Improving sensemaking in dynamic positioning operations: HMI and training measures

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A modern ship bridge is becoming increasingly digitalized, featuring multiple screen-based control systems and advanced automation. As with other industries that have gone through the transformation from analogue to digital control, computerization tend to improve overall safety but at the same time introduce new challenges. One such challenge is related to human-machine teamwork. In the maritime area the quality of this teamwork relies among other things on operators being able to make sense of the information that is being presented to them about the status and behaviour of the vessel, its control systems, as well as the potential threats to its capability. Dynamic Positioning (DP) is an example of a highly automated system where a number of unwanted situations has occurred, and where weaknesses in this teamwork has been identified as a major contributing factor. In this paper we explore Human Machine Interface (HMI) and training measures for improving the safety of such operations by strengthening the operators' ability to recognise and handle unexpected events.

Keywords: Dynamic Positioning (DP), Human Machine Interfaces (HMI), training, human-machine teamwork, maritime safety, human-machine interaction, sensemaking, situation awareness.

1. Introduction

In the maritime domain Dynamic Positioning systems (DP-systems) are utilized for station keeping in a wide variety of operations, such as drilling and well operations, cargo loading, diving operations, cable and pipe laying. A dedicated Dynamic Positioning Operator (DPO) on the vessel bridge is responsible for controlling this system during DP operations, see Figure 1.

Event reports indicate that the DPO is not always sufficiently informed about the status and behaviour of the system, and that "human error" is a significant contributing factor to such events. In the paper "Sensemaking in high-risk situations: The challenges faced by dynamic positioning operators" (Hurlen et al., 2019) the following main sensemaking-related challenges for dynamic positioning operators (DPOs) were identified: 1) Alarms, 2) Mode surprises, 3) Critical information hidden from view, 4) "Private" Human Machine Interfaces (HMIs) limits shared situation awareness , 5) Deskilling and 6) Out-of-the loop.

In this paper we explore two measures we believe can contribute to overcome these challenges and thereby improve safety in DP operations. The first measure targets the layout and design of HMI for the DP-system, exploring whether successful design strategies for improving situation awareness in other domains, such as petroleum and nuclear, can successfully be adopted for DP operations. The second measure is training. DPOs perform training on a regular basis. A methodological challenge is how to train for difficult, unexpected situations that may occur: Should particular situations be prepared with particular training scenarios and even tailor-made procedures? What then about other situations? The balance between procedure driven training and a focus on general knowledge building of e.g., the underlying physics and behavior, is discussed in this paper based on recent studies in the nuclear field.

These are efforts within an ongoing research project "Sensemaking in safety-critical situations" – SMACS (SINTEF, 2018). The next planned step is to evaluate the proposed measures with end users (DPOs) and other domain experts to further identify their safety improvement potential.

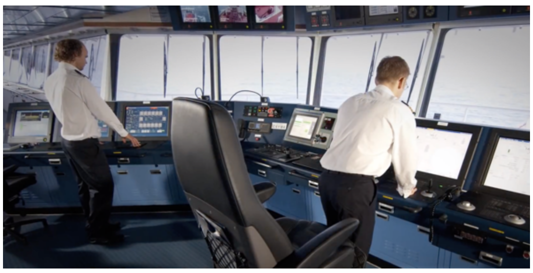

Figure 1 A modern ship bridge, here with DP-systems to the right (Kongsberg Group, 2013)

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2. HMIs and Training to Support Sensemaking

Situation awareness (SA) and related design principles (Endsley & Jones, 2012) are often used in design of HMI for safety-critical systems. In Bisio et al. (2019) we discuss this and conclude that "*HMI characteristics that support situation awareness are at least highly relevant for making sense of the same situation"* (ibid., p.3). Thus, design elements of SA are in this paper used also to support sensemaking without explicitly stating this for every element.

Also, in Bisio et al. (2019), the outlined seven dimensions of sensemaking are discussed related to HMI design in the maritime field and the conclusion is that especially the "Cue" dimension with its range from equivocal to confirmed cues is crucial with regard to implementation of the HMI. Complexity in the form of suboptimal HMIs is a big source of ambiguity for operators and relates to at least the four first challenges found in Hurlen et al. (2019): Alarms; Mode surprises; Critical information hidden from view; and "Private" Human Machine Interfaces (HMIs) limits shared SA.

