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Risk-based decision-making support model for offshore dynamic positioning operations

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ABSTRACT

A Dynamic Positioning (DP) system enables vessels and rigs to accurately maintain a predetermined position and heading or track. It enables precise operations under harsh environmental conditions. DP is used for a variety of purposes; however, the role of the DP operator (DPO) is considered the same regardless of type of operation: to monitor and keep the vessel in position. Some of the decisions that the DPO makes are safety critical, for example, decisions about the set-up of the system can prevent the vessel from colliding with an offshore oil and gas platform. Applied cognitive task analysis (ACTA) is performed to analyze how the different operational settings influence the role and decision-making of the DPO. Two DPOs with experience from five different operation types were interviewed. The results from the ACTA for the different operation types are compared with respect to technical steps, cues, the cognitive steps and components, actions, and decisions. The contextual factors are evaluated using an adapted version of Rasmussen's dynamic safety model. The results of the comparison are used to evaluate the current role of the DPO, in light of the DP system and different DP operations. Recommendations for the improvement of safety, the design of the DP system, training and set-up of DP operations are formulated.

1. Introduction

Dynamic Positioning (DP) systems were developed in the 1960′s for offshore drilling. The need arose when offshore drilling moved into deeper waters and the use of jack-up drilling platforms was no longer possible and anchoring was not a financially viable option or impossible due to a congested sea bottom. The first DP systems were simplistic, but when more advanced control theory was applied in the 1970′s the highly automated DP system was realized (Breivik et al., 2015).

DP vessels (including semi-submersibles and mobile drilling units, see also Table 1) allow for types of operations in new areas where it is important to be able to relocate easily and quickly (Sørensen, 2011). Within the offshore oil and gas industry, DP vessels are used for a variety of operations, such as offloading, drilling, diving, inspection, repair, and maintenance, subsea intervention, seismic, flotel, walk-to-work and construction operations. The operations performed by these vessels vary in position excursion tolerance and the potential consequences (Chen & Nygård, 2016). These vessels usually operate in close proximity to a fixed installation (some less than a few meters). Some vessels are even larger than the platforms they are serving, for example, some of the heavy lift vessels or flotels. Yet the design and training requirements for these various types of DP operations are similar. Considering the operational differences and uniform requirements for design and training, this study sets out to assess if the cognitive processes involved for various types of DP operations support such an approach. The objective of the study is to compare the critical decisions made by the DP operators during the different operations to evaluate the need for operation specific requirements related to, for example, training and Human Machine Interface (HMI).

The DP system's components are located throughout the entire vessel; they range from wind sensors all the way on the rooftop to the thrusters down in the water. A DP vessel relies on a computer system to interpret signals from reference systems, wind, motion and gyro sensors to maintain position and heading or stay on a predetermined track. This is accomplished by adjusting the direction and force of the thrusters of the vessel. The power management system controls, monitors, and

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Abbreviations: ACTA, Applied Cognitive Task Analysis; CSV, Construction Support Vessel; DP, Dynamic Positioning; DPO, Dynamic Positioning Operator; HMI, Human Machine Interface; HSE, Health, Safety, Environment; HTA, Hierarchical Task Analysis; LOP, Loss of Position; NCS, Norwegian Continental Shelf.

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Table 1
Overview and short description of DP operation types included in the study.

DP operation	Short description
Construction support vessel (CSV)	CSV, also known as offshore construction vessel, are designed to be able to offer support for complex construction, installation and maintenance activities. They are very similar to inspection, maintenance, and repair vessels. However, CSV are larger with greater crane capacity.
Drilling	Also known as mobile offshore drilling units. Drilling vessels perform exploratory drilling of new oil and/or gas wells and can drill for scientific purposes. A mobile offshore drilling unit can be of the semi-submersible or drill ship type. Semi-submersibles are more stable than drill ships, but drill ships are more mobile. The vessels can stay on DP for months, depending on the operational and environmental conditions.
Flotel	Flotels are designed as accommodation units to support installations. Most flotels operating on the NCS are large semi-submersibles and can sleep between 400 and 500 persons.
Offloading	Shuttle tankers are specifically equipped and designed to transport crude oil from offshore oilfields to an onshore terminal or processing plant, as an alternative to transportation via pipelines. There are different types of loading systems, some require the vessel to directly connect to the oil producing installation other systems utilize a buoy. The vessels have been designed and built to reduce the risk of transporting crude oil, for example double hulls.
Supply	Supply vessels are built and equipped to deliver supplies (e.g. provisions, fuel, and spare parts) to other offshore vessels and installations, and return other cargo to shore. Most supply vessels have the capability to transport deck as well as bulk cargo. Bulk cargo usually consists of water, fuel, chemicals, drilling fluids or cement. Crude oil is transported by vessels that are specifically designed for the job, shuttle tankers. Deck cargo is lifted on and off by use of a crane and bulk cargo with hoses. Supply vessels used on the NCS are equipped with either DP1 or DP2.

supplies the DP system with the required power.

1.1. Loss of position

All DP operations are inherently threatened by loss of position (LOP). Loss of position incidents where the vessel exceeds all predefined limits for position keeping are relatively rare, and operators often only have a short response time to correct or mitigate such losses (Chen & Moan, 2005). Furthermore, when active, the thrusters pose a risk to divers and remotely operated vehicles, and a full blackout could cause an uncontrollable LOP (Hogenboom et al., 2020). The weather conditions in which the DP vessels have to be able to maintain position can be rough; some areas are exposed to hurricanes, polar lows, or snowstorms. These conditions increase the risk of a collision and other potential consequences.

LOP is usually divided into two types of events: drive-off and drift-off. A drive-off means that there is active thrust driving the vessel away from the target position; a drift-off means that there is insufficient thrust to maintain the target vessel position and as a result the vessel drifts away due to the environmental forces (Chen et al., 2008). A third type of LOP is called a force-off; during a force-off the environmental forces exceed the total available power capacity to maintain position and/or heading.

A manifold of human and organizational factors, technical (design) failures, environmental conditions, or a combination of these, can initiate a loss of position (Dong et al., 2017). For example, poor training of DP operators (DPOs), operators being distracted by other work that they have been assigned, challenges with vigilance, lack of system understanding and procedures, switchboard failure due to an overload, bad weather, etc. LOP can result in major accidents, such as collision, loss of well integrity, damage to subsea structures, rupture of loading hoses, etc. (Chen & Nygård, 2016). For example, a supply vessel lost position in June 2019 and collided with a platform. There were significant damages to the lifeboats on the platform, which led to a partial evacuation of the platform, and a deck hand on the supply vessel sustained injuries when a loading hose ruptured (PSA, 2019).

1.2. The dynamic positioning operator

DP training and design requirements are the same or similar for nearly all DP operation types. However, the risks involved with DP operations vary. Collision risk is a concern for almost all DP operations, yet the consequences of a collision depend on the impact of the vessel on the installation. For example, the consequences of a supply vessel colliding with an installation during close proximity maneuvering are potentially less severe than a flotel colliding with that same installation due to differences in size of these two vessel types. Such operations have a low excursion tolerance since they operate close to a collision object, affecting the time available to an operator to respond. Yet, other operations are more complex, for example, drilling operations have phases where it is impossible to disconnect safely from the well, the DPO needs to be aware of this and work together with the driller when position-keeping capabilities are threatened. Consequently, the cognitive demands placed on the DPO vary. However, DP operators receive the same training and require the same certificate to operate these vessels.

The majority of DP operations are carried out with two operators on the bridge with one DPO manning the DP console and the other carrying out other bridge functions. These two DPOs then swap roles every hour. This practice varies depending on the DP operation, vessel, and even crew. The watch relief arrangement should allow staggered watch changeover such that there are never two fresh DPOs taking over at the same time (Bray, 2008). During this changeover a hand-over is performed based on the hand-over checklist (IMCA, 2018).

1.3. Dynamic positioning: The operator and the system

Designing a system with automated functionalities faces several challenges with regards to supporting the operator performance. Examples of these are transient workload, trust in the system, and situation awareness. This also is true for DP operations. For example, DP operations can involve long periods of boredom interrupted by sudden bursts of activity (Hogenboom et al., 2020; Hurlen et al., 2019; Utne et al, 2019; Utne et al., 2019).

Sudden transients in workload are often combined with an information overload and may increase the probability of human error and misjudgment (Endsley & Jones, 2012; Sheridan, 2002). These patterns can be observed in other highly automated systems, such as in aviation (Durso & Alexander, 2010) and autonomous vehicles (Neubauer et al., 2012; Saxby et al., 2013). This is also the case for DP operations. In addition, when a DPO needs to take over for the automation there is often limited time to do so before an accident becomes unavoidable, in some cases less than a minute (Hogenboom et al., 2020). Hence, automation needs to be able to support the situation awareness of the operators (Endsley & Jones, 2012; Stanton et al., 2001).

