



HUMAN PERFORMANCE MODELING

FOR MARITIME DESIGN AND OPERATIONS



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INTRODUCTION

Alarms sound. Conditions change. Decisions must be made in seconds.

Whether on a manned bridge or in a remote operations center, human performance remains one of the most important factors in maritime safety. As the industry adopts new technologies, design questions are becoming more difficult: How quickly can an operator respond? How small can a bridge team be without increasing risk? How many autonomous vessels can one remote operator safely supervise before workload becomes a liability?

These are not hypothetical questions. They are design decisions that shipbuilders, operators and Maritime Autonomous Surface Ships (MASS) developers are making right now.

Today, most of these decisions are informed by expert judgment, ergonomic checklists or simulator trials. These methods are valuable, but they share a common limitation: they typically occur after major design commitments have already been made, or after systems are already in operation. By that point, fixing a human performance problem means costly rework, schedule delays or operational workarounds.

Maritime does not need to invent human performance modeling (HPM). It needs to operationalize proven HPM methods for defined maritime use cases such as bridge staffing, remote operations, automation oversight and human-machine interface design, using a framework that is credible, practical and proportionate to risk.

This challenge is not unique to maritime. Other high-reliability industries faced the same challenge decades ago and have developed a solution: human performance models.

HPMs are simulations that predict how people will perform in complex systems before those systems are built. The defense, aerospace and nuclear industries use HPMs to evaluate crew sizing, workload, function allocation and automation interaction as part of the design process. These models have changed design requirements, prevented costly rework and improved safety.

Historically, the human element in system design has been assessed through qualitative data, subjective feedback and observation. While these methods provide useful insight, they can be difficult to quantify, difficult to repeat and difficult to defend when making the case for design changes. HPMs fill that gap by providing measurable, repeatable, scenario-specific predictions of human performance that decision-makers can act on.

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WHAT HUMAN PERFORMANCE MODELS DO

HPM encompasses a range of analytical and computational methods used to represent, predict and evaluate how people perform tasks and interact with systems [Card et al., 1986]. Approaches range from task-based analyses to sophisticated computer simulations, allowing organizations to assess the impact of staffing [Sebok & Plott, 2010], automation [Huey et al., 1990], interface design and operational concepts before implementation. By modeling human tasks, decisions, workload and interactions, HPM provides quantitative measures and actionable insights into system performance, safety and mission effectiveness.

HPMS CAN BE USED TO PREDICT AND EVALUATE:

- **Task timing:** How long it takes a crew to complete a procedure or respond to an event and how performance changes under different operating conditions.
- **Workload:** The cognitive, visual, auditory and physical demands placed on operators, identifying when workload approaches or exceeds sustainable levels.

One widely used approach for predicting workload is the VACP method, which assesses visual, auditory, cognitive and psychomotor demands. The method helps identify when multiple tasks compete for the same human processing channel at the same time, increasing the likelihood of overload [Zhang et al., 2024]. This multi-channel approach reflects an important operational reality: two tasks may each be manageable on their own but become difficult to sustain when performed together if they rely on the same processing resources.

CHALLENGES THAT HPMS CAN ADDRESS INCLUDE:

- **Task conflicts and delays:** When competing demands require an operator's attention simultaneously, this may potentially cause delays, omissions or degraded performance [Wickens, 1991].
- **Staffing sufficiency:** Whether available personnel can safely and effectively accomplish required functions across a range of scenarios.
- **Situational awareness support:** How well displays, alerts and information architectures support operators in perceiving, understanding and anticipating system states.
- **Error-likely conditions:** Where mistakes, delays or missed actions are most likely to occur, and the operational factors that contribute to those risks.

By quantifying the human element, HPM enables decision-makers to evaluate operational concepts, optimize staffing, assess emerging technologies and identify performance risks long before they appear in the real world.

HPMs are strongest for structured, procedural and repeatable activities, and their outputs are generally more reliable for comparing design alternatives than for predicting absolute real-world performance. Subject matter expert input and workload ratings introduce subjectivity, which should be managed through structured elicitation methods and sensitivity analysis. HPM results should support, not replace, simulator trials, operational validation and expert review. Model validity is also scenario-specific; a model validated for one operational context should not be assumed valid for another without additional review. These characteristics make HPMs a powerful decision-support tool, but only as one component of a broader human factors engineering process.



Setting appropriate expectations is essential. HPM is not a replacement for human factors engineering, which encompasses methods such as task analysis, ergonomic assessment and user-centered design. It is not a substitute for simulator validation, which provides empirical data from real operators. It is also not a universal predictor of human error, particularly for knowledge-based and diagnostic tasks. Recognizing these boundaries is essential to using HPMs effectively and credibly.

WHAT AN HPM OUTPUT LOOKS LIKE

HPMs produce quantitative data that can be compared across alternative designs, staffing concepts, procedures, or levels of automation. Depending on the modeling approach, outputs may include task timelines, workload profiles, staffing utilization, task delays, performance variability and mission outcomes [Wickens et al., 2007]. The goal is not to treat illustrative values as precise predictions, but to compare concepts consistently across repeated simulations.

For example, consider a simplified bridge crew workload analysis during a port approach scenario.