These challenges, plus the two on deskilling and out-of-the-loop, must be seen in relation to the nature of the task for DPOs. The DPO work situation is a combination of classical surveillance and monitoring in normal states, and that more of a driver or pilot in incident states. In normal situations, the DP system is working autonomously, and the DPO is monitoring the system just to check that everything is ok. However, in critical situations the nature of the task changes dramatically. In those situations, the time required to implement actions may be very short, within minutes and even seconds, and the role of the DPO is more similar to that of a driver or a pilot. This puts high requirements on the HMI design and the training. It must be made so that the DPOs are ready to go into "pilot mode" from a very calm monitoring mode when nothing happens. In other words, the DPO need to be ready to go from a situation requiring a knowledge-based behaviour, to a more skill-based behaviour in a very short time. This also puts extra requirements on the training.

3. Unexpected Situations and the "critical information hidden from view"- Challenge

DPOs require quite extensive information to maintain their situation awareness. As a response it is a common industry practice to provide a DP HMI that consists of a number of highly user-configurable display elements that can be adapted to the situation at hand. As an example, the much-used Kongsberg "K-POS" DP system offers an HMI with one to three dedicated graphical displays. The display layout consists of a number of "tiles" where users can select content and visualization parameters. Figure 2 shows the K-Pos layout principle and examples of display configurations utilized during a simulator training session (utilizing a two-screen setup).

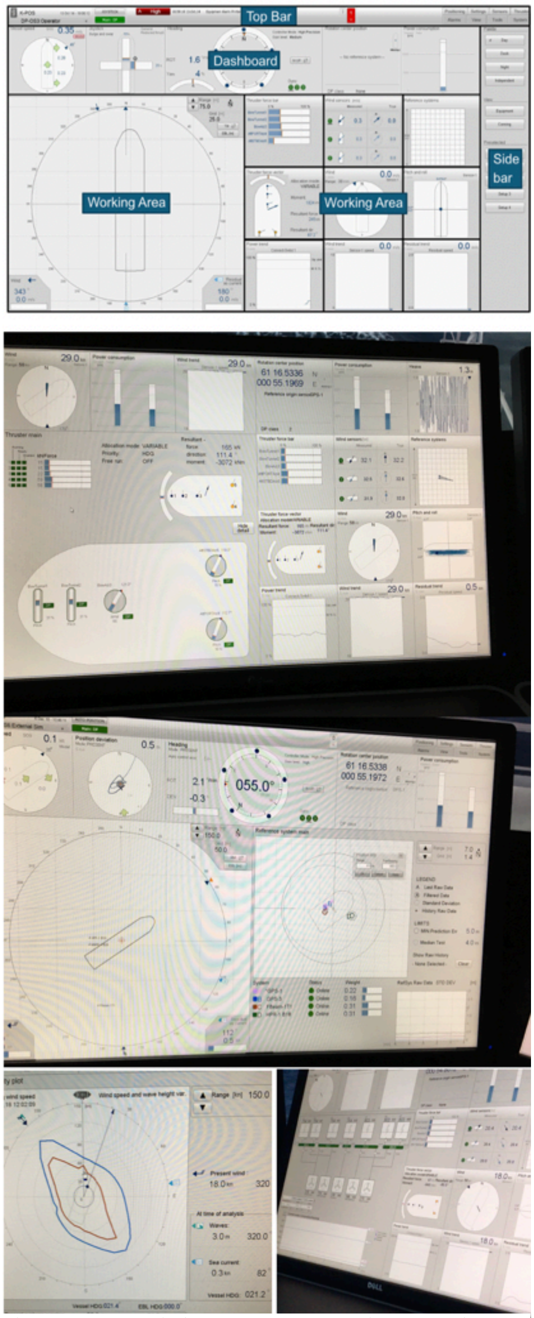

Figure 2 Current industry DP HMI practice. Kongsberg K-POS layout principle (top) and examples of display configurations in use during an advanced course simulator trainings session (bottom), two-screen setup.