Trust in automation is affected by how the operator perceives the performance of the automation, if the automation is perceived as reliable as is the case for DP systems; the operator will be inclined to trust the automation. However, if the automation gives many false alarms or irrelevant alarms, such as normal power fluctuation alarms on the DP system, then alarms will not be taken as seriously or might even be ignored and trust in the automation declines. Therefore, trust is critical for the success of the human-automation relationship (Lee & Moray, 1992).

Parasuraman et al. (1993) and Sorkin (1988) also pointed out that too much trust (over-trust) in automation can have negative consequences just as too little trust (under-trust). Whereas distrust can lead to inefficient use of the automation or, more seriously, ignoring important alarms, over-trust can lead to complacency, overdependence, degraded detection, awareness, and manual skill. These effects are known as out-of-the-loop (Endsley & Kiris, 1995). Furthermore, combined with the increasing complexity of automated systems and operations, as well as poor human machine interfaces and inadequate training, has also led to reduced system understanding. This causes the operator to be even more likely to be out-of-the-loop and it significantly affects the situation awareness. However, the better the operator understand how the automation works and its limitations under the various conditions, the better the operator will be at allocating the correct levels of trust (Sheridan, 2002).

1.4. Decision-making and dynamic positioning operations

Decision-making theory can be divided into two categories: normative and descriptive. Initial research focused on the optimal and rational decision-making (Wickens, 2004). Later research, realizing that decision-making in the “real” world did not necessarily follow these rules of logic, focused on the cognitive processes underlying decision-making and developed descriptive models. Experts have been known to adapt their decision strategy based on the situation. This theory relies on the skill, rule, knowledge based behavior classification from Rasmussen (1983) and formed the basis for the recognition primed decision making model (Klein et al., 1988). Recognition primed decision-making is based on the observations that experts mostly just recognize a pattern of cues and recall a course of action to be implemented. The assumptions that the model is based on revolve around the experts having experienced a similar decision situation before and with sufficient time to recognize the pattern and select the course of action. In cases where the expert is unsure about the course of action, she or he will utilize mental simulation, in which different outcome scenarios are considered based on the available courses of action (Klein & Crandall, 1995).

A study from Øvergård et al. (2015) focused on the characteristics of a DPO’s situation awareness and decision-making during critical incidents in dynamic positioning operations and found that operators mainly respond to recognized cues, much in line with recognition primed decision making theory (Klein et al., 1988). In another study, Imset et al. (2018) analyzed the decision of DPOs to perform an emergency disconnect when drilling on DP. They concluded that even though the decision is proceduralized, these were sometimes overridden by the DPO based on mental simulations of the event. A MSc thesis (Pedersen, 2015) also focused on drilling operations and mentions that a key performance factor for decision-making regarding the emergency disconnect is time. In a study from Chauvin et al. (2009) they found that supplementing training with decision-making exercises improved the performance of trainee watch officers in analyzing complex situations. The literature search on research focusing on decision-making for DP operations revealed that no other research work has been performed on this topic.

1.5. Comparing decision-making by dynamic positioning operators

This study, therefore, aims to compare different types of DP operations and evaluate the significance of their differences on the safety of the operations in light of the current DP system (human machine interface, HMI) design and training requirements. A comparison is made of the decisions and considerations a DP operator (DPO) has to make for different types of DP operations by using an applied cognitive task analysis (ACTA). ACTA can provide insights into the non-observable tasks that a DPO has to perform without affecting the safety of a DP operation. The decisions and considerations related to operation of the DP system made by DPOs are then mapped and evaluated, with an ACTA and the dynamic safety model from Rasmussen (1997). The main result of the study shows that the main cognitive tasks are very similar across the different DP operations, but that they are affected differently by contextual factors.

The analyses focus on the tasks of station-keeping and safe termination of the operation. Five DP operations on the Norwegian Continental Shelf (NCS) have been selected for the analyses to illustrate the variety of characteristics, risks types and operational requirements. An overview and a short description (Fossum et al., 2018; Hogenboom et al., 2020) of the five DP operation types selected is presented in Table 1.

2. Method

The study has a qualitative and multiple case study design. The design has been chosen to get most insight into the cognitive processes ongoing during DP operations. The study utilizes the Applied Cognitive Task Analysis ACTA to structure the interview process and obtain the information regarding cognitive tasks, such as decisions, etc. The method is applied to understand cognitive demands in several types of DP operations. This could provide insight into possible differences in requirements for design and training governing DP systems and DP operations.

2.1. Participants

For this study, ten informants were chosen based on their experience as DP operators; two informants per offshore operation type (i.e., CSV, drilling, flotel, offloading, and supply, see Table 1) were selected. The population of interest for the study is DPOs working or recently having worked on the NCS within the oil and gas industry. The study also required experienced operators. Nine out of ten participants had more than 15 years’ experience; one participant working with supply operations had six years’ experience. The participants were approached through the companies that they worked for and asked if they wanted to volunteer for the interviews based on a description of the study, method and purpose.

2.2. Interviews

As part of the ACTA, ten (10) semi-structured interviews were conducted in June-October 2019. The participants were recruited via the companies the participants work for. Eight of the interviews were conducted face-to-face, with only the interviewer and participant present. Two of the interviews were conducted via videoconference call. Three hours were set off for each of the interviews, with most interviews lasting 2,5 h. The interviews were recorded and transcribed.

2.3. Cognitive task analysis

A cognitive task analysis can be considered an extension of traditional tasks analysis. The technique is used to describe knowledge and cognitive processes underlying observable tasks (Shalin et al., 2000). The results from a cognitive task analysis can be used to aid, for example, design, procedures, allocation of function, development and evaluation of training, and performance (Stanton et al., 2005). Since the first cognitive task analysis performed by Flanagan and Dennis (1954) on near incidents in the aviation industry using the critical incident technique, numerous CTA techniques have been developed. According to Roth et al. (2002) the methods can be categorized into three approaches: 1) analyzing the domain in terms of goals and functions, 2) based on empirical techniques (e.g. observations and interviews), 3) simulator-based observations. Stanton et al. (2005) summarize five of the most popular CTA methods in their work: ACTA, Cognitive Walkthrough, Cognitive Work Analysis, Critical Decision Method, and Critical Incident Techniques.

The ACTA was selected after reviewing and comparing different cognitive task analyses (Stanton et al., 2005), because of its general generic domain application and its focus on a specific tasks, instead of an incident or object, as is the case with other cognitive task analysis methods.

ACTA is a streamlined methodology that requires less training, resources and time for its application and provides tools for extracting knowledge and coding complex decision-making skills. The method consists of four complementary techniques, each of them aiming to derive different aspects of cognitive skills that all add up to comprehensive results (Militello & Hutton, 1998). The ACTA was used to gain insight into the different decisions and cognitive tasks a DPO performs when preventing a loss of position.

2.4. Procedure

The ACTA procedure comprises the following four parts, which were followed (Militello & Hutton, 1998).

1. Task diagram interview providing the analyst with an in depth overview of the task under analysis. During the interview, the analyst highlights those elements of the task that are cognitively challenging.
2. Knowledge audit interview highlighting those parts of the task under analysis where expertise is required. Once examples of expertise are highlighted, the subject matter expert is probed for specific examples within the context of the task.
3. Simulation interview, probing the cognitive processes used during a simulated incident by the subject matter expert.
4. Cognitive demands table integrating the data obtained from the task diagram, the knowledge audit and simulation interviews.

The ACTA in this paper has been expanded with a simple timeline analysis to further compare the DP operations on time spent on DP and potential available time for the DPOs in case of an incident. Additionally, data was gathered regarding the operator's education and experiences with the DP operation. Ethical approval for the study was obtained from the Norwegian Center for Research Data. The data gathered from the participants was anonymized and no personal identifying information will be stored. The participants also signed an informed consent before the start of the interviews.

2.5. Analysis

The ACTA was used to structure the interview data. The task diagram was further analyzed with a hierarchical task analysis (Kirwan and Ainsworth, 1992) and coarse timeline analysis (Kirwan and Ainsworth, 1992).

The safety of a DP system is affected by the operations it supports, the operators interacting with it, the management that arranges contracts and sets operating limits together with clients, and last, but not least the physical environment in which it operates. Rasmusseńs (1997) model of dynamic safety describes human behaviors in an abstract work area. The work area is framed by boundaries that constrain the workers' degrees of freedom. The model distinguishes three organizational boundaries: economic failure, unacceptable workload, and a double edge describing both functionally acceptable performance and perceived acceptable performance.

