High reliability management and control operator risks in autonomous marine systems and operations

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Abstract: This paper's objective is to analyze the main real-time risks in operation of autonomous marine systems, which follow from various levels of autonomy (LoA). High reliability management (HRM) is an established framework for assessing real-time operator performance in complex infrastructures. In this paper, the framework is applied to two cases representing different uses and autonomy levels: one on marine underwater robotics focusing on remotely operated vehicles (ROVs) and subsea intervention, and the other addressing operation of a complex marine surface vessel with a dynamic positioning (DP) system. Usually, autonomous systems are associated with unmanned systems, but several manned systems (for example, ships with complex automation and DP systems) have specific control functionality that can be characterized as autonomous. This paper focuses on manned and unmanned systems with different levels of autonomy and major hazard potential. The most important research finding is having identified multiple, different operational states that vary across two or three LoAs, each state of operations having significantly different risks to be managed in real time. The application of the HRM framework highlights the importance of enabling reliable operator control and online risk management in the development of next generation autonomous marine systems.

Keywords: Autonomy; risk; high reliability management; human operator; marine systems; risk management

1. INTRODUCTION

Technological advances in autonomous systems enable new and promising marine operations, processes and exploration of the ocean space. The advances, nevertheless, pose demanding challenges to the managers and operators of these systems. An increased level of automation and autonomy in routine or otherwise tedious operations may improve safety, efficiency and performance, supporting the human operator in decision-making and supervision and reducing human work load (DoD, 2011). Autonomous systems, on the other hand, may have unique complexity and interlocks that are difficult to identify, assess, and manage in real time. New types of disruption and failure are introduced or emerge due to unforeseen (at times unforeseeable) interconnectivities in system design, mission complexities and environmental contingencies.

It is vital to ensure that autonomous marine systems and operations are highly reliable, available, maintainable and safe. Accordingly, the management of risks and uncertainties has become core to the design and safe operation of these highly automated intelligent systems. Functionally, becoming more autonomous means not only less physical human interaction, but also remote monitoring, supervision and intervention, thereby challenging real-time situation awareness (SA) for operators in the respective control centers. If such operations go according to plan, human operators do not and will not need to utilize fully their problem-solving and decision-making capabilities.

Operations in a challenging environment, such as the ocean space, often do not go according to plan, hence requiring the human operator to intervene, particularly when more problems or unexpected emergencies occur. Such intervention requires that the human operators involved have a high degree of SA to take control and manage the emergency or sudden difficulty. Currently, operators managing an autonomous system may have fewer possibilities to understand the system condition, the situation being faced, and contingencies that need to be addressed in real time. A dynamically positioned (DP) ship is able to keep its position and heading. It can manoeuvre slowly along a predefined track by using active thrusters. Studies of dynamic positioning (DP) systems and collision risk for shuttle tanker (ST) – floating, production, storage and offloading (FPSO) operations have shown that the DP operator may have around 45 seconds to solve a problem before a collision occurs, which is too short a time for an operator to resolve (Vinnem and Liyanage, 2008). This gap between the aspiration for increased operational performance through autonomous systems (for example the DP system) and the struggle of human operators to manage such advanced systems in the face of unique or otherwise unexpected events, makes it essential to examine further whether the technological drive towards higher autonomy improves, *on net*, the safety and high reliability of the marine operations under question.

High reliability management (HRM) has been developed as a framework for understanding and assessing the performance of control room operators. The research was initially undertaken in the form of a long-term study of the central control room at the California Independent System Operator (CAISO), an organization responsible for managing the high-voltage electricity grid in California (Roe and Schulman, 2008). Thereafter, subsequent control room research at other large-scale infrastructures supplemented and refined the approach (see also Roe and Schulman, 2016). The framework identifies and describes the real-time management challenges when operational experience, knowledge and management of systems must compensate for persisting limitations in design and technology. The framework underscores why and how complex technical systems must be managed *beyond* their technology and design if they are to be highly reliable and safe.

Although the HRM framework has been developed in research of control room operators of a variety of California critical infrastructures, including water and marine systems, the framework has had wide applicability to other complex sociotechnical systems operating under mandates of high reliability and in the face of environmental uncertainties and design/technology limitations (see [Roe and Schulman, 2017]). In this paper, we assess what the application of this framework implies for marine systems whose development towards increased autonomy poses a future of more remote operation and monitoring by human operators in control centers mandated to ensure the operating safety and reliability envelopes of the systems. The paper's specific objective is to investigate how the HRM framework identifies risks and challenges that need to be managed for autonomous marine systems, and analyze the implications that follow for real-time management.

The need for safer autonomous systems, such as unmanned aerial vehicles (UAVs), has been addressed by Clothier et al. (2015), Clarke (2014a; 2014b; 2014c), Clarke and Moses (2014), and Remenyte-Prescott et al. (2010). Reliability and risk issues related to autonomous underwater vehicles (AUVs) have been presented by Brito et al. (2016; 2012; 2010). Rødseth and Tjora (2014) further discuss challenges with unmanned ships, and Wrobel et al. (2016;

2017; 2018) have addressed risk aspects and scenarios of autonomous merchant ships. Utne et al. (2017) present a framework for risk management of autonomous marine systems and operations, exemplified for autonomous ships. More specifically, collision risk indicators for path planning of autonomous remotely operated vehicles (ROVs) have been presented by Hegde et al (2016). Here we seek to extend this research by examining the real-time management of these systems, the human operator in the loop, and the risks (including nonmeasurable uncertainties) posed by the autonomous marine systems. Uncertainties are high for these systems in the ocean environment and the operational experiences may be limited. The scientific results of the paper, we argue, provide a foundation for developing: (i) more focused safety requirements for autonomous systems and (ii) online risk monitoring and management systems providing improved decision support to the human operators.

Two case studies on systems with different levels of autonomy illustrate the utility of the HRM framework. The first case (1) addresses operation of ROVs from a subsea intervention vessel, i.e., inspection, maintenance and repair (IMR), while the second case (2) focuses on DP operation of marine surface vessels (ships). The latter case involves higher autonomy levels, enabling a focus on likely challenges ahead for human operators when systems in general become more autonomous. Thinking ahead about management and operational challenges is essential, given that the ongoing technological development aims at implementing higher autonomy levels in ROV operations in the years ahead (case study 1). In this way, the DP case study (2) identifies implications that need to be taken into considerations when developing autonomous ROV systems to achieve acceptable risk in the future. The scope of the paper is limited to risks associated with the autonomous marine system and its operation, i.e., we do not explicitly focus on or include risks to surrounding infrastructure, such as oil and gas platforms. The paper’s conclusion provides insights and recommendations for improved risk management strategies to achieve safe and reliable autonomous marine systems and operations.

The concerns raised by our findings do not argue against the development of autonomous systems—as long as their supervision is undertaken in real time by the operators involved. In so arguing, it is also essential that decision support systems be further developed for operators providing them early warnings, i.e., the operator must be warned ahead of time that operational constraints might be exceeded and that s/he may need to take over control (more in the concluding section). This would leave the operator more time to react properly when necessary.

The paper is structured as follows: Section 2 presents important concepts for autonomous marine systems; Section 3 gives and overview of the HRM framework for autonomous marine systems; and Section 4 presents the case studies, while Section 5 discusses the implications of the framework in light of the case material. Section 6, the last, states the conclusions and recommendations.

2. LEVELS OF AUTONOMY (LOA)

Autonomy is defined in this paper as a (sub-) system’s ability for integrated sensing, analyzing, communicating, planning, decision-making and acting so as to achieve its goals as assigned by its human operators through designed human-machine interface (HMI). This definition, formally based on NIST (2008), has been adjusted for manned and unmanned autonomous systems, designed with different LoA (Utne et al., 2017).

Different ways exist to categorizing LOA depending on functionality: from manual and automatic operation to fully or highly autonomous operation with an independent and “intelligent” system (NRC, 2005). By way of example, an unmanned (automatic) system, such as a remotely operated vehicle (ROV), may have low LoA, whereas a manned or unmanned intelligent system, such as an autonomous ship, may have high LoA. Table 1 (Utne et al., 2017) shows four main levels of autonomy (slightly adjusted and motivated by NRC [2005] and DoD [2011]), including examples of marine systems and operations relevant to this paper.

A persistent, major challenge with high autonomy is to facilitate cooperation and ensure information flow between the human operator and the system within and across differing LoAs. Autonomy is a functionality that must be developed to allow the operator and the autonomous system to interact in a reliable, safe, and efficient manner (DoD, 2011). Technological development means that systems are not leap-frogging directly from autonomy level 1 to 4; rather they are transitioning between levels. In addition, a system may have functionality in different autonomy levels and perform tasks and operations shifting from different levels, say, from manual operation to semi-autonomous (Utne et al., 2017). Ensuring designs and technology that enable, rather than limit, such shifts from one level of autonomy to another, especially under sudden and/or unforeseen events faced by operators and system managers, is a major concern.

Table 1. Levels of autonomy (LoA), adapted from (Utne et al., 2017) and including examples of systems and operations addressed in this paper.

LoA	Title	Description	Examples of marine systems and operations
1	Automatic operation (remote control)	System operates automatically at a distance from its human operators. Human operator directs and controls all functions; some functions are preprogrammed. System states, environmental conditions and sensor data are presented to operator through HMI (human-in-the-loop/human operated).	ROV/ subsea inspection and intervention.
2	Management by consent	System automatically makes recommendations for mission or process actions related to specific functions, where system prompts human operator at important points for information or decisions. At this level, system may have limited communication bandwidth, including time delay due to, e.g., physical remoteness. System can perform many functions independently of operator control when delegated to do so (human-delegated).	DP system; AUV inspection task with support by surface vessel.
3	Semi-autonomous operation or management by exception	System automatically executes mission-related functions when and where response times are too short for human intervention. Human operator may override or change parameters and cancel/redirect actions within defined time constraints. Operator´s attention is only brought to exceptions for certain decisions (human-supervisory control).	DP system; energy management systems; AUVs in ocean monitoring and surveillance.
4	Highly autonomous operation	System automatically executes mission- or process-related functions in unstructured environment with capability to plan and re-plan mission or process. The human operator may be informed about progress, but the system is independent and “intelligent” (“human-out-of-the loop”). In manned systems, the human operator is in the loop, has a more supervisory role, and may intervene.	AUV in ocean monitoring and surveillance without support of marine surface vessel; AUVs inspecting subsea installations.

3. HIGH RELIABILITY MANAGEMENT (HRM) OF AUTONOMOUS MARINE SYSTEMS AND OPERATIONS

3.1 Human operator performance modes under normal operations

HRM uses two main system dimensions, task volatility and options variety, to characterize the performance of control room operators during normal operations. The volatility a system faces refers to uncontrollable changes and/or unpredictable conditions in its task environment that influence control room operators in meeting its reliability mandates (e.g., balancing load and generation on the electric transmission grid). Options variety is the available resources for meeting the reliability mandate(s), such as keeping load and generation in balance.