"I had all the information, but I only used the thruster screen". "If the information is not already on the screen it will not be used". "None of them discovered the ahead thrust, which was shown in another DP monitor." These are quotes from interviews with DPOs and event reports/recollections (summarized in Hurlen et al, 2019). Findings from such events also points to the fact that unwanted situations often occur in unexpected ways and that DPOs often are required to respond very fast. As another DPO said: "DP is 99% boredom and 1% panic". Hurlen et al (2019) conclude: *"When individual DPOs are responsible for selecting and arranging the information visible on the DP screens, adjust warning and alarm limits and selecting position reference systems input specifics, critical information may be hidden from view and not used when unforeseen and often stressful situations occur."*

The "hidden from view"-challenge is not unique to the maritime domain. The nuclear industry has for safety reasons been highly conservative with regards to taking computerized control technology in use and has done extensive research on potential risks associated with the shift from analogue (physical) to graphical HMIs. A key finding is that operators are reluctant to perform interface management tasks (i.e. navigation and layout manipulations) during stressful situations. Instead they tend to rely on information that is immediately visible to them instead of searching for other potentially safety-critical information. O´Hara & Brown (2002, p.7) state: "*When HSIs* [Human System Interfaces] *are spatially dedicated, operators can use automatic information processing capabilities, such as scanning and pattern recognition, to rapidly assess plant situations. The flexibility of computer-based HSIs and their general lack of spatial dedication causes interface management tasks to be more dependent on controlled information processing. The flexibility also makes it easier for operators to mistake one display for another, and may cause them to improperly assess a situation or operate the wrong piece of equipment."*

This observation harmonizes well with the quotes from DPOs presented above. As they struggle to make sense of complex and time-critical situations their attention narrows and their willingness to engage in interface management tasks are reduced.

4. HMI Measures Addressing the "critical information hidden from view"- Challenge

So how can we reduce the risk of operators missing safety-critical information during stressful situations?

One possibility might be to engineer a system that is smart enough to present just the information needed at any one time. This has proven to be very difficult in complex and dynamic systems. Endsley & Jones (2012, p. 8) states: *"During the course of most operations, operators must rapidly and frequently switch between goals as situations dictate, often with very rapid responses required. Individuals do not instantly understand what is happening in a situation simply by looking at instantaneously presented information. ... Information-filtering concepts always place the operator in the role of being reactive rather that proactive, which severely limits performance effectiveness."*

It seems both user-configurable and system-configurable information displays have weaknesses in terms of supporting situation awareness in complex, fast-paced environments. Let us instead look at an alternative approach that is being utilized in many safety-critical domains.

4.1 *The overview-at-a-glance design principle*

In the energy and process industries, one of the most common HMI design strategies to improve situation awareness has been to introduce shared overview displays as a supplement to standard operating screens. Through displaying safety-critical information at fixed positions ("spatially dedicated") the overview display functions as a common frame of reference, supporting fast "at-a-glance" overview regardless of situation or user preference, directing users' attention towards system deviances in a way that supports pattern recognition or provides other visual cues that supports fast comprehension (see Figure 3). Some of these display solutions contain situation-specific elements or zones that changes content based on certain operating criteria but predominantly they show the same content (in the same location) in all situations. Also, alarms are typically displayed in a visual manner,

Figure 3 Petroleum control room with spatially dedicated shared display (top), and user-configurable workstation screens (bottom).

complementing traditional alarm lists in ways that make sense to operators through pattern recognition rather than having to read blocks of text.

4.2 *Is it feasible to create overview-at-a-glance HMIs for DP monitoring?*

Can a similar concept be utilized to improve situation awareness and sensemaking also in DP operations? Such an inquiry needs to address several feasibility questions:

1. Is it possible to define a unique set of safety-critical information that provides DPOs with «the big picture» relevant in all situations?
2. Is it possible to design an information surface based on the needs identified in 1) that is compact enough to fit within the DPOs field of view on existing bridge environments?
3. Does such a design concept improve DPO performance (sensemaking, situation awareness) in safety critical situations?

In the following we address the first two questions. Addressing the third is the next planned step of the SMACS project.