2.6. Limitations and assumptions

The study in the present paper focuses on DP operations related to oil and gas activities on the NCS. Results from this study might not be representative for DP operations related to oil and gas activities outside of this area. It is assumed that the differences between DP operation types are larger, than those between companies working on the same operations. The study focuses on the safety critical tasks related to the DP operation. The ACTA concentrates on the cognitive function of decision-making; other cognitive functions might be included, but are not in focus. A further limitation of the study is the small sample size, two informants per operational type. The population of experts within DP per operation type is relatively small as well. The need for further interviews was evaluated based on the first round of interviews, but the interviews quickly reached a level of saturation. Nevertheless, the representativeness of the results should be interpreted with the small sample size in mind.

3. Results

The results from the ACTA study are presented in the sections below. First, the selection of decisions included for further analysis is presented. Then the decisions and their cognitive processes are further broken down and presented in a hierarchical task analysis (HTA). This is followed by a presentation of the contextual differences and their impact on the cognitive processes. These contextual differences are further highlighted in a dynamic safety model for DP operations. The results then conclude with a summary of the main results.

3.1. Identifying critical decisions affecting DP operations

All DP operation types studied are built up of similar phases: departure, transit, arrival at field, move in, operation, move out, transit, and arrival at docks (see Fig. 1). Some operations have additional phases where they are connecting and disconnecting once they reach their loading or landing position.

During the departure, transit and arrival at dock phases, the DP system is not utilized to maintain position, heading or course. The phases of most interest for this study are the arrival at the field and the operation (see Fig. 1).

The critical decisions for the DP operations in the study occur at the same point in the operations (i.e., at the same decision gates, see Fig. 1):

1. In preparation for entering the 500-meter zone, if relevant (not relevant for drilling operations and some construction support operations), the DPO needs to decide whether the vessel will be capable of maintaining position, e.g. whether the weather is within prespecified limits, whether the vessel and all related DP systems perform according to specification, and whether field conditions are according to procedures. This is done with a checklist. There can be vessel and/or field specific requirements for the redundancy and operating weather that need to be complied with before the vessel can enter the field. Additional tasks at this time focus on setting up the DP system according to the specifications.
2. Arriving at operating location: When arriving at the operating location conditions might be different from what was expected during the preparations for entering the 500-meter zone. In this case, the DPO has to decide whether she/he needs to revise her/his operating plan or needs to abort the operation and wait for better operating conditions. This is a continuous evaluation. Once the DPO is certain that position can be maintained, based on main cues: available power, stability of the power consumption, weather conditions, and stability of position and heading, operations can be set up.
3. Detecting a potential threat to position-keeping capabilities whilst operating: During operations, several things could arise that could threaten the position-keeping capabilities of a vessel. A major element is the weather (e.g. increased wind, waves, current, or an interaction effect); worsening weather conditions could prime a DPO to make changes to the vessels position or heading, or modify the power and thruster configuration to improve position-keeping capabilities. However, if weather conditions become too harsh the DPO needs to inform operating personnel that operations need to be stopped and that the vessel needs to move out and wait for the weather to pass. Loss of redundancy, indicated by alarms and changes in system states, is another incident that would make the DPO reevaluate if the vessel is still able continue operations.

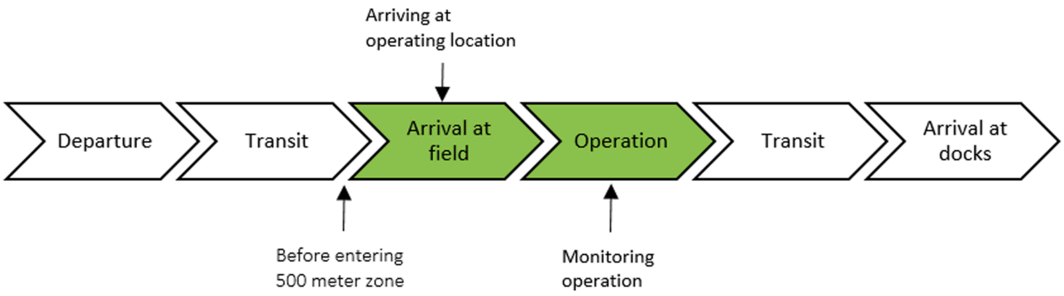

Fig. 1. Phases of DP Operations.

There are many decisions that affect the DP operation, during the planning phases (not included in Fig. 1) of the operation onshore management with some operational input decide, for example, what the operating limits should be and if the operation is feasible and safe enough based on the relevant risk criteria and based on the capacities of the vessel. However, these are not included in the study, which focuses on operational decision-making.

Most operations included in this study involve DP vessels with high levels of redundancy and should be able to maintain position even if some redundancy is lost. However, this should always be evaluated in context with the weather and operational requirements/limitations. In most circumstances, these decisions are not made by the DPO herself/himself, but by the captain or offshore installation manager and in discussion with the client. The DPO gives input to the discussion by providing information on the status of the DP system and weather conditions, and other relevant observations. The operational plan is also considered in the decision-making. For some operation types and some phases of those operations, it might be safer to continue operations than to abort them. For example, in certain drilling phases abandoning the well without finishing the casing, might increase the risk of hydrocarbon releases when opening the well again. Or time left of an operational phase, for example if a shuttle tanker has almost finished the offloading, then it might be safer to continue operations than to stop and move out and move in again to finish the job. The client can exert pressure to stick to the schedule as much as possible, and thereby influence the decision to continue operations.

3.2. The ACTA results presented in a hierachical task analysis (HTA)

A hierarchical task analysis was used to illustrate the DPO tasks (see Table 2, Table 3 and Table 4), with a focus on cognitive tasks related to the three main safety critical decisions (identified above) of the DPO during the operational phases when DP is used (see Fig. 1). The breakdown of the safety critical decisions made by DPOs from the five different DP operations studied did not reveal any significant differences. The HTA can therefore be considered to be representative for all DP operations included in this study.

There are some exceptions, however, for example, some of the position keeping indicators vary for the different operations: riser angle for drilling, gangway sensors for flotel, hose tension for shuttle tanker and some supply operations, and crane feedback for some CSV and some supply operations, and remotely operated vehicle feedback for some CSV operations. Moreover, the set up of the gain settings may differ between the DP operations' types studied, and sometimes also within some of the DP operation types. These differences are not made explicit in the HTA (Table 2, Table 3, and Table 4).

3.3. Differences in operational contexts for the DP operations studied

Even though the HTA breakdown of the safety critical decisions made by DPOs during the various DP operations studied did not reveal many significant differences in cognitive tasks, a few decisions/

Table 2
ACTA results from the first decision gate (i.e., 500-meter zone) presented as a HTA of safety critical decision during DP operations (with **technical steps**, indicators and cues, **cognitive components** and *actions and decisions*).

Enter 500-meter zone
Complete 500-meter zone checklist
1.1.1 *Decide* on gain settings, low, medium, high dependent on box-test results (verification of gain settings by moving the vessel 30 m starboard, 30 m, ahead, 30 m port and 30 m astern)
Evaluate local operating conditions
Weather
Operating location with regards to weather
Other activities happening on field
Time window for operation (if relevant)
Evaluate if additional operating limitations are necessary
Decide/conclude vessel is ready to enter 500-meter zone
Decide on operating location and heading/ *Decide* if planned operating location and/or heading needs to be revised
Evaluate operating requirements/limitations
Evaluate impact of weather
Evaluate pros, cons and risks associated with potential positions and headings
Decide how to get to operating location
Decide on DP mode (if not predefined by field or company procedures)
Evaluate the pros, cons and risks associated with each DP mode
Decide on speed (if not predefined by field or company procedures)
Evaluate the pros, cons and risks associated with each speed alternative
Decide on heading (if not predefined by field or company procedures)
Evaluate the pros, cons and risks associated with each heading alternative
Decide on size of steps (if not predefined by field or company procedures)
Evaluate the pros, cons and risks associated with each step size alternative
Communicate to installation that the vessel is ready to enter the 500-meter zone
Receive approval for entering 500-meter zone

Table 3
ACTA results from the second decision gate (i.e. arrival at operating location) presented as a HTA of safety critical decision during DP operations (with **technical steps**, indicators and cues, **cognitive components** and *actions and decisions*).