The two dimensions use the scores “high” and “low” for heuristic purposes, where the resulting four performance modes have different characteristics and safety envelopes for operators in the control room. Table 2 shows the four main operator modes in normal operations: just-in-time performance, just-in-case performance, just-for-now-performance, and just-this-way performance (Roe and Schulman, 2008).

Table 2. Performance modes of HRM in normal operations (Roe and Schulman, 2008).

Options variety		System volatility	
		High	Low
	High	1. Just in time	2. Just in case
	Low	3. Just for now	4. Just this way

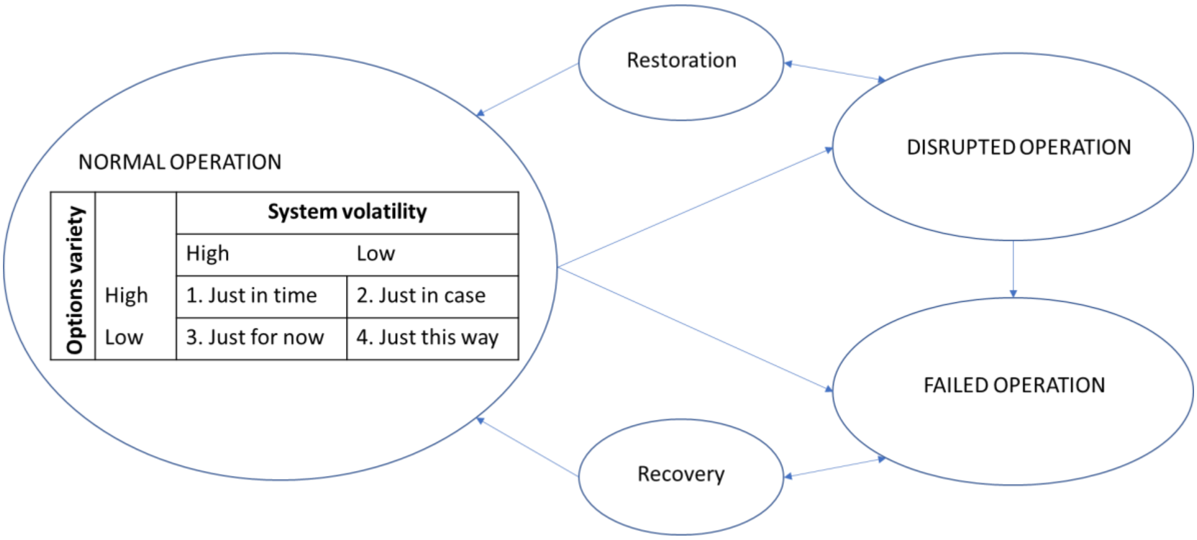
The key insight is that *to maintain even normal operations and manage their changing risks*, control room operators must be able to manoeuvre between and across the performance modes, as this gives them the requisite variety needed to handle different operating conditions. Key operational risks associated with each performance mode vary as system volatility and options variety change. In this way, performance modes can be used to identify risks related to a system that is mandated to meet overall reliability and safety performance requirements and associated operating envelopes, which is highly relevant for systems with different LoAs. In the actual practice of HRM, there are no sharp edges between performance modes (Roe and Schulman, 2016); an important finding as it increases the cognitive challenges of real-time management, which is also observed in the case material below.

Schematically, the four modes range from anticipatory exploration of options (*just in case*) when operations are routine, and many management strategies and options are available, to a real-time (*just in time*) improvisation of options and strategies when task conditions are more unstable. Control operators may have to operate temporarily in a highly challenging mode *(just for now*), when system instability is high and options are few. They may also be able, in emergencies when options have dwindled, to impose onto their members a single emergency scenario (*just this way*) in order to stabilize the situation (Roe and Schulman, 2008). It is important to underscore that these four performance modes are part and parcel of normal operations; even the occasional emergency (e.g., just-for-now performance) is a normal part of overall operations mandated for high reliability, and this is certainly true when operating in the ocean environment. Normal operations are *never* invariant; surprises happen all the time; operations not going according plan are the usual course of things.

In addition to normal operations, there are *disrupted operations* and *failed operations*. From the HRM perspective, these two states of operations arise when the control operators no longer have real-time knowledge of their task volatility and/or options variety. They no longer know in real time if options variety, let alone task volatility, is “high” or “low” or anywhere in between. (This could happen because of communications drop-outs.) The difference between disrupted operations and failed operation arises because the absence or suspension of real time knowledge for control operators can be temporary (disruption) or indefinite (failure). Either way, both are control room crises, not just setbacks to be expected during normal operations.

This is illustrated in Figure 1 and operationalized as follows. Disruption is a temporary and often partial loss of function or service, lasting < 24 hours. Failure is loss of function or service for more than 24 hours, where equipment and/or assets have been damaged and where repairs/replacement may have to take place over an indefinite period. Disruption requires restoration back to normal operations (and there is no guarantee that restoration will be achieved), whereas failed operations requires extensive recovery (asset damage, repair and/or replacement), leading to a “new normal” in notable cases.

In this paper, the main focus is on normal operations, for which the operators are required to be able to manoeuvre across the performance modes because of variable task volatility and available options (Roe and Schulman, 2016). We do, however, identify instances of disrupted and failed operations in the case material.



		System volatility	
		High	Low
Options variety	High	1. Just in time	2. Just in case
	Low	3. Just for now	4. Just this way

Figure 1. The different operational modes of HRM. Adapted from Roe and Schulman (2016).

3.2. HRM performance modes and risk management

The performance modes of HRM in normal operations have different dominant risks, which need particular attention paid to in risk management—in our case, managing risks associated with the operation of autonomous marine systems:

1. Just-in-case performance – One or more operators in the control center, in the face of many options and back-up resources, become complacent and inattentive to emerging or potential changes in system volatility or options variety.
2. Just-in-time performance – The risk is misjudgement by control operators with so many variables in the air at one time.
3. Just-this-way performance – Not everyone who needs to comply actually does comply with command and control measures to reduce the challenging task volatility faced.

While operators cannot reduce the volatility of the surrounding ocean environment, volatility in control operations specifically is reduced, e.g., by shifting to more manual or direct controls (if possible) and/or bringing in specialists to add expert advice for real-time operations.

4. Just-for-now performance – The most unstable performance mode of the four for normal operations and the one control operators and risk managers want most to avoid or exit from as soon as they can ("just keep that generator on line for now!"). Here the risk is losing manoeuverability by tunneling into a course of action without escape alternatives. What you do now increases greater risks later (in effect, options and volatility are no longer independent dimensions). The fewer options remaining may be such that to use any one of the few left increases the task volatility elsewhere in the system. Doing so can increase the probability of disrupted, let alone failed operations.

The management risks of complacency, misjudgement, loss of manoeuverability, and noncompliance are real-time risks, and they matter because they threaten system operations as a whole during normal operations. They also include a great deal of uncertainty that is difficult or impossible to measure when in real time with fast-changing task volatility and options in the ocean environment. From the perspective of HRM, these four main risks are imperative to consider and mitigate in risk management of autonomous marine systems, both during the design process and in real-time operations.

Risk management according to ISO 31000 (2009) is defined as the "coordinated activities to direct and control an organization with regard to risk". It encompasses an overall process, which includes establishing the context, risk identification, analysis, evaluation, and treatment. Communicating, consulting, monitoring and reviewing with experts, including human operators of a system, are core over the entire process. Figure 2 shows the link between HRM and the risk management process by ISO 31000 (2009). Information from the four HRM performance modes is intended to contribute directly to an improved risk management for the variety of "normal real-time operations" when in the ocean environment.

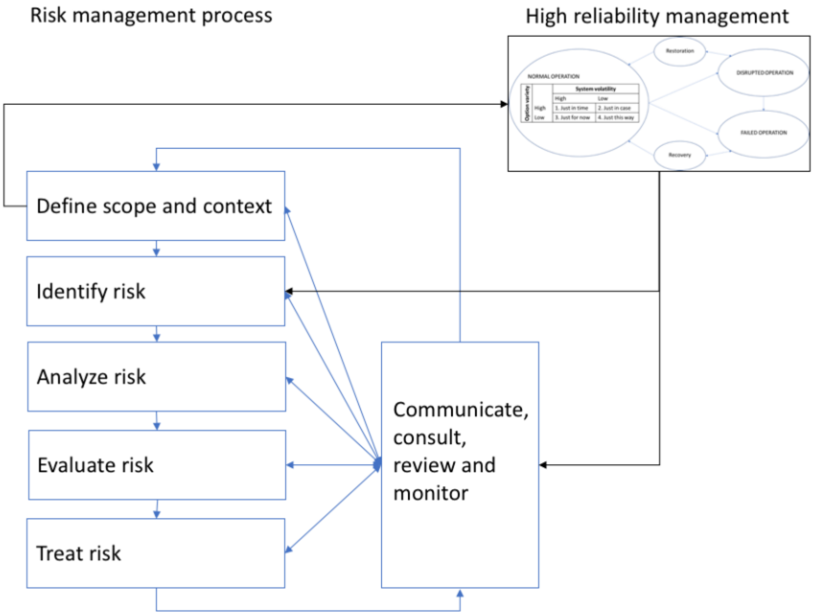


Figure 2. The links between risk management in blue (ISO 31000, 2009) and high reliability management in black.

Risk management is specific to context and scope, both of which in Figure 2 include an overall description of the system, its purpose, application area, and operational characteristics. The operational characteristics describe interactions with respect to the environment, humans, and organizations, as well as autonomous functionality and LoA. Given scope and context, the system and operational characteristics influence human operator performance and the prevailing modes (Table 2).

From the perspective of HRM, the key part of risk management is communicating and monitoring risks associated with operator complacency, misjudgement, loss of manoeuverability and noncompliance. The outcome of risk assessment may be a proposal for mitigating and reducing these risks, which must be closely evaluated and discussed with the human operators involved. For example, risk reduction measures could include the implementation of higher autonomy (the actual implementation and operation of which may, however, increase operator complacency, as we will see). In other words, risk mitigation must occur not only during the design of the system but also during real-time operations. This means that not just monitoring and review, but also ongoing evaluation and treatment are important features of the risk management process from the HRM perspective.

Finally, the risks associated with system disruption (with or without restoration) and failure (with or without recovery) must also be acknowledged and managed. For example, Roe and Schulman (2008, 2016) discuss cases where the probability of system failure in recovery is higher than probability of system failure in normal operations. The value added of the HRM framework is to insist that these different states of failed, disrupted and normal operations (where the latter have different performance modes for high reliability purposes) are absolutely crucial to distinguish when managing key risks.

