014) and *Kjell Ivar Øvergård* et al (2016) interviewed DP operators involved in incidents. They concluded that some of the DP operators were not able to identify the relevant initiating events. However, they were still able to make successful recoveries from critical incidents. Experience and recognition affected the operator's situation awareness that in turn influenced decision strategies. Since critical incidents imposed limited time, the DP operators often performed mental simulations of imaginary, but potential, future incidents. This mental simulation might allow operators to react faster and more appropriately to critical incidents. The interplay between procedures and the DP operators' technical skills or seamanship were apparent in six out of the 24 incidents where the DP operator either broke or adapted the procedures during the recoveries.

There is still a way to go from this research, to practical precautions. However, the procedures and DP operators' technical skills and seamanship are very important to recover situations.

Single failure-analysis

Our guidance to the management regulation section 5 entails that it should not be possible for multiple important barriers to be impaired or malfunction simultaneously, e.g. because of a single fault or a single incident. In the same way, the NMA anchoring regulation requires in section 6 that no single error, including operator's error, shall lead to a failure or release. The NMA risk analysis regulation also have an extended text in section 15 on reliability and vulnerability analysis. The single failure concept is also elaborated in the same regulation section 22. Possible single faults in equipment and systems shall not cause critical incidents.

The common method used to comply with the single failure requirements, is to do failure mode and effect analysis (FMEA). The quality of the design analysis and FMEA, is not discussed in any of the investigations. It is fair to say that the role could have been better investigated. In addition, it may be questioned if the requirements in the regulations are in fact complied with, as:

- Case 1 is low capacity in the network a single failure?
- Case 2 was the start-up of the drive off prevention system a single failure?
- Case 4, 5, 6, 7, 8 and 12 were sudden changes in weather single failures? Is the software logic of rejecting correct position data a single failure?
- Case 9 was the decision to DP test in survival draft a single failure?
- Case 10 and 14 was the stop of thrusters a single failure?
- Case 13 was the skewed distribution of power a single failure?

Some of the questions can be answered with yes, others with may be and some with no. It is not always easy to conclude if they were single failures according to the regulations. If they were not, compliance with the single failure requirement is not sufficient to avoid incidents. This is in line with Yining Dong et al (2016) and others concluding that FMEA analysis on DP operations are not sufficient to identify and remove all relevant single failure modes. FMEA also considers only hazards arising from single-point failures and will normally fail to identify hazard caused by combinations of failures. Furthermore, the actual system function could be overlooked, since the interactions between subsystems are not assessed in the FMEA when failure modes are reviewed separately in each subsystem. Similarly, *Børge Rokseth* et al (2017) indicated that FMEA, sea trials, and hardware-in-the loop testing, are insufficient and that their view on safety is too narrow. The safety constraints can be violated in other manners than component failures for DP systems, as with human errors.

If software in the main point of concern, the same software is typically used in two different DP computers. A discussion could be made if complete segregation should include two independent programs developed by two independent suppliers.

There is still a way to go to describe sufficiently good design principles, and methods to analyse according to them. The single failure concept of each component is practical, but not without limitations.

Experience from shuttle tanker incidents

The most common causes for the Norwegian shuttle tanker accidents and incidents investigated, as described above are (Kvitrud et al, 2012):

a) The procedures and instructions are not followed.

b) The crew on the bridge are not adequately trained to use technical equipment on the bridge in emergency situations. The crew has too much confidence in the systems, and when errors occur, the crew are not sufficiently attentive or trained to correct errors in time.

c) Several incident investigations are pinpointing malfunction of equipment, due to errors in design, insufficient quality of the testing or commissioning. In a special category are software errors being the most common cause of the severe cases.

The severity of incidents seems to be inverse proportional to the age of the colliding shuttle tankers. From their point of view, high attention should be given to have well designed and tested systems before a shuttle tanker was taken into service and in service to have a good safety culture, competence and training.

To a large extent the same conclusions may also be drawn from my 16 cases. However, the DP investigations did not go into the same detail as the investigations on some of the shuttle tanker incidents.

Slow response to changes in weather

Slow reaction on changes in position due to weather in moderate sea states, and including rejection of the reference systems have occurred in several incidents. We have three cases on autolift of bridges. Autolift is not a new phenomenon, and the oldest in our files, was from 1999. More recently were several cases on Floatel Superior in 2011 and 2012, resulting to two investigation report (Statoil, 2012 and Statoil, 2013). Before reuse of Floatel Superior in 2014, Statoil (2014) included several measures, as:

- Improved drive-off preventer function
- Simplified and improved location specific operational guidelines
- Increased margins for manual operation of walkway and autolift, and for demobilization of personnel
- Weather measurements and forecast of bridge motions
- Predefined actions at different situations
- Training on compliance with location specific operational guidelines
- Verification was routinely carried out by the crews
- Training on emergency preparedness functions
- Management reviews were conducted.

Since 2014 no autolift situations have been reported to us on Floatel Superior.

Transocean (2015b) had eleven recommendations in case 5, including:

- A "wide" setting on prediction error acceptance limit
- Predict weather requiring 'Yellow DP Alert'.
- Improved performance and robustness, and upgrades to the HPR system.
- Evaluate GPS for better diversity.
- Forecast vessel motions from weather forecasts.

In the investigation report in case 7, Songa Offshore (2016) had nine recommendations, including:

- Better monitoring and control of thruster and power usage and position control.
- Implement “insufficient thrust” as an additional trigger or alarm.
- Review of the software related to the rejection of the position reference systems.
- Review of working environment with respect to communication and number of alarms.

It can be discussed if the units had sufficient capacity to maintain position, if the DP system reacts too slow or if the thrusters were not sufficiently on alert. The investigation reports points at the DP systems, but is it always correct? Do the owners buy thrusters with too low capacity, and are they not running the thrusters properly to be sufficient on alert in unexpected situations?

Some of my main points of concern are listed below. It seems obvious that the criteria in the software or the software itself, can be improved:

- Slow reaction time to changes in position. None of the investigations investigated why the DP system did not stop the movements before they became a problem.
- It is not obvious why correct position data should be rejected. It creates loss of time and escalate the incidents.
- Lack of manual intervention when the system is malfunctioning. The DP operator should be capable to understand when the system doesn’t work as it should, and have the possibility to intervene manually.

QUESTIONS

To make improvements, several subjects should be discussed with the responsible parties, as:
• Is the single failure principle implemented correctly, and is compliance with the principle sufficient to avoid incidents?
• How are smaller margins, due to saving of investments, fuel and NOx emissions charges, compensated for in case of unforeseen events?
• What can be done in design to reduce technical errors, and errors by the operators despite increased complexity?
• Are the capacities to hold position in specified sea state known, and can it be connected to forecasts of movements?
• Why are unintentional movements due to weather changes not stopped earlier? Are the thruster capacities or response time too slow in moderate sea states? Why do the systems reject correct position data?
• How can the DP systems be used to reduce pitch and roll?
• How can the owner improve the technical and seamanship skills of the DP operators, despite low revenues?
• Do the procedures limit the possibilities of manual intervention unnecessary?
• Are suppliers challenged to improve their products based on experience from testing, completion and incidents?

We give functional requirements in our regulations, and some additional recommendations. For most cases the requirements should be sufficient. However, the number and the severity of incidents should trigger more supervisory activity, product improvements and research activity.

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