Arrive at operating location
Verify that local operating conditions are as expected
Complete checklist
Evaluate the effect of the weather on position keeping capabilities
Evaluate if a change in heading would improve the position keeping capabilities
Evaluate if a change in heading would make position keeping more stable
Evaluate if a change in heading would reduce the power required to maintain position
Evaluate if a change in heading would keep power and thruster use more stable
Evaluate if gain settings are optimal for the accuracy and power consumption trade-off
Evaluate if it is possible to conduct necessary test with ongoing start-up activities
Communicate with operative personnel about planned tests of DP system and DP related systems, and consequences of those tests
Decide/conclude that vessel will be able to maintain position during the start-up of operations and for the foreseeable future
Evaluate the time it will take to safely abort start-up operations (if relevant)
Evaluate if the operating conditions are favorable enough to be able to complete start-up of operations
Evaluate if start-up activities for operations leave sufficient power available for maintaining position given the weather conditions

Table 4
ACTA results from the third decision gate (i.e. during operations) presented as a HTA of safety critical decision during DP operations (with **technical steps**, indicators and cues, **cognitive components** and *actions and decisions*).

During operations
Monitor position keeping capabilities
Evaluate the effect of the weather on position keeping capabilities
Evaluate if a change in heading would improve the position keeping capabilities
Evaluate if a change in heading would make position keeping more stable
Evaluate if a change in heading would reduce the power required to maintain position
Evaluate if a change in heading would keep power and thruster use more stable
Evaluate if gain settings are optimal for the accuracy and power consumption trade-off
Detect if vessel is operating in a drift-on position
Evaluate if the safety margin under the current operational stage is sufficient to remain in a drift-on position
Evaluate if the safety margin under the foreseeable future circumstances is sufficient to remain in a drift-on position
Inform other DPO about the drift-on position and *communicate* the evaluation of the consequences of this for the operation
Observe a drift-off
Increased weather
Recognize increase in weather
Verify if vessel cannot maintain position
Check position keeping at position plot
Check distance to collision object (if relevant)
Check power general consumption
Check if additional generators can be started
Check thruster power consumption
Check status consequence alarm
Look out window at weather and motion of vessel
Check wind sensors
Check other activities ongoing that could be draining power
Interpret the increase in weather as a potential drift-off
Anticipate a loss of position and *prepare* accordingly
Increased power consumption
Detect increased power consumption
Verify if vessel cannot maintain position
Check position keeping at position plot
Check distance to collision object (if relevant)
Check weather conditions
Check if additional generators can be started
Check thruster power consumption
Check status consequence alarm
Look out window at weather and motion of vessel
Check wind sensors
Check other activities ongoing that could be draining power
Loss of redundancy
Detect loss of redundancy
Evaluate the consequences of the loss of redundancy
Verify if vessel cannot maintain position
Check position keeping at position plot
Check distance to collision object (if relevant)
Check power general consumption
Check if additional generators can be started
Check thruster power consumption
Check status consequence alarm
Look out window at weather and motion of vessel
Check wind sensors
Check other activities ongoing that could be draining power
Interpret the loss of redundancy as a potential drift-off
Anticipate a loss of position and *prepare* accordingly
Observe a drive-off
Thruster not responding
Detect thruster not responding
Verify if vessel cannot maintain position
Check position keeping at position plot
Check distance to collision object (if relevant)
Check speed
Check power general consumption
Check thruster power consumption
Check status consequence alarm
Look out window at weather and motion of vessel
Verify settings
Confirm thruster not responding
Stop thruster not responding
Contact engine room
Interpret the thruster not responding as a potential drive-off

Table 4 (*continued*)

Anticipate a loss of position and *prepare* accordingly
Drifting reference system
Detect drifting of a reference system
Verify which reference system is drifting
Deselect drifting reference system
Verify if vessel is able to maintain position
Check position keeping at position plot
Check distance to collision object (if relevant)
Check speed
Check thruster power consumption
Look out window at weather and motion of vessel
Verify settings
Interpret the drifting reference system as a potential drive-off
Anticipate a loss of position and *prepare* accordingly
Project position keeping capabilities in the future
Monitor the weather report data
Monitor and *communicate* with operative and managerial personnel on the operation's schedule and the requirements to position keeping capabilities
Plan how to adapt DP settings to manage changes in requirements/challenges to position keeping capabilities
Evaluate if a change in location or heading is necessary
Prepare for planned changes

evaluations are operations type specific:

CSV:

- Is there crane activity?
  - o Is there sufficient power available for the DP operation considering the weather?

Drilling:

- Phase of the drilling operation
  - o Non-shearables in the blow-out-preventor mean that there is a need for stricter requirements for position keeping (a disconnect is not likely to be successful with non-shearables in the blow-out-preventor)

Flotel:

- Personnel on board the flotel vs. personnel on board the installation (in case of a disconnect there needs to be sufficient lifeboat capacity on the flotel and installation)
- Anyone on the gangway? (in case of an auto-lift someone on the gangway could get hurt)
- Are hoses connected through the gangway? (would cause damage in case of an auto-lift)
  - o Are there hydrocarbon hoses? (a ruptured hose during an auto-lift could cause a fire or explosion)

Shuttle tanker:

- Phase of operation: connecting/loading/disconnecting? (in case of a need to disconnect could lead to an oil spill or personnel on the loading deck getting hurt)

Supply:

- Connected with hose for bulk loading/offloading (smaller excursion margins for the vessel, closer proximity to the installation)

The contextual variations are most apparent in the consequences of a LOP, the frequency of the operations, and the time spent in DP for each operation's type (see Fig. 2 and Fig. 3). The data on which the figures are based were gathered during the interviews. The order of the DP operations in the scales is based on relative differences, meaning the frequency of supply vessel operations is higher than the frequency of CSV

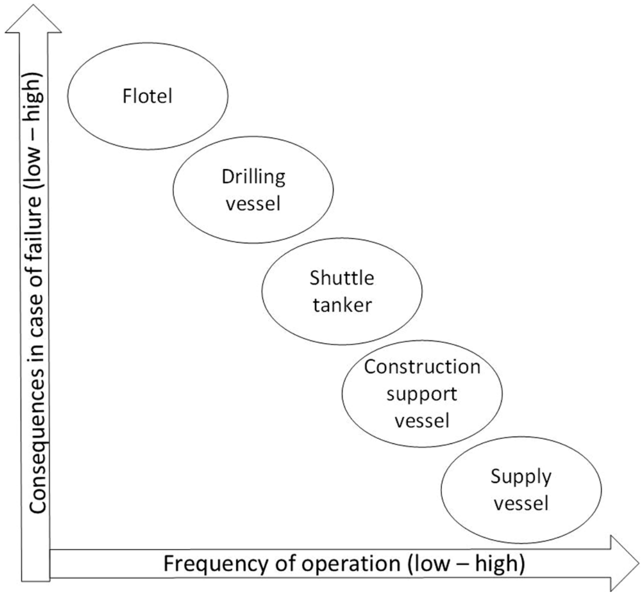

Fig. 2. Frequency and consequences in case of failure (LOP) of the DP operations studied.

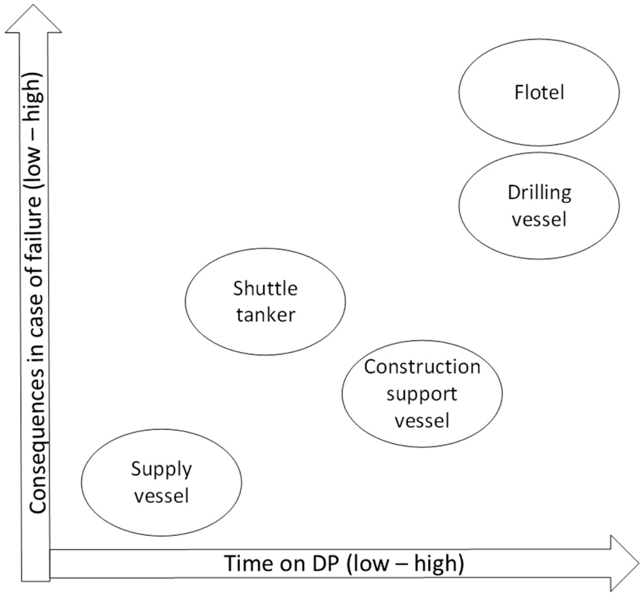

Fig. 3. Time on DP and consequences in case of failures (LOP) of the DP operations studied.

operations and the consequences of a LOP for a shuttle tanker are less severe than the potential consequences of a LOP of a flotel. These contextual factors do not emerge from the HTA, because of the task-focused structure of the HTA. However, they do affect the way the tasks are performed. The effect of the contextual factors become clearer when reviewing how they affect cognitive processes through situation awareness (Endsley & Garland, 2000) and a dynamic safety model (Rasmussen, 1997).