3.3. Performance modes and their characteristics for operators of autonomous marine systems

Table 3 shows the characteristics of the four HRM performance modes during normal operations adapted to autonomous marine systems and operations and closely linked to the risk management process. The key features of the performance modes are task environment volatility, decision options variety, main operational feature, procedures and rules, and dominant risk. These factors are especially important to be aware of and manage for in autonomous marine systems, since they change with different LoAs as demonstrated by the case studies.

Table 3. High reliability management of autonomous marine systems and operations and the links to risk management in normal operations. Adapted and expanded from (Roe and Schulman, 2008).

HRM characteristics	**HRM performance modes of normal operation**				**Risk management process**
	Just-in-time	**Just-in-case**	**Just-for-now**	**Just-this-way**	
Decision options variety	High	High	Low	Low	Definition of scope and operational context (Figure 2) provide input to the task
Task environment volatility	High	Low	High	Low	

					environment volatility and decision options variety.
Procedures and rules	Key situations not covered by procedures, but addressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and on the fly, typically through quick fixes and short-term expedients	Performing to established command & control procedures	Procedures and rules are important to consider for risk identification and risk mitigation (Figure 2).
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator manoeuverability	Command and control	Main operational feature influences risk management strategies and priorities.
Dominant risk	Risk of misjudgement	Risk of complacency and inattention	Risk of losing manoeuverability and initiating cascading error	Risk of failing to comply with command and control requirements	Main risks provide input to risk identification and monitoring during operation (Figure 2).

The promise of autonomous system technology is that they increase operator decision options variety considerably, i.e., these systems provide options well beyond human cognition and team SA. Fortunately, the DP system has very clear criteria as to when it can be activated or must be deactivated in light of operational requirements, waves and wind, with governing cut-off criteria.

External task volatility posed by the ocean environment challenges is not the only source of task volatility for human operators. The autonomous systems themselves pose *internal* task volatility for control operators. As has been documented for DP systems, the human operator can be prompted too late to be able to restore back to normal operation (Vinnem et al., 2015). Alarms produced by autonomous systems may turn out to be, after further analysis, false alarms occurring under already turbulent task conditions.

The operators responsible for managing autonomous systems may think they are facing conditions of low task volatility and high options because the external environmental criteria have been met for activating the autonomous systems, which afforded a variety of options for improved operations during past use. Unbeknownst to the operators, conditions can change where now the system technology increases overall task volatility for the operator. What prove only later to be false alarms increasing with greater frequency actually reduce operator real-time options, i.e., there is less and less time for human operators to cognitively confirm "solutions" or restore the system back to normal operations.

To reiterate, there are no distinct borders between "high" and "low" in Table 2 and 3. These categories are based on how the human operators perceive their task work situation, which to some extent necessarily varies across operators (cf. Section 3.1). In fact, one cognitive challenge under team SA that individual operators face is that there are "no bright red lines" separating performance modes from each other (Roe and Schulman, 2017). Fortunately, the qualitative approach in this paper allows us to capture this ambiguity without imposing overly-restrictive yes-or-no criteria for factors in Table 3. If more specific boundaries are desirable at some point in addition to the HRM framework, it might be possible to define specific attributes, an,d for example, use fuzzy logic theory to determine whether a score should be "high" or "low". Fuzzy inference systems may support decisions, for example, related to ROV operations (Hegde et al., 2015). With this background in mind, we now turn to the case material.

4. CASE STUDIES

This Section presents two case studies demonstrating the impact of higher autonomy on human operator performance and risks within the terms of the HRM framework. The two cases are selected because they represent typical marine systems and operations with differing autonomy levels and complexities, as summarized in Table 4.

In case study 1, ROVs are operated remotely from a control room onboard an intervention vessel and fully depend on human input and control to perform subsea IMR. Case study 2 focuses on DP operators on the bridge of a ship during subsea intervention. For the purposes of this paper, it is assumed that increasing the level of autonomy would mean that the performance conditions of ROV operators will become increasingly similar to the DP operators in case study 2. By identifying the challenges and risks related to case study 2, we seek to identify important implications for the development and risk management of more autonomous operations.

Table 4. General overview of the two case studies. Stakeholders highlighted in **bold** are the key focus with respect to autonomy.

System/operation	Case study 1 - ROV	Case study 2 - DP
Description	A ROV is a comparatively "simple" system, but one involved in complex marine operations under demanding environmental conditions. In general, ROVs are operated from a control room onboard a ship or an oil and gas platform/rig.	A DP system has advanced control functionality and enables complex marine operations, such as intervention and drilling. DP systems are operated from the bridge on ships/rigs. The crew on the bridge has to cooperate with the ship control room.
Stakeholders involved	Client's onshore planning unit, client's representative onboard, **vessel's ROV control room operators**, crane operator, subsea tooling or specialist sub-contractors, and shift manager.	Client's onshore planning unit, client's representative onboard, and vessels' bridge management team/**DP operators**.
Main purpose of system/operation	To maintain/ensure high production availability in oil and gas subsea production systems. Facilitates inspection, maintenance and repair of subsea wells and production systems, including pipelines.	To maintain ship position to enable subsea intervention as means for maintaining high availability of subsea production systems. Enables complex marine operations, including subsea intervention.
Autonomy level	LoA 1	LoA 2-3
Normal operations	Year-round operation. May or may not disrupt oil and gas production during intervention. ROVs are not operated when ship is in transit, i.e., to/from shore, in between locations, or when waiting on	When activated, DP maintains the ship's position during operation or when waiting on weather at a location.

	weather. Operational limits for subsea operation may be exceeded, i.e., waiting for acceptable weather conditions to perform operation.	
Disrupted operations	ROV mission aborted by being temporarily delayed; main consequence is extended operation time and increased ship operation cost. If oil/gas production is shut down, high costs for delays ensue.	System alarms occur. May temporarily lead to delays or aborted mission, the main consequence of which is extended operation time and increased ship operation cost.
Failed operations	Mission aborted by being indefinitely delayed, due to major physical damage to the ROV, a specialized tool needed for the operation, or the subsea production system. The operation cannot be recommenced without extensive repairs and onshore support. The ship has to return to shore.	Loss of position, i.e., drift off or drive off, with serious consequences, including but not limited to loss of ROVs and collision with rig/platform.

4.1 Case study 1 – ROV operation onboard a subsea intervention vessel in the North Sea

4.1.1 Background

The technological trend to developing more autonomous ROVs is well-established (Schjølberg et al, 2015). It is expected that underwater vehicles will be stationed in subsea garages on the seabed in the future, equipped with mechanical arms (manipulators) for performing intervention tasks and replacing some routine maintenance tasks performed by current ROVs from vessels.

The ROV case study is based on: i) observations and interviews with ship personnel in the control room, at their work stations, and on the bridge; and ii) data on operations collected during 12 days onboard a subsea IMR vessel in fall 2016. The ship operates year-round in the North Sea. The vessel has two heavy duty (HD) ROVs and one observation ROV. The vessel performs different types of subsea intervention using the ROVs and specialized subsea tools, if needed. The IMR operations are performed on subsea structures and systems, and include repair of flowlines, surveys of pipelines, inspection of subsea systems, injection of chemicals and testing of barriers, such as subsea valves. During transit from/to shore and in between the locations, the ROVs (and tools) are stored onboard the ship.

Each HD ROV is operated remotely from the ship's control room by three ROV operators: one pilot, one co-pilot and one pilot who video-records the operation and who monitors/operates the hydraulic utility system when connected to subsea tools. The layout of the control room with operators (black outlined box) and the location of the ROVs (outside the control room/black outlined box), are shown in Figure 3. There are usually two ROVs in the water at the same time. When tools are used for different subsea operations, the software for controlling and monitoring is operated by the ROV crew in the control room.

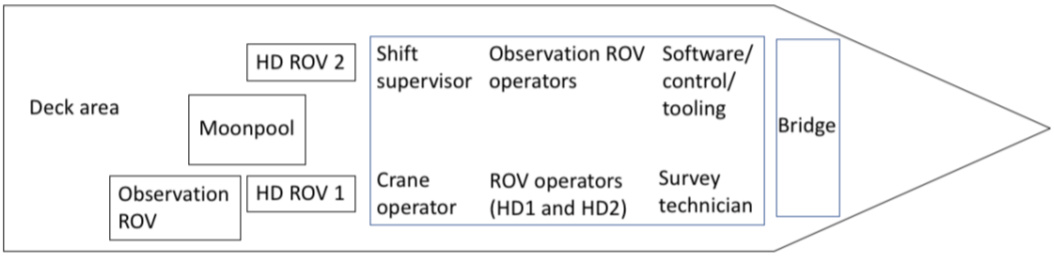


Figure 3. Layout of vessel control room and location of ROVs. (The scale is not correct).

4.1.2 Work operations during observation period

During the onboard observation period, the main task to be performed was a flowline disconnection, cutting and recovery operation using a pull-in and connection tool (PICT; similar to a wrench). The PICT, which weighs 12 tonnes, is controlled via an ROV. The task was to seal off the flowline, cut and collect some samples of the flow line for laboratory analysis of degradation, and prepare for installation of a new flowline some months later. To seal off the flowline, high pressure (HP) caps are used. Part of the operation was to install a HP cap on a subsea manifold and on an oil platform's production riser base to ensure sufficient integrity of the flowline. The affected oil wells were shut down during operation, which means that the oil production at the nearby offshore platform was partly impacted. On the way to the operation site, the tool was lowered to 50 m depth in the seawater for testing and worked fine. The water depth at the site is around 300 m. Table 5 presents more data regarding the operations performed during the case study period.

Table 5. Data on operations. Operational tasks and challenges describing the work operations onboard the observation period, including the consequences.