4.2.1 *DPO information needs*

We have interviewed DPOs about the system information they need to monitor during DP operations. We have also observed what information is being used during advanced simulator training, which corresponds closely to what was highlighted in the interviews. This indicate that a finite set of information may indeed be useful for creating a useful system overview across situations. The following has been identified as the most critical (Hurlen et al, 2019):

- Absolute and relative position of the vessel
- DP capability plot: A real-time consequence analysis of worst single failure
- Status of position reference systems
- Weather conditons
- Status of thrusters
- Status of power systems
- Alarms

4.2.2 *Compact overview display concept*

Compared to information-rich control environments, such as a petroleum control room, a DP control system is relatively simple. Three screens may well be sufficient to display the information needed for a proper overview at all times using current HMIs, as was the opinion of a rig-operator we interviewed (Hurlen et al, 2019). But rigs spend most of their time in DP, making it possible to dedicate considerable screen real-estate to this system. This may be less practical on e.g. a cargo vessel where other functions and tools need more focus (and space). Here, one or two

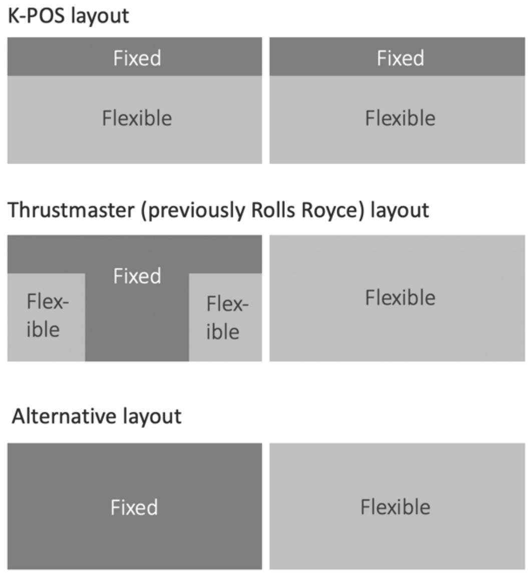

Figure 4 Examples of two-screen HMI layout alternatives. Current industry practice generally allows much flexibility (user configurability) in terms of content selection. To improve situation awareness an alternative design strategy is to dedicate a larger, confined screen area to fixed (spatially dedicated) information elements.

DP-screens seem more common, and users are forced to engage in interface management tasks to obtain a sufficient overview and to reach hidden control functions.

It would therefore be necessary to introduce an overview information surface that is fairly compact in order to fit into a variety of common bridge environments. Such a surface would have to support an "at-a-glance" system overview that is useful and relevant for DPOs across all states and situations without the need for user interaction. We thus propose a dedicated overview display that will supplement other user-configurable DP HMIs.

This overview display could be grouped with the other DP-screen(s) or positioned elsewhere in the field of view of the DPO, possibly providing shared information to the whole bridge crew. An advantage of grouping it with other DP HMIs is that monitoring can more easily be combined with other DP control activities without the need for changing the direction of attention. It may also more easily be considered as a safety-critical part of the DP system itself, and less of an add-on to be used more optionally and sparingly. For this reason we have conceived of the display as an integral part of the DP HMI, see Figure 4.

4.2.3 *Compact overview display – layout and content selection*

So, is it possible to create a visual information design based on the DPO information needs described earlier that is compact enough to fit on a display of approx. the same size as is currently being used for DP systems (20-24 inches)? When investigating the graphical properties of the current K-POS HMI (see Figure 2), several opportunities for improving sensemaking and making graphics more compact present themselves.

Many graphical elements seem to augment numerical information in a positive way with regards to sensemaking and at-a-glance monitoring, such as graphs, trends and bar charts. Still, may the visual presentation be further simplified, condensed and/or improved?

Research indicate that trended information improves sensemaking, helping the operators to detect deviances before they reach alarm states and act proactively (e.g. Svengren et al., 2014). Can more data be trended, thus reducing the need for further enquiries involving interface management (display navigation)?

Much information, such as vessel movements, forces, thrusters and GPS, seem to be duplicated across different graphical elements. Can some be integrated in the same graphics without cluttering the display, thus making it more compact without reducing its usefulness?

Might there be additional useful content that is currently not included in the DP-system that can improve sensemaking, such as close-by objects, new types of alarms or other decision support functions?