3.4. Effect of the operational context on the cognitive processes

The three levels of situation awareness (Endsley & Garland, 2000): perception, comprehension, and projection give and receive input from a mental model. This mental model used by the DPOs is based on the operational context, and is different from operation type (see Fig. 4). External cues, such as if a DPO perceives a spike in power usage during a DP operation might be explained as a drive-off by the mental model of the understanding of the DP system. Or as a sign that the weather suddenly changed, which could also threaten position keeping capabilities. However, for CSV operations power spikes might also be explained by the DPO's mental model of the DP operation as crane activity or for drilling operations by the DP operation's understanding of drilling activities requiring additional power. The mental models of DP operation's understanding for flotels, shuttle tankers, or supply vessels, on the other hand, would not expect such spikes and would therefore respond differently to such external cues. Therefore, the mental model of the DPO interprets cues differently based on the DP operational context and type.

Furthermore, for the cognitive processes happening during the operational phase, such as diagnosis and decision-making during a drive-off or drift-off, they are mainly affected by time available to the operator, as was the case for the studies summarized in section 1.4. When short time is available, the operator will utilize a recognition primed decision-making style. How much time is available is again dependent on the operational context. Moreover, available time does not only affect the decision process, but also the number of decision alternatives, when less time is available there are fewer decision alternatives.

3.5. Dynamic safety model for DP operations

To illustrate the effects the main operational context factors have on the cognitive processes and action of the operator, they were modelled in an adapted version of the framework of a dynamic safety model to the application area of DP operations (see Fig. 5).

Rasmussen's (1997) model of dynamic safety framed the control structure with boundaries. The model describes human behaviors in an abstract work area framed by a set of boundaries that constrain the workers' degrees of freedom. The degrees of freedom of an operator can be limited by pressures from a gradient, for example, pressures from management to take on additional responsibilities that take away attention from the main task of monitoring position-keeping capabilities and migrate the performance of the operator closer to the boundary of acceptable performance. A counter gradient can counteract the impact of the gradients, such as the cost effective gradient, and thereby increase the safety margin. An example of such a counter gradient is a safety campaign, where awareness is raised for the acceptable performance boundary and safety (Rasmussen, 1997).

Based on the data gathered during the ACTA interviews, boundaries for the DP operations emerged. To highlight how safety is impacted and how the boundaries are pushed for the different types of DP operations an adapted version of Rasmussen's (1997) dynamic safety model is proposed (see Fig. 5).

At the center of the workspace are the operators' main objectives: maintaining and optimizing position keeping and efficient and safe power management. The following three boundaries are suggested for generalizing Rasmussen's (1997) model to DP operations: (i) the acceptable performance of the DP system boundary, (ii) the acceptable information-processing boundary, (iii) the economic failure boundary.

The **acceptable performance** of the DP system boundary corresponds to the main performance criterion for DP vessel and has two additional perceived limits, the green zone and the yellow zone. These zones represent the DP vessels footprint and alarm limits as shown in Fig. 6.

The DPO is tasked with monitoring the DP system and avoiding unwanted movement outside of the green zone. If the vessel moves into the yellow zone, indicated by predefined limits in either procedures or a specific operating guideline for the vessel and operation at hand, the error margin is entered. The DPO can start additional thrust, if available, change heading and gain setting, or alter reference system settings to improve position keeping and avoid the yellow zone. When the red limit is met and the vessel has crossed the acceptable performance limit the

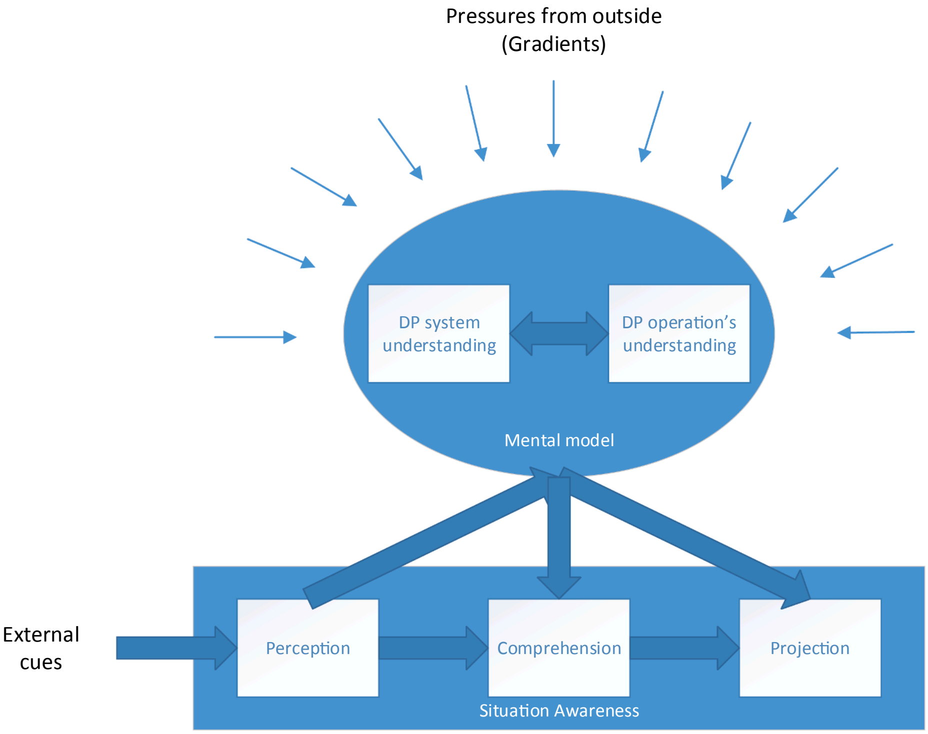

Fig. 4. Situation awareness and mental model for DP operations, based on Endsley and Garland (2000).

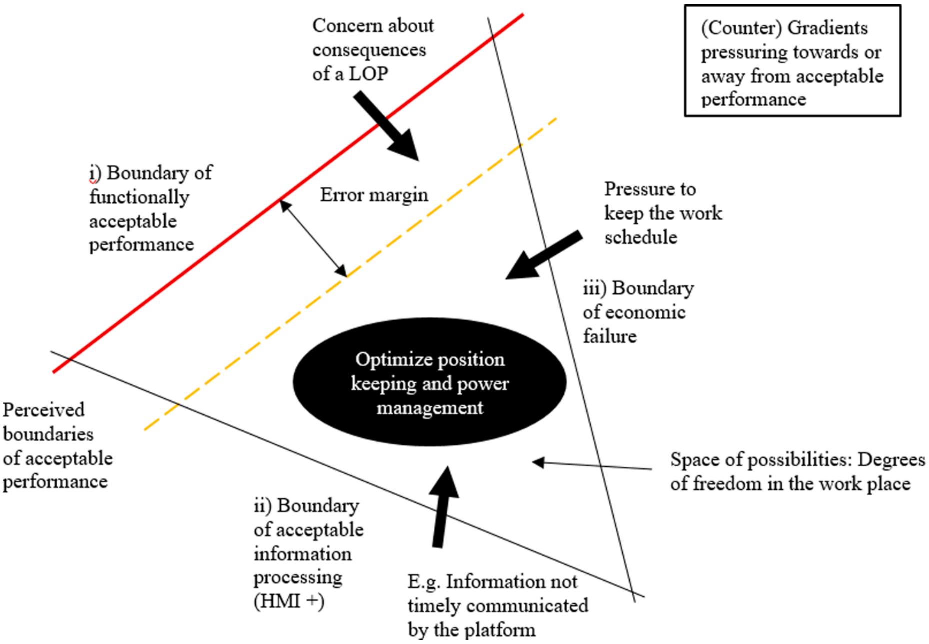

Fig. 5. Dynamic safety model for DP operations.

Fig. 6. DP operation limits.

vessel can no longer continue operations and has to stop and move to a safe location. The acceptable performance limits differ from operation to operation, and the distances may vary in each direction. For example, for a drilling operation, the distance to each limit is the same from the base position, because it is defined by the maximum riser angle. However, the other operational types are confronted with collision risk, which makes the distance dependent on the direction of movement, e.g. flotel, supply, shuttle tanker, and construction operations.

The consequences of crossing the limit are not the same for all operation types. A drilling operation usually has an automatic disconnect, which closes in the well and severs the drill string and umbilical when the red limit is met. Although, it is costly and time consuming to start up operations after an automatic disconnect, the safety concerns of unacceptable performance are less. This means that the counter gradient of concern for major risk consequences of a LOP can push both the boundary of acceptable performance and perceived acceptable performance inwards (see Table 3). These boundaries are in part supported by alarm set points, gain settings, and procedures. However, they also effect the operational risk the DPO perceives, and might cause the DPO to be more alert or on the lookout for certain deviations.