Operational tasks	**Description**	**Challenges**	**Consequences**
PICT operation started on site	Testing of the PICT. Performed onboard the vessel.	Short-circuiting occurred. No spare printed circuit board (PCB) was found. The crew improvised and found a similar PCB in another tool. The PICT was then tested again and worked properly.	Operational delay. Remaining weather window not sufficient for continuing the PICT operation.
Ship relocated	Other tasks performed at new location while waiting for better weather conditions to commence PICT operation.		
PICT operation commenced	PICT lowered to the sea bottom.	A ground fault occurred in the electrical system. PICT was lifted back to the deck for inspection.	Operational delay.
	Installation of HP cap.	Error was found on a "seal". PICT was lifted to deck to investigate. Operation performed again with a new seal.	Operational delay.
		A technical problem with the PICT's elevator was discovered. The PICT was lifted to deck for repair, and spare parts were found. The spares did not fit correctly and had to be modified before use.	Operational delay.
	Repair of PICT. ROVs lowered to inspect socket.	A crack on the socket was found, which had to be polished away before the HP cap could be mounted.	Operational delay. Highly challenging task for the ROV operators to assess the

			depth of the crack due to the lack of depth sight (3D sight), as they only have video camera images available (2D).
	The PICT was then relowered to the sea bottom with a new seal.	The new seal did not fit the pipe socket. PICT did not function properly, and had to be lifted again to deck for repair. The only seal left onboard was the original seal, which was mounted on the pipe socket before the operation commenced. Two additional spare seals turned out to have the wrong dimensions.	Operational delay. After several hours of work, the HP cap was mounted on the pipe socket and the flowline was sealed again. Possible to proceed to the next phase of the work program, namely, to start the cutting.
Cutting of the flowline	Use of a specialized saw, operated by ROVs.	A technical problem arose with the saw. The saw was lifted to deck for inspection, yet no faults were found. The saw was lowered once more, but the blade was bent by the ROV. The saw had to be lifted back to the deck and the blade changed.	Operational delay. The actual cutting in the operation took much longer time than initially planned. Crew lifted the saw to deck again to change the blade to a supposedly faster one.
		The saw was relowered, but instead of faster cutting, it went slower. The flowline collapsed and blade broke. The saw was lifted to deck to change the blade. It was then lowered again, but there was a hydraulic leakage in the stab (connected to the ROV).	Operational delay. The leakage reduced pressure and the cutting process ended up being much slower. Some cuts were finalized, but fewer than planned.
Sealing of the flowline	The PICT tool was ready to be lowered again to the riser base of an oil and gas platform to seal the flowline.	Weather changed to a “drift on situation”. Work operation at the riser base, and in a drift on situation, the wind blows in a direction right on the platform. This means that if the vessel experiences a propulsion failure, it will drift on to the platform and collide with risers filled with hydrocarbons.	Operational delay. Waiting on weather. A drift on situation may lead to an undesired event with major hazard potential. The intervention vessel had to wait for better wind conditions.
	PICT relowered to sea bottom.	Wind conditions acceptable, but still problems with the seal.	The entire cutting operation could not be completed as originally planned and had to be aborted “indefinitely”.

What are we to make of all these challenges, setbacks and the risks they posed in Table 5? The HRM framework highlights the following as extremely critical for real-time risk management purposes and safe operations:

(1) That unexpected weather problems arise or that a task in real-time takes longer than initially planned onshore (holding other factors constant) are all part of normal operations in the ocean environment. Delays during normal operations happen all the time. Risks don’t disappear in routine operations, but risk management becomes focused on the performance modes manoeuvered across during those operations.

(2) More problematic for risk management purposes is the fact that real-time normal operations with respect to the flowline task appear to have been restricted primarily to

the left side of the HRM typology, namely just-in-time performance with high improvisation and just-for-now performance, where task volatility was high in part because of the lack of onboard resources, such as spare parts that limit the ability of operators to manoeuvre.

(3) Disrupted operations with respect to the flowline task occurred when bad weather at the first site led to the temporary suspension of the task, resuming only when the weather improved. The risk here was the added one of leaving the flowline issue unaddressed in the interim at the original site.

(4) Failed operations with respect to the flowline task occurred when the cutting task had to be suspended indefinitely. Recovery would consist of replanning and then continuing the operation several months later with new equipment. The risk here was not only the added one of leaving the flowline task unattended, but also that recommencing task operations at that latter date could face new risks as well, not least of which related to working with different equipment.

It is clear that weather conditions and human error contributed to some delays and problems. Still, the key fact in this case study is that task-based risk management, even during a short span of a 12-day study period, had to be focused on and spread over disrupted and failed operations as well as two different performance modes in normal operations (namely, just-in-time and just-for-now). This highly variable and demanding state of affairs for risk management in a compressed period of time raises acute issues for current and future research over whether (and if so the degree to which) the challenges followed specifically from the ROV technology and tools. To analyze the challenges, we must examine more closely the determinants of the options variety and task volatility faced by the control operators across a variety of real-time ROV-related tasks.

4.1.3 ROV operator decision options

The ROV operators are the main focus when it comes to options variety, since they are operating the ROVs by remote control (see LoA 1 in Table 1). What follows describes the determinants of real-time options from the operator perspective.

The significant wave height, H_{s}, determines the **operational limits** for the onboard equipment and launch and recovery of the ROVs (as well as their tools). (**Bold** terms are the influencing factors included in Figure 3-7.) The criteria are not strict cut-off points but can be and are adjusted depending on the experience and knowledge by personnel and shift supervisor of the ship motion, current weather conditions and the weather forecast, all of which constitute the setting for deploying the tools as well as the complexity and duration of the task operations performed. If the operational limits are exceeded, waiting on weather occurs, which means that commencement is delayed or the operation, if already underway, is disrupted. The ship might activate DP while waiting or move to another location to perform a different task.

Professionals onshore create the work task plans and have a good deal of knowledge about how to design and engineer tools. **On-shore planners** necessarily make assumptions about the operating conditions and the subsea structure—assumptions which, to repeat, turn out not always to hold in real time at the site. Yet **detailed drawings** of the subsea templates and structures are essential for onshore planners and others to reduce uncertainties. Indeed, they are a prerequisite for systems with high LoAs, such as AUVs, to enable navigation and precise localization in the ocean space for intervention purposes. Nonetheless, there may be no detailed drawings of the subsea production systems for the specific sea bottom site, such that tools and equipment designed onshore for the specific operation offshore may turn out not to be fit-for-purpose.

The fact that ROVs and **specialized tools** are operated remotely and manually from the vessel control room means that the systems and operations correspond to a low LoA, i.e., level one (1) in Table 1. Most control room crew onboard work two shifts – 12h on/12h off. As we saw in the preceding subsection, the ROV work program changed many times due to problems, including the aforementioned weather conditions exceeding the operational limits and delays in jobs arising because of the technical glitches or other setbacks.

Last but arguably the most important determinant of options variety for the ROV control operators follows from the determinants of SA in the ship's control room at the same time. In the ship's control room, there may be 10-15 people with different tasks from different companies, depending on the specific task operation. Understandably, **communication and cooperation** among the different actors are very important to working efficiently and achieving reliable success (cf. Table 4 for the many stakeholders involved in IMR operations)

Figure 4 sums up the most important influencing factors observed on the operator decision option variety (Table 3 in the background). As we saw in the preceding subsection, during the study period ROV operators spent most of their normal operation in just-in-time and just-for-now performance modes, where option variety varied from high to low (low options variety being more problematic).

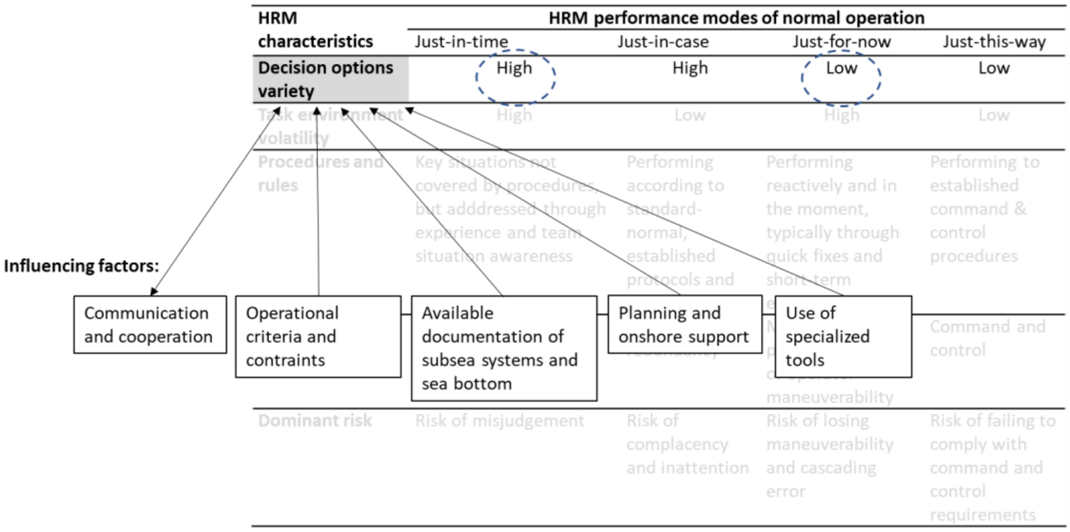


Figure 4. Decision options variety of ROV normal operations, performance modes and influencing factors.

4.1.4 ROV operator task volatility

Two operators must control one ROV at the same time, each operator having the responsibility for one manipulator arm. One of the manipulators does the coarse work, while the other performs the high precision activities. Hence, the two operators collectively are responsible for operating one "ROV-body," where effective **communication and cooperation** are decisive for efficient and reliable operations. In fact, some personnel onboard claimed that "flying an ROV" is more difficult than flying an aircraft.

Since the ROVs are remotely operated, the operators must depend on the ROV's sensor systems, not least of which are the video cameras, sonar, Doppler and the information presented to them through the HMI in the control room (again, "manual control" is at a distance under

LoA 1). One major real-time challenge for the control room ROV operators is visibility in the water, a key task **environment** determinant for the operators. Often visibility is low when the ROV propellers stir sediments from the sea bottom. In addition, the operators need good lighting from the ROV to be able to see the subsea templates and pipelines and reliably perform their work tasks. Light, however, attracts fish, which when in numbers disturb the operators' line of sight. Visibility problems frequently delay control center operations, where the operator has few alternatives (options variety) except wait for the visibility to improve or try to manoeuvre the ROV so that fish are not obstructing the view or continue the work more slowly. The lack of 3D sight and the challenges with visibility are the main reason for having two ROVs in the water at the same time, with their control operators in active communication with each other.

A brief example demonstrating the importance of crew experience, good **SA**, and effective communications based on clear roles and responsibilities was evident when it came to potential conflicts arising from the fact that several people had the same first name in the control room. The point of this example is what didn't happen: There were no conflicts emerging from having the same name. When the name was called out, everybody knew immediately the person being addressed, and with no apparent confusion. It is difficult to imagine how this could occur in the absence of crew experience, SA, and proven prior communications. Part of this lack of confusion is because communications are both formal and informal and across multiple levels in real time: Again, the ROV operators are in continual communication with each other, and operation progress entirely depends on their cooperation, including between the two ROVs, the shift supervisor, and the crane operator, and those operating any software for tooling. Equally important is the experience of the latter personnel: For instance, the shift supervisor, who has the overall responsibility in the control room and monitors the ROV operation, must be aware of the ship's position, the location of the subsea template and geographical directions, where the ROVs are positioned, along with their tether management systems, the positioning of any guide wires, as well as any other tools.

More, when it comes to task volatility facing the ROV operators, control center-related communication must occur across multiple levels among the long line of stakeholders leading up to and including real-time operations. As we have seen, the **onshore organization** unit develops the overall vessel IMR plan including tasks, location, duration time, start and finish times. The plan is discussed and agreed upon with the client representative onboard the ship and communicated to the captain, the offshore manager, and other crew representatives onboard. These actors may then comment on the plan and the tasks. Any delays and problems the last 24 hours are to be communicated—but here too there may be time-sensitive changes, since ultimately it is the client who pays for the ship and the priorities do shift. Even when the vessel has detailed work plans for the coming weeks, new critical jobs could emerge due to intervening incidents and new needs on the various oil and gas platforms in the North Sea. Since these decisions are more or less outside the control of the vessel's control center crew, any abrupt changes in the decisions necessarily become part of the center's task volatility.