Figure 5 shows a principle sketch describing a possible overview display layout. In this proposal the current DP mode and overall capability is displayed on the left half of the display, which also includes the vessel position, a summary of the forces acting on the vessel, resulting vessel movement, surrounding structures, capability plot, as well as key alarms and alerts. It is also proposed that nearby objects should be represented in this view, making it easier for DPOs to determine the space available for vessel movements. The idea is that, as much as possible, this part of the display alone should be able to serve as a quick status overview, useful for controlling the DP system during undisturbed

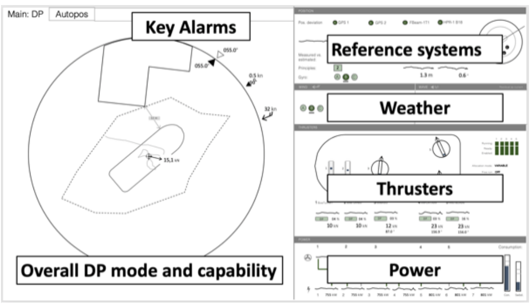

Figure 5 Principal sketch for a possible overview display layout.

operations. This graphic is not too different from what is commonly available in industry practice HMIs, but with a stronger focus on monitoring support, stripping away less important data that the users can rather choose to display elsewhere, thus increasing the salience of safety-critical information.

The right side of the display shows a more detailed status information about the position reference systems, weather, thrusters and power supply for quick reference.

4.2.4 *Information graphics*

A fairly detailed graphical design proposal is required to effectively assess the feasibility and potential of the overview display idea, exploring ways to achieve a compact visualization of all the required information without clutter – at the appropriate level of detail and with a clarity that communicates effectively with users.

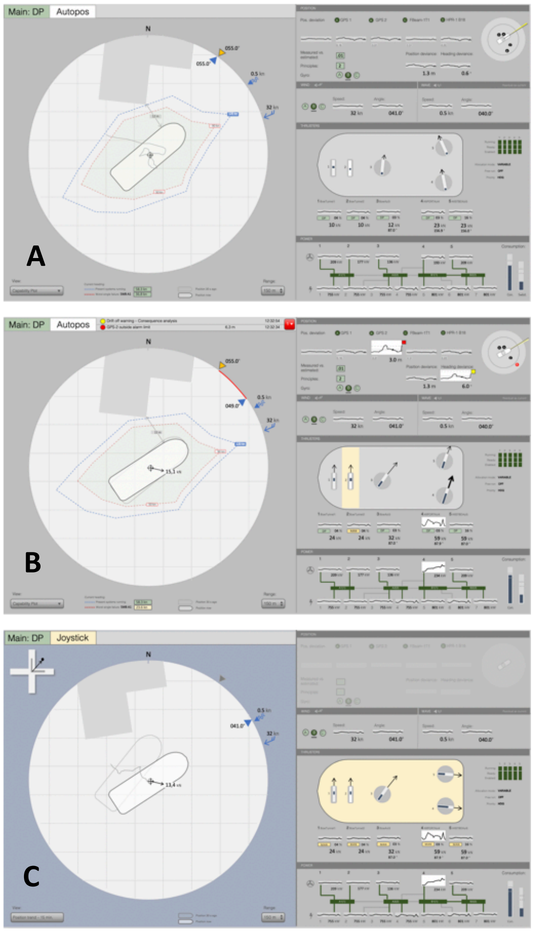

Figure 6 First draft of an overview display design, shown in three different states: A – expected, undisturbed operations in full auto DP mode, B – Several disturbances building, C – Joystick mode (manual mode, DP turned off).

Figure 6 shows a first draft for an overview display design. It is meant as a starting point for user feedback and other feasibility evaluations planned in the SMACS project.

The proposal is based on the following key principles in order to support situation awareness (SA) and sensemaking.

The general appearance and layout remain the same across all operating modes, allowing users to develop effective "information scanning" habits. The graphics are optimized for a 24 inch screen viewed from a close range. Some elements will still be clearly visible from a larger distance, opening up for possible use by the larger bridge crew supporting shared situation awareness – a copy of the display could e.g. be located elsewhere on the bridge during DP operations.