The DPOs also expressed concern about personnel being injured during a loss of position that would be considered HSE (health, safety, and environment) risk (see Table 3). An example, for supply vessel operations lifting unstable loads due to difficulties in maintaining position could crush one of the people working on deck and seriously injure them, or when position keeping becomes unstable on a flotel an auto-lift of the gangway could take place with people on it. These concerns affect the decision making of the DPO and ensure that the DPO keeps a solid safety margin.

The **boundary of economic failure** is similar to the boundary in the original model from Rasmussen (1997). Management will supply an effective cost gradient, which aims to keep the operation and the actions of the DPO within the boundary of economic failure, meaning that if the costs of the operation exceed that boundary than the operation is no longer financially viable and needs to be redesigned or canceled entirely. The gradients provided by management are not all, necessarily, directly related to money. Reputation and customer service are also important factors that ultimately determine the financial success of the operation.

The economic failure boundary is pushed by gradients (see Table 3) relating to the direct cost of the operation, for example fuel consumption and duration of the operation, as well as the their perceived customer service. The DPO might be, explicitly or implicitly asked to push the operation to maintain a schedule or comply with wishes from a client. Furthermore, fuel usage are a major cost saving measure and a DPO might feel pressured to set the DP system up differently during operations (for example turning of a generator or closing a bus-tie on the switchboards) and give in to these pressures. Other pressures that were identified in this studied are focused on the efficiency by increasing the responsibilities of the DPOs, for example, helicopter duties that take the focus away from monitoring the DP system.

The **information-processing boundary** reflects the cognitive and time cost involved in acquiring information from technical systems and the communication with others. If information processing is too difficult or too time consuming then the DPO can reach the boundary. For the DP operations information is obtained from the DP systems, weather data, communication with management and client/platform, but it also constitutes sensory data processing, such as the view out of the window, the sound of the engines and thrusters, the vibration in the vessel, and the sound of alarms. Morineau et al. (2017) also used an updated version of Rasmussen's (1997) dynamic safety model that included an information processing boundary in their study of multitasking behaviors during medical emergencies.

The gradients that put pressure on the acceptable information processing boundary (see Table 3), such as levels of vigilance vary for the different types of operations, and during operations. Some DP operations have more variation in activity and the DPO plays a more interactive role. For example, during flotel or drilling operations the vessel can stay on the same location for months on end, during this period the DPO is tasked with monitoring the DP performance, power management, and weather. It is challenging to maintain the same level of vigilance over such long periods, even with watch shifts, and a DPO might miss some information that is critical to the operation, or not interpret it correctly.

Another gradient that pressures the boundary of information is alarms. Across all operation types, alarms were described as problematic by interviewees. They reported that alarm floods were common, especially in emergencies where one alarm would trigger many consequence alarms that were not relevant for understanding the problem and would obscure relevant information. Furthermore, they reported alarms on the bridge where it was not clear where the alarms were coming from or in some cases alarm texts were unclear not providing the operator with sufficient information to understand the problem and project the consequences of the alarm. The issues with alarms were reported to lead operators to simply ignore or cancel alarms.

Another gradient identified during the ACTA interviews is training on the job. Interviewees across most DP operation types reported that there are no or few formal structures for training on the job and experience transfer. In most cases, it was up to the individual to gather or share information. Interviewees also reported that it greatly dependents on the Captain or OIM whether this was actively done. The only reported exception was for training of DPOs on shuttle tankers; there some clients have required retraining in a simulator setting for the DPOs.

An overview of the identified gradients and counter gradients in the current study can be found in Table 5, Table 6, and Table 7.

3.6. *Summary of results*

The main safety critical decision that a DPO has to make is:

"Can the vessel continue its operation on DP?"

This decision is made at three different stages of the operation (see Fig. 4):

1. Before entering the 500-meter zone (with the exception of drilling vessels, which usually define their own 500-meter zone)
2. At arrival on operating location
3. During the operation on DP

The cognitive tasks for all five types of DP operations studied in this paper are similar and described in the HTA. However, the contextual factors of the different DP operation types studied affect the cognitive tasks. They differ in frequency, time spent on DP, and potential consequences. The DPOs of the different DP operations experience different pressures from the perceived potential consequences of a LOP, as well as differences in economic pressures, such as: keeping the schedule, keeping costs down, customer service and taking on additional tasks. Furthermore, the DPO's performance of the DP operation types studied is threatened by different challenges posed to their vigilance level, the alarms they experience, and the training they receive on the job. This is included in the adapted safety model for DP systems that can be used to highlight the significance of the contextual factors on the cognitive processes of the operator and the safety of the various DP operations.

4. Discussion

The DP operations types studied in this paper differ in a few fundamental ways that are predefined by their operating characteristics. For example, supply and shuttle tanker operations happen regularly and are on DP for limited amount of time (see Fig. 3). They have a frequent exposure to the risks associated with the operating types (see Fig. 2) and can try to adapt their schedule slightly to reduce the risks of weather on their position keeping capabilities during the operations phase. Drilling and flotel operations, on the other hand, do not have this flexibility; they need to be able to stay on location for long periods on end. Therefore, if they decide that they cannot operate under these conditions then operations stop and money is lost for every moment they are not on location. These operations are thoroughly planned, and scrutinized in risk analysis, before start-up of operations to try to reduce the risks. Construction support operations are also well planned, but do not last as long, and a favorable weather window is usually selected for these operations, if possible, to allow for smooth and continuous operations.

Table 5
The effect of the gradients on the behavior of a DPO during the various DP operations on the boundary of acceptable performance.

Gradient	Construction support vessel (CSV)	Drilling	Flotel	Shuttle tanker	Supply
Concern about major accident risk of a LOP (e.g. determining dynamic factors proximity to other potential collision objects, consequences of a LOP)	Collision risk resulting potentially in damaged structures, fires and explosions, injuries, and fatalities. * (medium vessel, distance to collision varies per operation)	Risk damaging the well potentially resulting in oil spills and fire and explosion, injuries and fatalities.	* (large vessel so damages would be more severe, very short distance to collision object, ca. 60 m)	* (medium vessel, carrying hydrocarbons increases risk of oils spill, fire and explosions, short distance to collision object, 120 m)	* (small vessel, short distance to collision object 60 m)
Concern about HSE (health, safety, environment) risk due to a LOP (e.g. determining dynamic factors location of field personnel, phase of operation)	Crush injuries due to unstable load.	Injury to personnel in moonpool area in case there is a need for an emergency disconnect.	Injury to people on the gangway in case of an auto-lift.	Injury to personnel on the loading dock due to ruptured hoses.	Crush injuries due to unstable load and injury to personnel due to ruptured hoses.

- = Gradient is not considered to have a significant effect on the behavior of the DPO.
* = Same effect of gradient as for other DP operation type (any differences in parenthesis).

Table 6
The effect of the gradients on the behavior of a DPO during the various DP operations on the boundary of economic failure.

Gradient	Construction support vessel (CSV)	Drilling	Flotel	Shuttle Tanker	Supply
Keep the work schedule (e.g., delays due to weather or operational circumstances)	DPO and client representative work together on the steps that the DP vessel needs to take. Therefore, the client can see personally that some circumstances are force majeure.	Not keeping the schedule can lead to fines or extra costs for the company. The client has a lot of contractual power.	Availability of the flotel for the client primarily has major consequences for the safety and work productivity on the platform the flotel is serving. The client has a lot of contractual power and influence over future jobs.	Not being able to offload in time can have major financial repercussions for the client, where the might not be able to produce more oil. The client has influence over future jobs, if they are unhappy they will not hire the vessel again.	Delays can cause production stops on a platform if for example they are waiting for critical parts to be delivered. The client has influence over future jobs, if they are unhappy they will not hire the vessel again.
Keep the costs down (sometimes conflicting goal with keeping the schedule)	Keep more generators in standby and use less fuel*	*	*	*	*
Provide good customer service (sometimes this conflicting goal with keeping schedule and cost keeping)	DPO and client representative work closely together on the bridge of the DP vessel. The DPO performs the steps dictated by the client representative.	–	–	–	Client prefers to receive cargo a certain order. The DPO will maneuver the vessel so that this is possible.
Take on additional tasks/ responsibilities (sometimes this can lead to high workload situations)	–	Additional tasks and responsibilities might be transferred to the DPOs, for example helicopter duties.	–	–	The DPO on watch might also perform ballasting of wet cargo and communication with the pump rooms.