Figure 5 sums up the most important influencing factors on the operator task volatility. In general, task volatility is high during normal operations, which implies that the operators most of the time are in the just-in-time or just-for-now in performance mode of HRM.

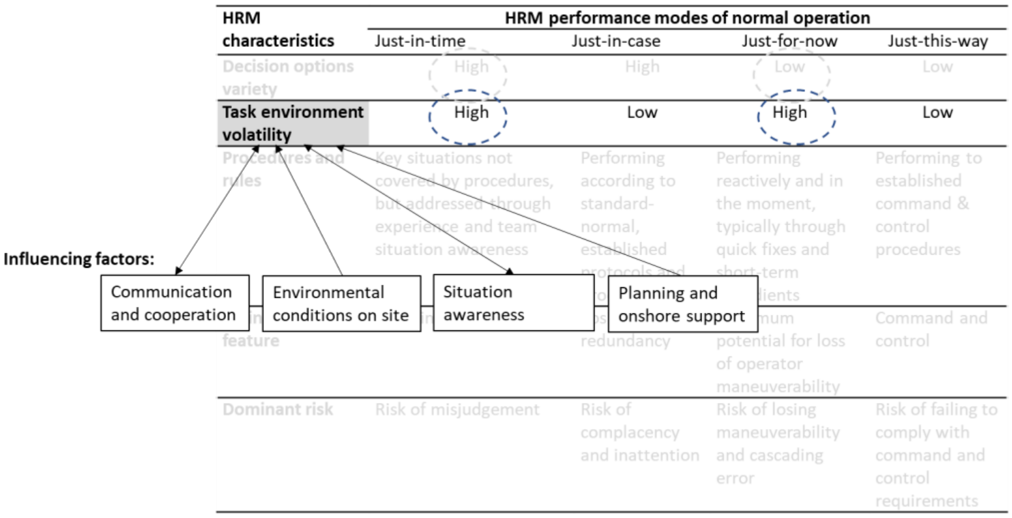


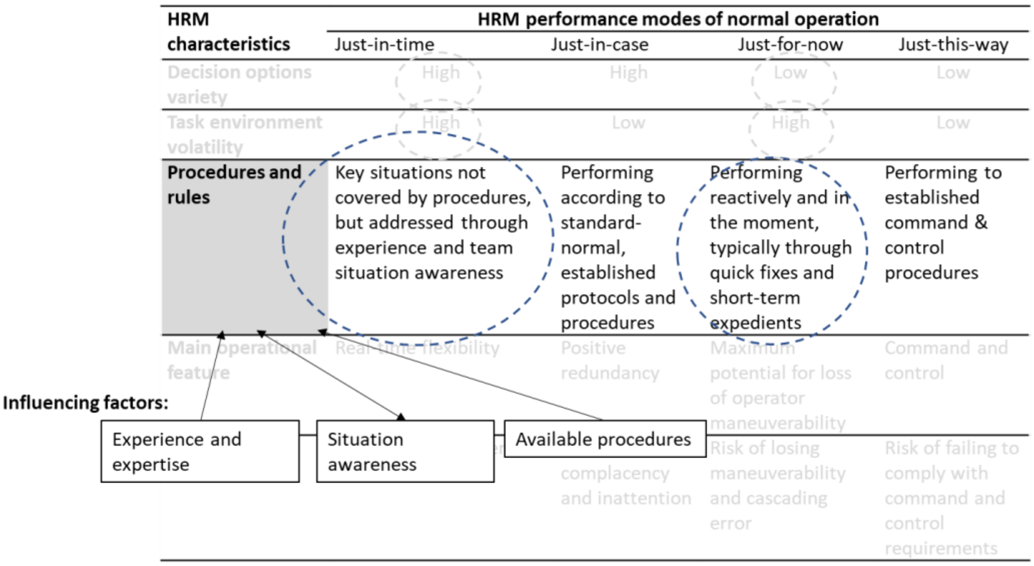
Figure 5. Operator task volatility of ROV normal operations, performance modes, and influencing factors.

4.1.5 Procedures and rules

Many procedures are followed for operating the ROVs and subsea tools. There are, for instance: (1) procedures related to the vessel being in DP mode during operation of the ROVs, regarding distance to the installation and the oil and gas platform safety zone; (2) procedures regarding the limits for utilization of the ROVs; (3) procedural constraints related to the use of the moonpool (the opening in the ship hull giving access to the ocean) for subsea tools; and (4) procedures for subsea barrier tests and leakages. It bears repeating that when unexpected events occur, as they invariably do, the ROV operators have to use their **experience and expertise** to develop improvised solutions required beyond the existing repertoire of procedures—which entails that dominant risk of misjudgement when performing just-in-time.

As detailed above and to summarize here, the ROV operators undertake the planned task based on existing procedures, their own experience and **SA**, the operational limits of the ROV as well as built-in limits of control room software and hardware, the subsea template layout along with the physical access to any valves, and weather and wave conditions in the area, among other factors contingent on specific time and site. During normal operations and when activities proceed according to plan, the operators have their **procedures** and ways to solve the tasks, with defined decision points. The external environmental and/or internal system volatility means, however, that real-time performance is often adaptive rather than as-planned, this being especially true during ROV launching and relaunching operations when wave conditions affect vessel motion. Even when there is a slight deviation from the plan, practical problem-solving and improvisation start immediately and proceed in light of the options available at the moment. If it is not possible to solve the problem subsea, the option is to abort and get the ROV/tool to deck to address the problem (that is, the task is disrupted), where trouble shooting, maintenance, and repairs are to take place. In the absence of spare parts onboard, there is little the crew can do except wait for the missing parts to be delivered by helicopter (which in turn assumes no procurement delay requiring the ship returning to shore, if so, the operation has failed).

Figure 6 sums up the most important influencing factors related to procedures and rules. In general, operators use procedures when these are available, combined with expertise-based improvisation.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures, but addressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
		complacency and inattention	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

Influencing factors:

Experience and expertise

Situation awareness

Available procedures

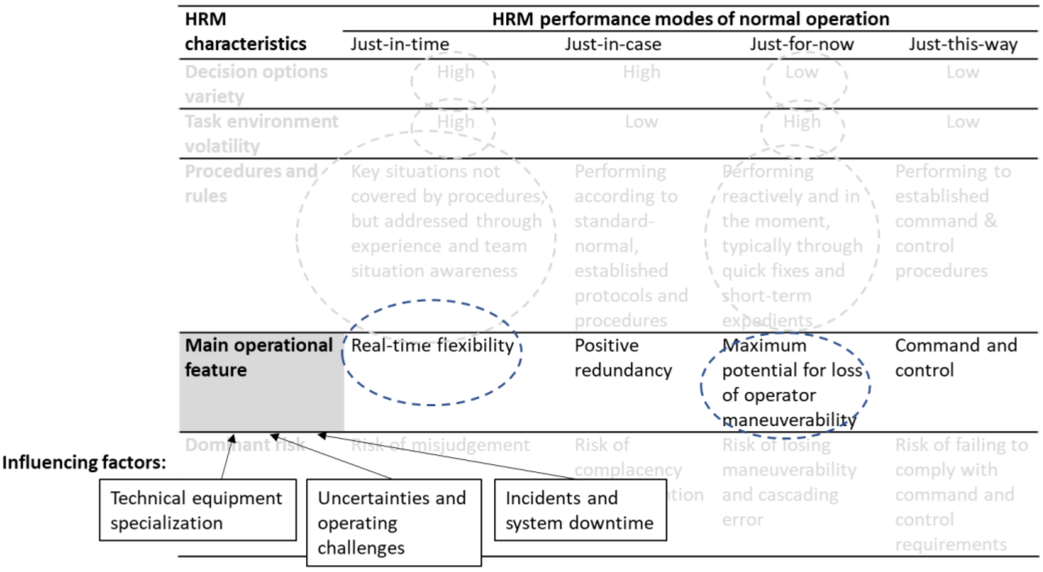
Figure 6. Procedures and rules of ROV normal operations, performance modes and influencing factors.

4.1.6 Main operational feature

It is important to recognize that there is limited redundancy in the systems involved in the ROV operations. If one ROV fails, the other one may, in theory, take over the operation. This, nonetheless, is most often not possible as the ROVs are equipped differently. Hence, the ROV has to up to deck to be repaired and task operation is disrupted. Also, as noted, for most jobs two ROVs are needed to get sufficient camera overview of the area to perform the job. The ROVs may as well need to do different tasks: One may work at the template/flowline, when the other goes up to deck to collect or deliver **tools or subsea components** not used any longer. Such operations require real-time flexibility (operator improvisation) in part because there is less just-in-case redundancy available within a short time notice (again, the problem of missing spare parts). A problem or other interruption may cause an operational delay, immediately. These considerations again imply that the control room operators during normal operation mostly operate in the just-in-time performance mode.

Compared to the CAISO operators discussed earlier, whose real-time balance requirements are related to electricity generation and load, the crew in the control room onboard the subsea intervention vessel is balancing the demand to minimize production losses and meet the planned work schedule, while at the same time taking into account the risks, **uncertainties and challenges** posed by working in a hostile ocean space that determines the progress of the subsea operations. The situation in normal operations of waiting on weather increases time pressures on the operators, because (1) they know they should finish an operation before bad weather arrives and the operation is aborted (e.g., the task is disrupted at the site), and (2) if the operation is not completed, there will be even more delays due to having to wait on the forthcoming weather (e.g., when the task has failed, the vessel returns to port, and recommencing operations at the original site may be delayed indefinitely). Increasing the time pressures even further on the control room operators are those unexpected contingencies that emerge with the ROV tool deployment and operation under real-time conditions.