Off-normal information is designed to "stand out" (increased salience), attracting the operators' attention to deviances. Unsaturated (greyish) colours of medium lightness are used for static information and background elements, black for live numerical data, and lighter more saturated colours for alert information (such as alarms). As with all other graphical user interfaces on the bridge the display palette needs to be adaptable to changing light conditions, through e.g. a "dark mode" (not yet developed).

Information that deviates from an expected normal state are designed to attract attention even though they are not (yet) in a defined alarm state, supporting proactive monitoring. The trend-time may vary for different kinds of information, but since the DPO needs to react decisively to fast-changing conditions, one to five minutes is suggested for most overview display trends, allowing the operators to get a sense of the overall system performance and recent developments. Complimentary tools can still be utilized for further information needs. Such "mini trends" are becoming a standard practice in petroleum overview display designs, originally developed within the nuclear domain (Svengren et al., 2014). Figure 7 illustrates how a trended value can be displayed in different conditions in a relatively compact manner, the salience increases as the deviation develops.

To help prevent misunderstandings about who is in control of what, functions that are not operated automatically during active DP mode is highlighted (marked with the off-yellow colour in Figure 6). Information is trended whenever relevant. Figure 6 illustrates how the display is proposed to behave during different operating conditions, from normal (expected) operations in DP mode (A), through deviances that starts to develop (B), and when DP has been turned off and joystick (manual) mode is active (C).

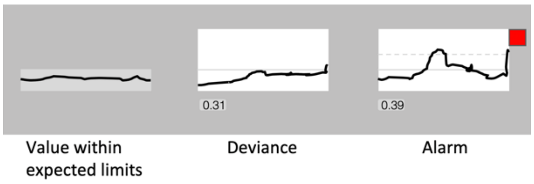

Figure 5 A "mini-trend" information graphic in various states

The design proposal incorporates all the major information elements shown across the two screens as being used in a practical simulator setting (shown in Figure 2), pointing towards the feasibility of the concept.

5 Training Measures

5.1 *The need for deep system knowledge and adaptive expertise*

As discussed in section 2 above, the nature of the work for DPOs change when going from a normal state to accident handling. When entering a critical situation, the time windows are often so short that the DPOs need to be able to make fast decisions and take skill-based actions. This is an argument in itself for training in general, and simulator training in particular. It is not possible to obtain skills without performing the actions required and also repeating this on a regular basis.

Safety-critical situations often origin from unexpected events or combinations of events. Since they are unexpected, these exact events might not be trained for and there is probably a lack of procedures for how to deal with them in detail. So, is it at all possible to train for unexpected events in which you have to rely on skills in order to save the situation, skills that might have to be applied on another situation than the one you trained them for? Our claim is that this training needs to be based on adaptive expertise and deep system knowledge. If this is the case, the DPO can form a strategy in a short timeframe and apply this to the situation at hand. In the following, we will outline a training approach applied to the nuclear field and then discuss whether this can be applied to DPOs.

Hurlen et al. (2019) recommends: "*One strategy may be to focus training more on unforeseen events and the underlying principles that govern the process systems, controlled by the operator, instead of training on procedures for known or hypothetical events.*"

Skjerve and Holmgren (2017, p.1) states: *"Training aimed at promoting competence for handling unforeseen events will target situations that cannot be solved based on strict adherence to detailed operating procedures only. It will be directed at situations in which operators need to make sense of the current state of the plant, and to adapt the operating procedures or develop new performance strategies. To promote the* *operators' ability to make sense of the situation at hand, training should be designed to promote a deepening of the operators' integrated understanding of plant processes and responses."* This was concluded for nuclear cases, based on the experience from the Fukushima accident and other nuclear events. Skjerve and Holmgren (2017) based a new training approach called CIAU (Coaching for Improved Ability to handle Unforeseen events) on the Adaptive-Expertise theory (Hatano and Inagaki, 1986). The idea is that for unforeseen events one needs adaptive expertise that can be applied in various ways not restricted to a-priori strategies as laid out in procedures. For the nuclear case, operating procedures are made for most accident and incident situations that are within the design basis of the plants. The argument for not only to train these predetermined accident sequences is that a too high reliance on procedures and work routines may deteriorate operators' skills and knowledge (ibid., p.1) and this is supported by event investigations by IAEA (Haage, 2016).