- = Gradient is not considered to have a significant effect on the behavior of the DPO.
* = Same effect of gradient as for other DP operation type (any differences in parenthesis).

The contextual differences of the DP operations affect the cognitive processes and the results of the safety critical decisions that the DPOs have to make. The types of pressures exerted by the gradients might be the same, but their weights vary. For example, the (perceived) consequences of a loss of position are relatively greater for a flotel operation, than a supply vessel, this implies that the DPO of a flotel could feel more anxious or stress about a potential LOP and does not want to take any risks and consequently stay further away from the boundary of acceptable performance.

The results from the study have several implications; effects of the results are discussed in the following subsections:

- Safety critical decisions made by DPO
- Effects of gradients on the safety of DP operations
- Cognitive differences in DP operations and their effect on training
- Cognitive differences in DP operations and their effect on design

4.1. *Safety critical decisions made by DPOs*

The details of the three decision gates show different cognitive functions that dominate; the entering of the 500-meter zone is dominated by information gathering, planning and anticipating; the arrival at location by verifying if conditions are as expected and the operational phase by monitoring. The training onboard is not formalized or structured, other than weekly tabletop exercises. Experience transfer and learning on the job happens based on personal initiatives and can vary greatly from vessel to vessel and even crew to crew.

During the operational phase, the DPO has to stay vigilant whilst monitoring DP performance. DPOs from all types of DP operations reported that it is cognitively challenging to stay vigilant over a long period, because there are few changes in the DP system and there are many distractions on the bridge. In addition to monitoring the DP performance, the DPO has to be aware of the operational status and needs to

Table 7
The effect of the gradients on the behavior of a DPO during the various DP operations on the boundary of information processing.

Gradient	Construction support vessel (CSV)	Drilling	Flotel	Shuttle Tanker	Supply
Vigilance level(e.g., vigilance in detecting early indicators of a LOP, such as power usage of the thrusters, reference systems changes)	Variation depending on the job: sometimes the work is monotonous over weeks, sometimes there are more moves.	Monotonous work, can be on location for months on end.	Monotonous work, can be on location for months on end	On DP for 2–3 days.	On DP for 6–12 h.
Alarms	Alarm floods are common, as well as alarms with an unknown origin. Important information sometimes obscured or unclear.*	*	*	*	*
Training on the job	Experience transfer and on the job training is not formally structured. Much is dependent on individuals taking the initiative.*	*	*	Some clients have additional requirements for retraining with a simulator.	*

- = Gradient is not considered to have a significant effect on the behavior of the DPO.
* = Same effect of gradient as for other DP operation type (any differences in parenthesis).

know and anticipate how the operation can affect the DP performance. For example, heavy lifts with a crane require a lot of power, which means that for a short period there is less power available for the thrusters.

During the preparations to enter the 500-meter zone, the decisions that the DPO makes, are mainly affected by communications with the installation and logistics (e.g. location of landing/loading zones). When arriving at location the decisions and tasks of the DPO has to make are affected by setting up the main activity of the vessel, and how this might take attention away from the DP set up and monitoring its performance. During operations, the DPOs expressed being concerned about the safety of operative personnel working in the areas where they might be injured if the vessel suddenly loses position. These concerns can make a loss of position scenario stressful for the DPO.

Another safety critical decision that affects the DP operation is the decision to operate in a drift-on position. This decision is not relevant for all DP operation types. For example, if the vessel is in a location where it cannot collide with anything in case of a drift-off (e.g. drilling operations and some construction operations), then this decision is not relevant. Furthermore, shuttle tanker operations are not allowed to operate on the NCS in a drift-on position. However, for supply operations, flotel operations, and most construction support operations, the decision has to be made whether the vessel can operate in a drift-on position. For some locations or jobs there is the option of operating in a drift-on or drift-off position, and in those cases a drift-off position is to be preferred. This decision, however, is not always made by the DPO. This is a decision made by the installation and the vessels management, with input from the DPO prior to setting up the activity.

During operations, however, the DPO does have deciding role, and has to judge whether position-keeping capabilities are stable enough and the safety margin is sufficient in order to be able to maintain in a drift-on position. A DPO always has the right to say that she/he does not feel comfortable operating under these conditions, although, this rarely happens. When deciding to operate in a drift-on position, a barrier is removed that could avoid a collision in case of a drift-off. The DPO needs to be aware of the loss of safety margin and adopt a more vigilant attitude towards the performance of the DP system and weather. Therefore, the decision to operate in a drift-on position affects the DPO's cognitive processes during the operational phase and could affect the decision of whether the vessel is able to maintain position.

4.2. *The effects of gradients on the safety of DP operations*

In line with the conclusions from the studies of Imset et al. (2018) and Pedersen (2015), this study identifies time and the subjective evaluation of the performance of the system as the gradients that affect the decisions made by the DPO. These are represented in the dynamic safety model for DP operations as the perceived boundary for acceptable performance, and the counter-gradient of concern about consequences of a LOP, as well as the error margin between the perceived and actual boundary of acceptable performance.

Rasmussen (1997) assumed a defence-in-depth strategy that protects work systems. As is the case for DP operations, there are barriers in place that should prevent a LOP and should mitigate the consequences in case it does happen. However, the DPO cannot only affect the integrity of some of the barriers by the decisions and adjustments he/she can make in the course of the operation, the DPO is also considered the last barrier in preventing a LOP or recovering from a LOP. So if the DPO is operating outside the boundaries of acceptable performance, then this directly affects the safety of the operation and there might not be a possibility to recover due to the operation contexts of some of the DP operation types. That external pressures can affect the safety decisions of operators is not exclusive to DP operations. Helicopter pilots also reported that they experienced pressure to fly from clients even though they felt that safety had been compromised (Bye, et al., 2013).

The gradients affecting the operators' cognitive processes associated with the information-processing boundary are the same across all DP operation types and are indicative of underlying problems. The monotonous character of the job challenges the vigilance levels, some of the DP operation types have slightly more variation, and might not be affected as much. Nevertheless, vigilance is an absolute threat to the safety of DP operations. Alarms are also a recurring theme in all ACTA interviews and are a challenge for all types of DP operations. Alarm flooding and unclear origins of alarms obscure critical information to the DPO in situations where the DPO needs to make decisions in a matter of seconds. Training and experience transfer are not formalized for any of the DP operations and initiatives that exist are dependent on the individual him/herself. All these gradients make information processing more challenging and push the operator further towards the boundary of acceptable performance.

The gradients associated with the boundary of economic failure show a bit more variety. Supply vessels are the most pressured, they experience pressure from all identified gradients. All DP operation types experience pressure from the work schedule and keeping the costs down.

The counter gradients affecting the boundary of acceptable performance are related to the consequences of a LOP; either related to major accident risk or the HSE risks. During the ACTA interviews, the interviewees expressed to have concerns about HSE risks more in the forefront, especially about injury to personnel. The collision risk is also influenced by the size of the vessel and the proximity of the vessel to a collision object. All interviewees expressed concern about the consequences of a LOP; it is difficult to estimate how much these concerns affect their cognitive processes relatively to other DP operations. Even though some DP operations are exposed to a higher level of "objective" risk, this does not automatically mean that this is experienced as such nor that the relationship, between the behaviors of the DPO and the risk the DPO is exposed to, is directly causal.

4.3. Cognitive differences in DP operations and their effect on training

In a study from Vanderhaegen (1999) error prevention support is divided into two categories: offline (e.g., training, ergonomics) and online (e.g., HMI, assistance tools). This section focuses on offline error prevention support, and training in particular. There are few requirements for the training and certification of DPOs, and there is none that is operation specific. Once the DPO has obtained a certificate, she/he can apply for a job on any type of vessel.

Often the only requirements for training are tabletop based. It is important for DPOs to train on emergency scenarios that they are expected to handle, but rarely encounter, as also described by Hurlen et al. (2019) and Wahl et al. (2020). A realistic training setting is necessary to ensure that the DPOs are familiar with the scenario and to be able to better anticipate the course of events, improve overall situation awareness, and build up experience with these types of emergency scenarios. Without these realistic experiences, it is less likely that a DPO will be able to function as that last barrier in the safety of a DP operation.