In general, and by way of summary, the ROVs onboard the intervention vessel have a low **downtime** due to technical failures (<5%). Nevertheless, during the period of observation, several **incidents** leading to the disruptions of operational delays and aborted operations were observed onboard, including those aforementioned human errors in misjudging the planning of the operations; the inadequate preparations for deployment of specialized subsea tools; and technical (internal system) problems, such as few or no spare parts. The effect of these latter factors were that the ROV operators responded just-in-time and just-for-now. Figure 7 sums up the most important influencing factors related to the main operational feature of ROV operations. In general, operators are characterized by real-time flexibility.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures but addressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
Dominant risk	Risk of misjudgement	Risk of complacency tion	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

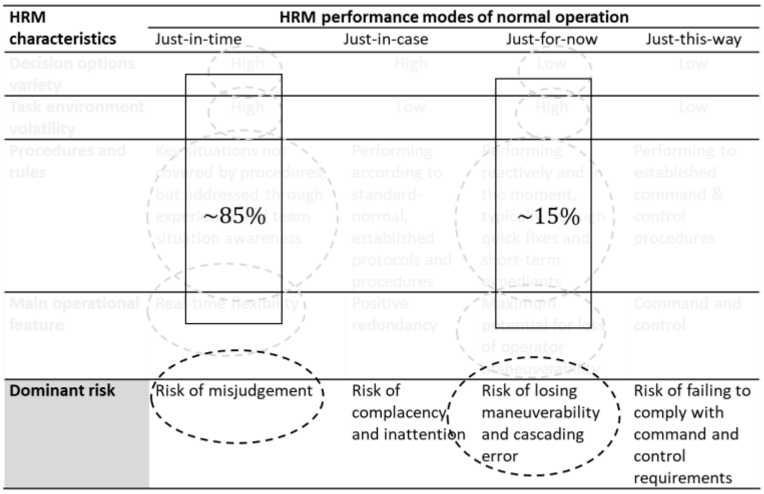
Influencing factors:

- Technical equipment specialization
- Uncertainties and operating challenges
- Incidents and system downtime

Figure 7. Main operational feature of ROV operations and influencing factors.

4.1.7 Normal operations – dominant risks—and the risks associated with task disruption & failure.

Figure 8 sums up the HRM characteristics and performance modes related to the ROV operations. We estimate that, during normal operations (disrupted/failed operations are discussed in a moment), the crew in the control room spent the majority of operation time (~85%) in the just-in-time performance mode. We also estimate that approx. 15% of the normal operations was spent in the just-for-now performance mode, where control operator options had dwindled and their effort was one of making due with what was at hand. This distribution of time during normal operations spent confirms that the dominant risk for the ROV operators during the study period was misjudgement, with the risk of losing manoeuverability also important at times. Our observations and interviews lead us to believe that this distribution of normal operation time was not atypical of the year as a whole.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures but addressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
Dominant risk	Risk of misjudgement	Risk of complacency and inattention	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

Figure 8. The HRM performance modes, our observations, and the resulting main risks related to the ROV operators during normal operations.

Our case study demonstrates that there were also disrupted operations (the flowline task at one site was temporary suspended and resumed only when the weather improved) and failed operations (the cutting task had to be suspended indefinitely). Even though downtime was not substantial, there were associated risks during it. The risks associated with disruption and failure are very different (if not far greater) than the risks associated with normal operations. We already know the dominant risks of normal operations—complacency, misjudgement, loss of manoeuverability, and non-compliance—and what can and should be done to mitigate them (see [Roe and Schulman 2008, 2016]). But when it comes to disrupted and failed operations, we are in a very different and demanding world for risk management. The risk of disrupted operations in our case study was risk associated with forgoing flowline remedial activities then considered necessary by the client and the onshore organization. The risk associated with failed operations was not only the added one of leaving the flowline task unattended indefinitely, but also that of renewing task operations at that latter date and under different environmental conditions.

In general, the past record demonstrates that hazardous events can interrupt ROV normal operations *at any point* and include events that that lead to disrupted (or failed) operations:

- Technical failures can occur in sensors and communication systems, including hydraulic leakages and seawater ingression.
- Entanglements with cables and wires can occur, as well as damage and tear off during launch and recovery due to severe sea currents, weather and wave conditions.
- Collisions can occur with the subsea production system (e.g., template), the seabed, other ROVs, the intervention vessel, subsea tools, or other obstacles in the ocean. More, the use of subsea tools involves other risks, e.g., related to heavy loads and falling objects. If a heavy tool falls and hits the subsea template underneath the ship, the structure and the tool can be damaged.
- Human operator errors do occur, including misjudgements due to, e.g., lack of competence and training, misunderstandings in the communication between the ROV operators or other personnel in the control room, or deficient prior planning of ROV tasks.

Damages to subsea systems and equipment, such as operating the wrong valve or colliding a large subsea tool into a structure, may lead, in the worst case, to leakage of oil and gas, wider system failure and associated shutdowns. Human operators are exposed to hazards during launching and recovery of the ROVs, notwithstanding improvements in safeguards and protection. In general, one major consequence of delays in ROV operations can be increased vessel costs and higher production losses. To sum up, the main risks and their presence during normal operations for this case study are shown in Table 6.

Table 6. HRM characteristics and main risks.

HRM characteristics	**ROV: LoA 1**
Risk of misjudgement	High
Risk of complacency	Low
Risk of losing manoeuverability	Low
Risk of noncompliance with procedures	Low

4.2 Case study 2 – DP operation of intervention vessel in the North Sea

4.2.1 Background

A DP system enables the vessel to keep its position and heading and can manoeuvre slowly along a predefined track by using active thrusters only. There are different classes of DP systems, and the vessel in the case study is a DP 2 class IMR vessel. This means that loss of position shall not be caused by a single fault of a system or component (for example, generators, thruster, switchboards [DNV, 2011]). The case study is based on observations onboard the ship and, on the bridge, manned with two dynamic positioning operators (DPOs) working 12/12 shifts (four operators in total) during the study period onboard the intervention vessel in the North Sea, as described in Section 4.1.

The DP case study is shorter because many of the problems affecting control operator task volatility and available options have been more fully explained in the preceding ROV case study for the same ship and study period.

4.2.2 Work operations during observation period

Normal operations for the DP bridge crew are typically focused on an oil and gas platform and/or a subsea system in need of maintenance or some kind of assistance. The intervention vessel is called out to the location and during vessel transit, i.e., from one location to another, the DP operators manually operate the ship and the DP is not activated. Once at the subsea or platform location, the DP system is put into operation. The basic task of the bridge crew, when the DP is activated, is to monitor the status of the operating system.

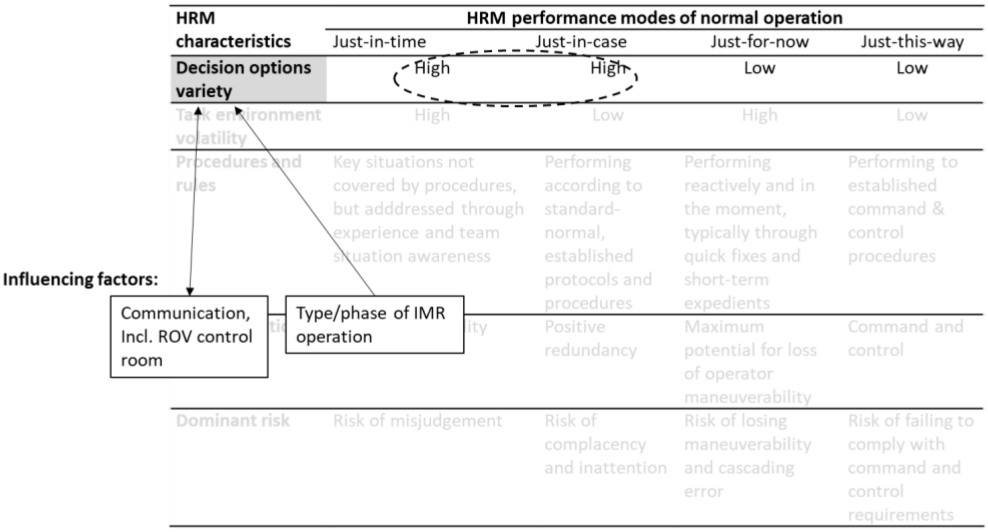
During the observation period, the vessel transited between the shore supply base in Western Norway and some sites for the subsea operations in the North Sea. We did not observe instances of disrupted or failed operations with respect to the DP system when in operation.

4.2.3 DP operator decision options

There is direct DP status communication between the bridge and the ROV control room. The overall **communication** on the bridge and between the bridge and the control room is typically relaxed during DP operations when they go according to plan. (**Bold** terms are the influencing factors included in Figure 9-11.) A great deal of DP operator time is spent in just-in-case performance mode, undertaking that basic task of monitoring the screens and ensuring the activated system works as planned.

The DP operators first slow down the vessel's speed on location for the subsea operation, and then start the activation of the DP system so as to station the vessel in the desired position. When the DP system is fully operational, the subsea IMR operations commence from the control room of the vessel. When activities proceed as planned, the DP operators are on the bridge awaiting possible instructions from the **ROV control operators** regarding the need for moving the vessel into a new position. Any new-position requests are based on the **type of IMR operation** underway, the phase of that operation along with its operational constraints, and the tasks necessary to be accomplished by the ROVs and subsea tools.

Options variety, in brief, remained high overall during the case study of the operated DP system. Alarms did occur, but even then options with which to respond were available to operators. Figure 9 sums up the most important influencing factors on the operator decision option variety. In general, operators were observed to be in the just-in-case performance, or at times in just-in-time mode.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures, but adddressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
ti	ity	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
Dominant risk	Risk of misjudgement	Risk of complacency and inattention	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

Figure 9. Decision option variety of DP normal operations, performance modes and influencing factors.

4.2.4 DP operator task volatility

Although DP operator time was largely spent in just-in-case performance mode by monitoring the screens and ensuring the activated system works as planned, there were instances of higher task volatility. When things do not go according to plan, i.e., when the DP system produces an alarm, it can be difficult for DP operators to ascertain why the alarm has been triggered, as insufficient information from the system may be provided in the time required for operators to take effective action. Furthermore, several alarms may be activated at the same time, leading to potential information overload challenging operator **SA**. When DP operators must respond quickly, sometimes with (too) little time available, reliable problem-solving becomes even more challenging for the operators.

In short, the internal volatility produced by the DP system and the consequences that follow for operations and attendant risk management must be distinguished from the external volatility produced by the **environmental conditions**, i.e., weather and ocean site conditions. Waiting on weather can occur, which means that even if the DP system has been activated, there is no intervention operation with the ROVs. That said, neither the ship waiting on weather nor a

ROV operation already underway need make a notable difference to the DP operators in terms of their work tasks. Failure with respect to work tasks, however, in the operated **DP system** can cause hazardous events, such as loss of position due to drive-off or drift-off, complete or partial black-out, damage to the ROVs and any tools, subsea templates, and possibly collisions with a platform or other vessels, as a secondary effect.

Figure 10 sums up the most important influencing factors on task volatility for DP operators when managing the activated DP system. Overall, task volatility with respect to the operated DP system was low during the study period, though higher when alarms occurred, indicating normal operations, just-in-case and just-in-time, respectively.