5.2 *The CAIU method*

Skjerve and Holmgren (2017) describes the CIAU method: "*To promote adaptive expertise, constructivist training techniques were applied, emphasising exploration, experimentation and critical thinking.*" An important point about adaptive expertise is that it is not enough to use this without having a clear basis and knowledge of the routines and procedures of the work (ibid, p.3): *According Hatano and Inagaki (1986), adaptive expertise presupposes and encompasses routine expertise."* First ensuring that this would be in place, "[CAIU] *was designed to promote adaptive expertise in licensed NPP operators by specifically enhancing the their (1) conceptual understanding of the domain, i.e., plant processes and responses, and (2) awareness of and flexibility in metacognitive skills"* (ibid., p.7). The coaching process of CAIU consists first of an observation phase in which the coach assesses the knowledge level of the trainee, and thereafter an exploring phase in which the trainee attempts to develop and apply a strategy for the problem at hand. The point is to be able to build strategies, without consulting procedures, based on the situation in the plant and the basic knowledge of the operator. This is an advantage also in cases when one has limited time available.

Skjerve and Holmgren assessed the CAIU method in a simulator with licensed operators as test subjects. The results were (ibid., p.37): *"both trainees and coaches judged that CIAU training had a positive effect on the operators conceptual understanding of plant processes and responses, and that the strategies developed by the trainees for how to handle an unforeseen event improved following CIAU coaching, as compared to prior to coaching".*

5.3 *CAIU can be applied in the maritime domain*

CIAU was developed for the nuclear industry. Can this be transferred to the maritime domain and DP operators?

In Hurlen et al. (2019), we analysed the nature of challenges that DP operators were exposed to, especially in safety-critical situations. The challenges identified for DPOs were quite similar to the ones nuclear power plant operators struggle with. However, DPOs are not that reliant on operational procedures for critical situations as nuclear power plant operators are. DPOs at most have a checklist for what to do, but they don't have detailed operational procedures that are adapted to each of the critical situations that they may encounter (Bye et al., 2017, pp.126-127). When they are accustomed to no procedures and just checklists, this should be an argument for that they need to apply deep knowledge since they have no procedures to apply. The issue of deskilling identified by Hurlen et al. (2019, p.6) proposes that more training is needed.

Bye et al. (2017, p. 127) states regarding the training factor: "*The DPOs do not receive specific training on the correct response to a drive-off event, and must rely on experience and process knowledge to know what to do."* The proposed measure to improve this was then: "*to provide regular simulator training to DPOs to drill them in the expected operator response to drive-off and similar events".* Our claim is that in order to train on "*drive-off and similar events"*, it is not enough to train on one basic event, since these events are typically unexpected, and they may be quite different in appearance. Thus, one needs deep system knowledge and adaptive expertise. Training for how to achieve this is first and foremost simulator training, but also the coaching and strategy forming exercises in CAIU would be of immense use for DPOs.

Some actions might be "automated" in the DPO's skill set. However, these actions will always be related to a strategy, based on the DPO's evaluation of the situation. These strategies will normally be based on fulfilling a major goal, not to understand the details of the situation and fix it before you can do something about it. Here there are similarities between the nuclear and the DP case: In a very difficult situation in the nuclear case, the operators would have the goal to cool the core by getting water to the core, independent of the reason why there is little water there. Cooling of the core is the overall goal, and whether the water comes from an auxiliary system or, in an extreme case, from a fire truck, doesn't matter. Similarly, the DPO will in the case of a near collision try to avoid the collision regardless of the reason why this situation has occurred.

There may be slightly different motivation in the nuclear and for DP for CAIU based training. However, they both need adaptive expertise and deep knowledge, since the goal (and measures) may be similar, to handle the unexpected. Strategy forming based on deep knowledge is vital in both industries, even though DP requires quicker actions.

6 Conclusions

In this paper we have explored two measures to improve the safety of DP operations: HMI and training. Both measures address challenges found earlier in the SMACS research project, as described in Hurlen et al. (2019). We have outlined an HMI design principle that particularly but not solely addresses the "critical information hidden from view"- challenge. The proposed solution will be evaluated in a later stage of the project. The training measure is adapted from lessons learned in the nuclear domain and addresses the need for deep system knowledge and adaptive expertise to be able to handle unforeseen events.

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