Companies might have some guidelines on training onboard, etc., but the biggest factors influencing the training and experience of the DPOs is access to motivated mentors, learning culture onboard the vessel, learning culture amongst the crew, and the intrinsic motivation of the DPO to learn and ask questions. As a DPO, you can be on a vessel with a captain or offshore installation manager that does not actively promote learning and training, without a mentor that explains the reasons underlying processes and decisions, or not feeling comfortable asking questions. In this case, you will have a slow learning curve, and might not feel comfortable operating alone, make independent decisions, or be entrusted with certain responsibilities. This greatly affects the cognitive processes of the DPO and the situation awareness. Moreover, this lack of formalized requirements for training onboard and retraining or recertification with realistic training conditions affects the safety of the operation. Finally, training could be improved by supplementing it with decision-making exercises for analyzing complex situations, as demonstrated by Chauvin et al. (2009), such as early warning scenarios for a loss of position.

4.4. Cognitive differences in DP operations and their effect on design

This section mainly focuses on online error prevention support (Vanderhaegen, 1999), and HMI design in particular. Presently, the maritime industry applies a one-size-fits-all strategy when it comes to the HMI design of DP systems. The ACTA results for the five types of operations uncovered many similarities on a high level. The cognitive tasks are nearly the same, however, the context of these tasks are not. The major contextual differences are the exposure time (i.e. time on DP) and the potential consequences of a LOP. These two factors affect the ability to stay vigilant and in the loop, and the stress experienced in case the vessel starts to lose position. Unfortunately, the DP operation types that spent the most time on DP, flotel and drilling operations, are also the ones that have the most severe potential consequences (see Fig. 3).

In general, the interviewees expressed a high level of trust in the DP system and few reported having experienced incidents; none had experienced accidents themselves. For the drilling vessels a high level of trust was also expressed towards the functioning of the automatic emergency disconnect. However, they also said that they preferred to not let it go that far and preferred to disconnect prior to the automation kicking in. The high levels of trust combined with long periods of monitoring the automation increases the risk of the DPOs being out-of-the-loop. This affects the situation awareness of the operators on all three levels: perception, comprehension and projection. LOP situations are often characterized by little response time (Chen & Nygård, 2016; Hogenboom et al., 2020) and little distance between the vessel and collision object. It is therefore of the utmost importance that the DPO detects a LOP immediately and comprehends what is going on and can project the potential consequences of the situation. In some operational settings, a DPO does not have more than a minute to respond before an accident becomes unavoidable.

Almost all participants in the study expressed complaints about the alarm systems. The complaints indicated serious problems with alarm management and integration, leading to alarm floods and ambiguous alarms that take attention away from the actual pressing problem at hand. This is a general problem on bridges on all types of vessels, however, in the case of the DPO monitoring the DP operation and being able to intervene prior to or when a LOP occurs, the DPO is considered the last barrier in avoiding a potentially serious accident. The DPO therefore needs to be supported in this role and a well-functioning alarm system is therefore critical to the safety of the operation. It is therefore recommended to review and improve the alarms, alarm design, and alarm management on the DP system in specific and on the bridge in general.

The study reveals many similarities between the DP operation types, same tasks and similar types of concerns. There are some operation specific indicators for the stability of position keeping capabilities that are important as input for detecting if a LOP is happening, as well as for verifying information from other indicators (reference systems, power management system). For drilling this is the riser angle, for flotel operations it is the sensors on the gangway, for shuttle tankers and supply the tension on the hoses, and for supply and construction support operations the stability of the crane load. These are important indicators and need to be highlighted in the design of the DP HMI.

4.5. Implications for (risk) analyses of DP system design and operation

One important implication of this study is that risk and reliability analyses of DP operations need to include operation specific factors. One factor that potentially has the highest impact on safety for DP operations is time. It is pertinent that the analyses include time available, and compare that to the time the DPO and DP system require to successfully manage and control a potential loss of position scenario. Time will vary between operating types, as well as per operating condition. These types of analyses will also be useful in developing operating limits. These limits can offer, if supplemented with guidance on how to handle situations in which these limits are exceeded, good decision support to the operator as well as fortify their mental model of the DP operation.

Furthermore, it is important that attention is given to the salience of early indicators of a loss of position, such as power consumption, reference systems, and operation type specific indicators in the verification of the DP system design. In addition, a careful review of the alarms is necessary, as this is a notorious problem within DP as well as bridge design.

For the validation of DP system design and operation it is important to focus on the functionality of the design and if it is capable of supporting DPOs in their role and tasks and improve their performance both in terms of safety and productivity.

4.6. Limitations of the study

Commonly, a regular task analysis is used to evaluate the risk and reliability of operational settings. A regular task analysis does include, to some extent, cognitive tasks. However, the advantage of utilizing a cognitive task analysis instead of a regular task analysis is that it emphasizes the aspects of the operations that cannot be directly observed. It focuses the study on worries and pressure experienced by the operator that otherwise might not be brought to light. Additionally, the shift in focus to the cognitive task can reveal great differences in ways tasks and situations are experienced and open up for discussions of assumptions and experience transfer, and perhaps even, formalizing best practices into explicit operating procedures. Furthermore, it gives insight into the mental model formed by the experiences of expert, which can also be used for training purposes.

A part of the ACTA is based on the experience with a major event in the simulation interview part. The study, however, did not select its participants based on their experience with incidents or accidents. This part of the interviews was therefore based on a common scenario; however, the responses from the participants might not reflect the insights they would have had if they had indeed experienced these scenarios. Although this represents a lack of reliable data on this topic and is considered a limitation of the study, it is also an indication that the DP system is very reliable and that serious incidents are relatively rare.

Additionally, the study is based on only two representatives from each type of DP operations and this limits the representativeness of the results. As mentioned previously, the population of DPOs working on the NCS in the oil and gas industry is relatively small; concerns about representativeness of the study could be raised. However, the data saturation from the interviews was quite high and few new topics arose during the second interview. Nonetheless, the quality of the study could be improved with a greater sample size.

The study has focused on DP operations related to oil and gas activities on the NCS. Some of the interviewees had experience from other areas as well, and the differences in local cultures and work cultures, as well as different environmental challenges, are indicative of differences between operations on the NCS and there, as well as potentially other types of differences between the operation’s types.

5. Conclusion

The aim of this paper is to evaluate the differences between various DP operations on the NCS, and how they affect the cognitive tasks performed by the DPO. The results from the ACTA analysis of the five DP operational types studied (construction support vessels, drilling vessels, flotels, shuttle tankers, and supply vessels) show no significant differences in the cognitive tasks performed by the DPOs of these vessel types. However, the context of these operational types is very different and these differences have an effect on the cognitive processes.

The differences in duration of the operation, variation within the operations, and the size of the vessels affect the decisions and considerations that DPOs make. These differences have been illustrated with a dynamic safety model adapted to DP operations. The model is framed by three types of boundaries: acceptable performance, economic failure and information processing. The gradients affecting the DPO’s performance within the degrees of freedom of the work area are similar in character for those pressuring from the acceptable performance and economic failure boundaries, although, arguably different in strength. However, the gradients pushing the DPO’s away from the information processing boundaries towards the acceptable performance boundary show some differences between the DP operation types. Especially concerning vigilance and variation of the job, for example drilling and a flotel operation can stay on the same location for months on end leaving the operator to monitor a constant, often stable, situation. Whereas, supply vessels move to and from one location within a day, this makes the job, though repetitive in a different way, relatively more varied.

The model illustrates how safety is affected through pressures that the DPO is exposed to. This should create boundary awareness amongst managers and designers about how they may support operator performance and safety. DPOs are made aware of the boundary of acceptable performance by various alarm limits. Vessel and operations management can be made aware of the effect the pressure they are asserting on the boundary of economic failure by, for example, means of employee surveys, internal and external audits etc. Designers could be made aware of the boundary of acceptable information processing and the impact of their design on safety by utilizing user-centered design and user-friendliness studies.

Some of the decisions that DPOs have to make are safety critical and it is important that the training and design of the HMI are supporting the DPO in doing his/her job and for maintaining good situation awareness. Therefore, it is critical that the differences in DP operation types are reflected in training and design, and that it addresses some apparent, underlying general challenges. Therefore, this paper recommends that training and experience transfer procedures on the job to be formalized. Additionally, (re)training of DP operation specific scenarios in realistic settings (e.g., simulator training) could better prepare DPOs for handling various types of LOP.

This paper recommends that the DP operation specific position keeping indicators are highlighted in the HMI design. In addition, the implementation of (further) automation and function allocation and job organization should be (re)evaluated based on improving vigilance amongst operators. DP alarms, and other alarms on the bridge should be evaluated; relevant and critical alarms should be presented to the DPOs in a clear way through good alarm management.

The study includes five types of DP operations on the NCS. It might be that other types of DP operations would bring forth a confirmation of the results from this study or shed light on some other issues. Therefore, it is recommended that other types of DP operations are included in further work, as well as a consideration of the need to expand the study to other areas of the world.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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