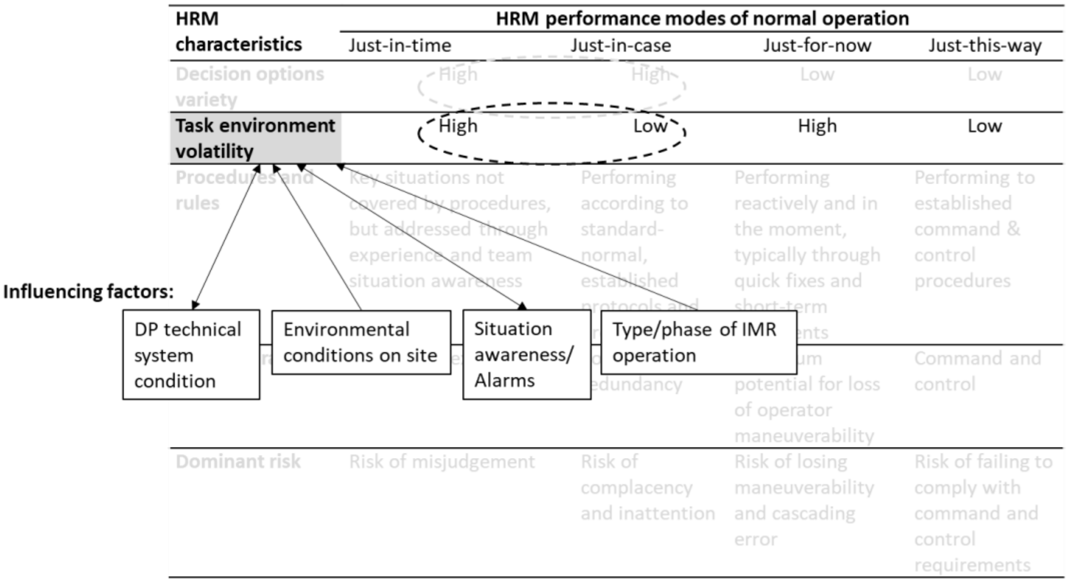


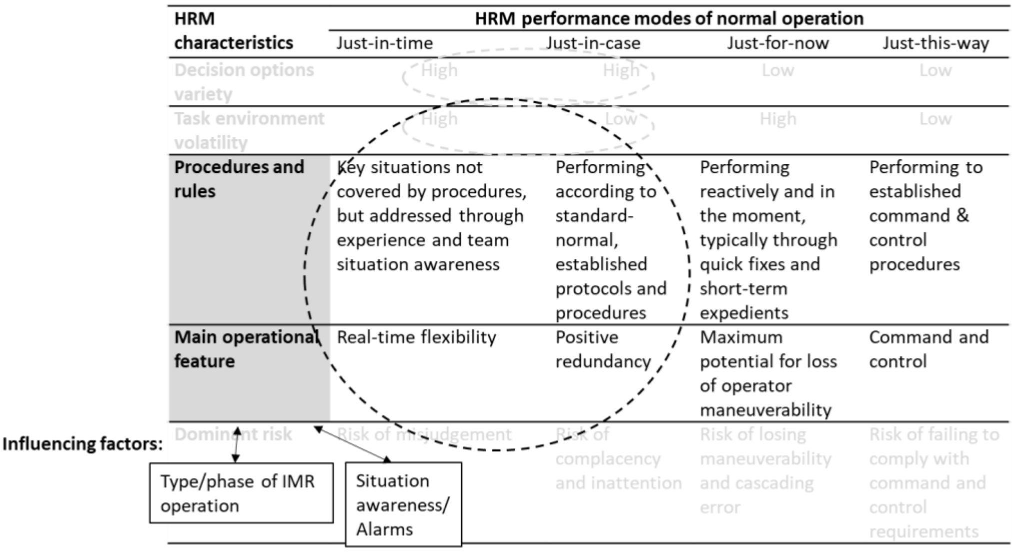
Figure 10. Operator task volatility of DP normal operations, performance modes and influencing factors.

4.2.5 Procedures and rules

There are **detailed procedures** to follow when activating and deactivating the DP system, due to regulations. Normally, it takes around 30-60 minutes to fully activate the DP system for the vessel. According to the bridge crew, too many **alarms** are often the case for many non-critical situations. When alarms are activated, it is not automatically easy to understand what the alarm is about, such that operator experience necessarily comes into play to determine if an alarm can be ignored or not (cf. Figure 11).

4.2.6 Main operational feature

A DP system, once in actual operation, has functionality in LoA of 2 - 3 (Table 1 and Table 4). There is a good deal less human interaction with the DP system compared to the ROV operations. While one DPO is sufficient for monitoring the system, client regulations require the presence of two DPOs on the bridge. Hence, there is positive redundancy in normal operations for **activating, running and deactivating the DP system**, corresponding to the just-in-case performance mode, as shown in Figure 11. When the DP system is in the process of activation and deactivation, more real-time flexibility on the part of the DP operators is required, given the problematic nature of **alarms** just mentioned.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures, but addressed through experience and team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
Dominant risk	Risk of misjudgement	Risk of complacency and inattention	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

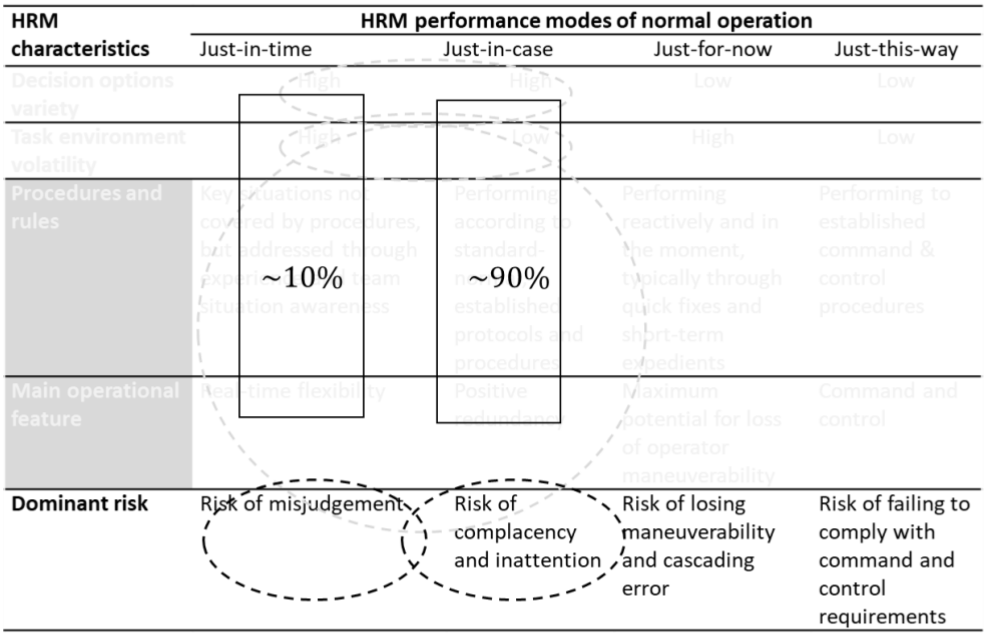
Figure 11. Procedures and rules and main operational feature of DP normal operations, performance modes and influencing factors.

4.*2.7 Normal operations – dominant risks—and the risks associated with task disruption & failure.*

During normal operation, the status of the activated DP system is officially “green.” If there is a problem, DP operators report a status of “yellow” to warn the vessel control room operators about a possible aborting of their mission; and if “red” is activated, the ship moves off position regardless of where the ROVs are. In an emergency, the DP operators are expected to revert to just-for-now performance (when they are doing trouble shooting) or to just-this-way performance (when they have to act according to emergency procedures [command and control in Table 3]).

No such emergencies were observed during our study period. Our interviews confirm, on the other hand, that when unexpected events and hazards do occur, DP operators must rely on their experience and expertise to manage the changing risks and requirements that ensue. While undesired incidents with the DP system are not inherently disruptive or failure-inducing, DP operators had experienced problems with the system—again those alarms that they do not fully understand or that do not provide them useful information. Such alarms, it bears repeating, occurred during the period of observation.

Risks change—as does their management—because DP operators do not operate invariantly in one performance mode only during normal operations. Figure 12 sums up the HRM characteristics and performance modes related to the DP operations recorded in our study period. During the observation period of the case (which again was absent emergencies), the crew was approximately 90% of the time in the just-in-case performance mode, and 10% in the just-in-time mode, the latter corresponding to deactivating and activating the DP system. The DP operators during the day shift reported that at least they got to enjoy a nice view of the ocean from the bridge. All the night shift could see was darkness. In these circumstances, the chief risk from the HRM perspective is one of operators’ becoming complacent or inattentive as and when such conditions persist.



HRM characteristics	HRM performance modes of normal operation			
	Just-in-time	Just-in-case	Just-for-now	Just-this-way
Decision options variety	High	High	Low	Low
Task environment volatility	High	Low	High	Low
Procedures and rules	Key situations not covered by procedures, but addressed through experienced team situation awareness	Performing according to standard-normal, established protocols and procedures	Performing reactively and in the moment, typically through quick fixes and short-term expedients	Performing to established command & control procedures
Main operational feature	Real-time flexibility	Positive redundancy	Maximum potential for loss of operator maneuverability	Command and control
Dominant risk	Risk of misjudgement	Risk of complacency and inattention	Risk of losing maneuverability and cascading error	Risk of failing to comply with command and control requirements

Figure 12. The HRM performance modes, our observations, and the resulting dominant risks related to the DP operators during normal operations.

It bears underscoring, however, that a very real challenge posed by the DP system is that its operators may not understand alarms and may not have sufficient response time to mitigate the hazardous events they confront. Misjudgement is very much the HRM risk during these occasions. According to (Lundborg, 2014), the frequency of loss of position of the shuttle tanker (ST) is in the order of 10^{-3}, which is an order of magnitude higher than accepted in the oil and gas industry (Vinnem et al., 2015). For more information of hazardous events and causes related to DP operation, see Dong et al. (2017). To sum up, Table 7 presents the main risks and their presence identified and analyzed in the DP case study.

Table 7. DP case Study LoA and main risks.

HRM characteristics	**DP: LoA 2 - 3**
Risk of misjudgement	Low
Risk of complacency	High
Risk of losing manoeuverability	Might be high
Risk of noncompliance with procedures	Might be high

5. DISCUSSION OF FINDINGS AND POSSIBLE APPLICATIONS

5.1. Case studies´ performance modes

The presence of multiple performance modes in normal operations, combined with the fact that normal operations may be disrupted, or end in failure only to be recommenced later (if at all), pose huge challenges to control center operators and risk management of autonomous marine systems. It must be questioned whether autonomous marine systems, within and across LoAs, facilitate manoeuvering between the different performance modes to maintain normal operations or if they hamper that manoeuverability. A major issue is the degree to which these autonomous systems facilitate or hamper restoration back to normal operations when disrupted.

When systems are developed with increasing autonomous functionality, the expected design advantage is that the probability of human operator error is reduced, and that system performance is generally improved if not transformed. However, removing direct manual tasks from the control operators implies that they end up in a primarily monitoring situation during normal operations (cf. the DP operators), which may lead to human complacency and inattention (the risks of which must also be managed). When a manual intervention by the human operator becomes suddenly necessary, the operator may have to move into the improvisatory just-in-time or the command and control of just-this-way, or, worse, just-for-now performance, where in each mode the risks to be managed for the purposes of reliable and safe operations differ considerably in real time. What were hours of tedium in monitoring DP performance (just-in-case performance) can veer into just-for-now performance where task volatility abruptly becomes higher, human options unexpectedly become fewer, the ability to manoeuvre or escape out of the situation becomes far more difficult, and the risk of temporary or indefinite loss of system operability turns out to be greater than supposed.

The challenges of risk management are not reserved to having multiple performance modes and risks to manoeuvre in order to maintain safe and reliable normal operations. When disrupted or failed operations occur, control operators and support staff have then to ask: Is the restoration of that now-disrupted service back to normal operations done in a reliable and safe fashion? From a high reliability perspective, can we afford the risks in deferred IMR due temporary, let alone indefinite delays?

Such questions and the multiple stages of operations (normal, disrupted, failed) have a profound implication for risk management: When focusing on real-time operations in the ocean environment, the focus of the design and utilization of autonomous marine systems necessarily becomes one of *reducing* their internal task volatility (cf. Section 3) and *increasing* the option decision variety for the human operator *at whatever the LoA*. Indeed, LoAs should increase (rather than decrease) operator decision options and/or reduce (rather than increase) their task volatility—*in real time*.

5.2. Levels of autonomy and HRM performance modes

Table 8 summarizes main risks of the HRM found for the two case studies, as well as important influencing factors identified and involved. The influencing factors can be useful for investigating underlying causes to the dominant or main risks observed in the case studies.

From the perspective of the HRM framework, the starting point in reducing internal task volatility and increasing options is recognizing that the different LoAs in the case studies entail very different risks that have to be managed: with LoA 1 (the ROV case study), the dominant risk was one of operator misjudgement (the prevalence of time spent in just-in-time performance), while with LoA 2-3 (the DP case study), the dominant risk was one of operator complacency or inattention (the prevalence of time spent in just-in-case performance).

These are very different operator risks, because the internal task volatility and the option sets associated with LoA 1 on the one side, and with LoA 2-3 on the other side, differ substantially. These differences matter because, when external conditions change suddenly, initial complacency or initial misjudgement lead to other very different risks and hazards (particularly those of disrupted and failed operations) that have to be managed in real time as well. Reducing or otherwise managing such different risks must be not just considered but also satisfactorily addressed during the design of these systems.

Table 8. Case Study LoA influencing factors, and main risks identified in the case studies.

Influencing factors – case study 1: ROV	**Influencing factors – case study 2: DP**	**HRM characteristics**	**ROV: LoA 1**	**DP: LoA 2 - 3**	**Higher LoA leads to:**
Communication and cooperation. Operational criteria and constraints. Available documention of subsea systems and sea bottom. Planning and onshore support. Use of specialized tools. Environmental conditions on site. Situation awareness. Experience and expertise. Available procedures. Technical equipment specialization. Uncertainties and operating challenges. Incidents and system downtime.	Communication, including ROV control room. Type/phase of IMR operation. DP technical system condition. Environmental conditions on site. Situation awareness/ alarms. Type/phase of IMR operation.	Risk of misjudgement	High	Low	Reduction
		Risk of complacency	Low	High	Increase
		Risk of losing manoeuverability	Low	Might be high	Might increase
		Risk of noncompliance with procedures	Low	Might be high	Might increase

It is true that a DP system enables operations that would scarcely be possible if human operators were to manually position the vessel over long periods of time. However, if alarms are activated in this system with high LoA, the DP operator would want to take over control by manually moving the system into what is effectively a lower LoA. If so, the operator could then enter the just-this-way or just-for-now performance modes. In the former, the operator would try to reduce volatility by complying with command and control procedures to resolve alarms and problems in the absence of any other options being available. In the latter, task volatility may be still high even under manual controls in the face of an unprecedented event or emergency for which there are no command and control procedures. In both cases, even though the operator may have ideally taken over more direct control from the autonomous system (that is, necessitating a lower LoA), there may be limited time available to avoid serious consequences, with the decision options for the operator remaining limited. An important issue regarding the DP autonomous system with its higher LoA is to determe whether it is able to default over to a lower LoA and increase the operator options to respond quickly.

As illustrated in the case study for the ROV with its lower LoA, when conditions are not as planned, the control room crew, including ROV operators and tooling specialists, were often left to improvise by relying on experience to handle the contingencies arising in normal operations. Options variety remained high even when task volatility was high, and the prevailing performance mode is just-in-time. During those latter periods, undesired incidents were observed to occur because of operator misjudgement. In a few instances of the just-for-now performance, the control room crew knew that they were using components or spare parts other than those originally brought onboard for a particular operation, thus risking loss of manoeuverability as component supply ran out. Although performance modes and their main risks change during normal operations, procedures don’t disappear. Even in cases of disrupted/failed operations, operators we observed following the procedures related to aborting operations in the face of unfavourable weather conditions and how to retrieve tools and the ROVs to the deck.

The above contrasts sharply with what occurs when shifting to a higher LoA:

- The frequency of human error related to risk of misjudgement may be reduced with the higher LoA;
- The risk of complacency, however, associated with the higher LoA can result in operators not being sensitive to early signals of critical deviations in the system; and
- Furthermore, if the operation is in a disrupted state or has actually failed, it may be more difficult for the operator to handle the situation, particularly when the higher-LoA system is unable or otherwise more difficult to default to lower LoA controls.

Notice that the concerns raised here are not about the pros and cons of automated technology generally, but are more specifically about different levels of autonomy and their very different risk management implications. Human cognition is at its limits during unforeseen or unexpected events, and cognition is further stressed if higher LoAs afford even less time for operators to manoeuvre than lower LoAs. The mental work load is reduced by higher LoA, but there is evidence that human SA can be affected adversely as well (Lackman and Söderlund, 2013; Lin et al., 2010). More speculatively (cf. Table 8), the risks of operators losing manoeuverability and coping with noncompliant machine or human behavior (i.e., the risks in those demanding performance modes of just-for-now and just-this-way, respectively) may be higher for complex systems in higher LoAs, such as DP. We did not observe these performance modes during the case study of the DP operations nor did we observed DP disrupted or failed operations (though cases were reported to us by the onboard interviewees), but evidence from the literature also supports this caution and cannot be ignored.

An additional concern is that, while software-intensive technological systems, such as DP, require considerable testing, current testing and verification regimes typically focus on single failures, i.e., loss of position, rather than system integration and couplings (Rokseth et al., 2017) differentiated by or across multiple LoAs. Chen and Moan (2005) analyzed DP incidents for mobile offshore drilling units (MODU) on the Norwegian Continental Shelf and found the DP control system to be a cause involved in all drive-off incidents. Dong et al. (2017) assessed DP incidents for shuttle tanker (ST) – floating, production, storage and offloading (FPSO) and concluded that the DP incidents were caused by a combination of technical, human and organizational factors—meaning that technical problems often escalate into undesired incidents through human operators not being able to handle the situation, caused by insufficient HMI and training, for example.

6. CONCLUSION

The most important research finding in this paper is our having observed many different operational states that varied across two or three levels of autonomy, each state of operations having different main risks to be managed by the vessel control room. We have also found important influencing factors to these risks that may be useful for identifying risk reduction measures in the design and operation of autonomous marine systems.

We have shown that the demands on real-time risk management are acute for vessel control operators, not only because the modern intervention vessel has multiple automated systems (we studied only two, the ROV and DP), each of which varies in terms of its LoA. The demands are also challenging because normal operations are open to being disrupted and sometime failed (i.e., the risks associated with restoration or recovery can be severe), while normal operations themselves entail the different risks of complacency, misjudgement, loss of manoeuverability and non-compliance, which require management as performance conditions change under mandates for highly reliable and safe operations.

The results of the research in this paper pinpoint a core contradiction with autonomous marine systems: While the higher autonomy level, the less demand for a human operator; but that demand for the experienced operator is highest during unforeseen contingencies or emergencies, let alone full-blown crises when so little time remains for the operator to take effective action in the face of an already high degree of system complexity. Simulations and operator training are not just necessary, they are imperative and paramount in such conditions.

Our overall recommendation is that when designing systems with functionality in higher LoA, it is essential to consider the main risks for the human operators, decompose and operationalize them, analyze influencing factors and the potential causes of these risks in the relevant system/operation, and further determine how the risks can be mitigated. Where a hostile ocean environment must be taken as given, design transformations and management improvements for marine systems will have to focus more on reducing internal task volatility limiting real-time operator interventions; doing so most certainly requires increasing real-time decision options for the control room operators, including their decision support systems.

Improved decision support systems could improve SA and operational efficiency with respect to autonomous functionalities and decision support in real time. By way of example, the present need for an enhanced ROV operation relates to the hot-stab, where a manipulator arm holding a stabbing tool is applied, as illustrated in Figure 13.

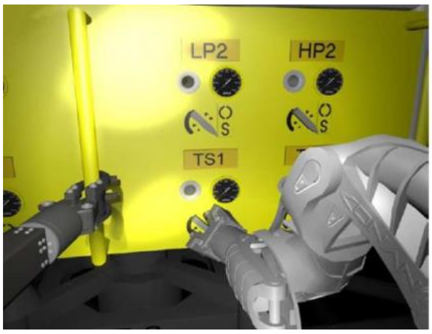


Figure 13. Subsea manipulation task in the NTNU marine cybernetics lab.

The need for such an online risk management and operator decision support system is directly tied to the LoA involved. At present, testing in our own laboratory (NTNU marine cybernetics lab) shows that the medium-trained operator manually performs a hot-stab in 10-120 minutes, but an autonomous function performs the hot-stab operation in less than 30 seconds. The operational efficiency could therefore significantly be improved with higher autonomy; but the time available for human corrective intervention in response to deviations is significantly reduced. From the HRM perspective that places a premium on highly reliable and safe operations, software and hardware must *increase* operator options to respond to deviations. To put the point from the other direction, the design hazard to be avoided is developing and installing an online risk management and decision support system that, while increasing the LoA of the entire system, nonetheless reduces operator real-time options already available at lower LoAs for the operator to intervene when necessary.

It is important that we do not lose a key insight in all this necessary detail, namely: the major role of effective real-time communications—and not just for risk management purposes—in the control room *at both low and high LoAs*. Throughout the study period, communication in the control room was observed to be important, along with the communication to the bridge, the deck area, and between the bridge and engine room. Accordingly, any software or hardware support that improves real-time information and communications within and across the operator crews is to be encouraged *if and only if* it increases options and decreases task volatility—especially internal volatility arising out of technological complexity.

That said, it may be that the future research required confirms a possibly emergent finding from our case studies, namely: Preference for higher LoAs over lower ones requires balancing very different reliability and safety mandates, each with very different risks and costs to be managed. That, though, awaits further work.

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