METRIC	4-PERSON CREW	3-PERSON CREW	DIFFERENCE
Mean peak workload for officer of the watch (OOW)	18.4	27.6	50%
Tasks delayed per scenario	0.3	4.7	1,467%
Tasks dropped per scenario	0.0	1.2	—
Runs where OOW exceeded overload threshold	8%	61%	53%
Scenario completion time	62.4 minutes Standard deviation 4.1	68.9 minutes Standard deviation 7.3	10%

Crew Comparison (100 simulation runs per variant)
Values are illustrative and provided for demonstration purposes.

Even in this simplified example, reducing bridge staffing increases operator workload, delays task execution, raises the likelihood of overload and lengthens scenario completion time. Rather than relying on assumptions or subjective assessments, HPM provides quantitative evidence that allows stakeholders to evaluate tradeoffs and identify performance risks before implementation.

When interpreting workload outputs, it is useful to distinguish between workload amount and workload intensity. The workload amount reflects the total demand for a set of tasks. Workload intensity reflects that demand relative to the time available to complete it. The same total workload spread across a full watch presents a very different challenge than the same workload compressed into a ten-minute port approach

phase. HPM workload timelines capture this distinction by showing how demand concentrates or spreads across the operational timeline, making it possible to identify not just whether workload is high, but when and for how long.

This ability to compare alternatives in a repeatable, data-driven manner is one of the primary strengths of HPM. It enables organizations to assess concepts, procedures, staffing models and system designs before hardware is built; software is deployed, or operators enter a simulator.

HOW OTHER INDUSTRIES USE HPMS

HPM is not an emerging or experimental practice. For decades, defense, aerospace and nuclear power industries have used HPMS to inform decisions involving staffing, automation, operator interfaces and system design. In many cases, these models have influenced requirements, reduced development risk and provided quantitative evidence before costly prototypes or operational testing were conducted.



DEFENSE: CREW SIZING AND FUNCTION ALLOCATION

The United States (U.S.) Department of Defense has incorporated HPMS into the MANPRINT (Manpower and Personnel Integration) process for decades [Booher & Hewitt, 1990]. These models are routinely used to assess crew sizing, workload, function allocation, training requirements and automation concepts during system acquisition.

In one widely cited example, task-network modeling was used to evaluate two- and three-soldier crew concepts for a mounted combat platform. The analysis predicted unacceptable workload levels for the two-person crew across much of the mission profile. Based in part on these findings, the Army adopted a three-person crew requirement for the system [Mitchell et al., 2003]. This demonstrates how HPMS can inform major design decisions before systems are operationalized.

The Army Research Lab has also used HPM to address reduced manning issues for naval ship operations [Archer et al., 1996]. Similar approaches have been applied extensively to unmanned aerial vehicle (UAV) operations, where HPMS are used to determine how many systems a single operator can supervise and to identify the workload conditions that lead to degraded performance [Humann & Spero, 2018]. These challenges closely resemble those emerging in maritime remote operations centers and autonomous vessel supervision.

The principal takeaway for maritime stakeholders is that the underlying human performance challenges associated with reduced crew sizes, remote operations and multi-vessel oversight have already been addressed in the defense sector. Mature methods, assessment frameworks and validation processes are available and can be leveraged immediately. The opportunity is not to reinvent these approaches, but to tailor them to the unique operational demands, mission profiles and workforce configurations of the maritime domain.

AEROSPACE: DISPLAY DESIGN AND SITUATIONAL AWARENESS

National Aeronautics and Space Administration (NASA) developed integrated HPM environments that combine task modeling, cognitive architecture and 3D visualization to evaluate crew station designs before building physical prototypes [Gore, 2011]. These

tools simulate how operators scan displays, allocate attention, manage workload, maintain situational awareness and make errors.

A key capability is the modeling of attention allocation by predicting where operators will look and what information they will notice based on measurable display properties (saliency, effort to shift gaze) and task characteristics (information update frequency, task importance) [Santiago-Espada et al., 2011]. This allows designers to compare alternative display layouts and alarm configurations based on predicted operator awareness, not just compliance with ergonomic guidelines.

By predicting where operators focus their attention and how quickly they recognize critical information, aerospace HPMs allow designers to compare display concepts before constructing physical prototypes. This reduces development costs while improving situational awareness and operator effectiveness.

For maritime, this means HPMs can evaluate not only staffing levels, but also whether bridge displays, alarm configurations and MASS remote operations center interfaces actually support operator awareness under realistic conditions. Display design decisions currently rely on ergonomic guidelines and expert review.

Attention-based HPM methods can augment current practices and offer a way to compare alternative layouts quantitatively before hardware is committed.

NUCLEAR: VALIDATION AND REGULATORY INTEGRATION

The nuclear industry provides perhaps the most relevant example for maritime adoption. Recognizing the growing use of HPMs in staffing and human reliability analyses, the U.S. Nuclear Regulatory Commission (NRC) developed formal guidance governing model verification, validation and application [O'Hara, 2009].

Nuclear experience demonstrated that HPMs can reliably predict procedural and rule-based activities when properly validated against empirical data. Equally important, it highlighted where models are less effective, particularly for complex diagnostic and judgment-intensive tasks. This balanced understanding of both capabilities and limitations has enabled HPMs to be used as a decision-support tool rather than a replacement for human testing.

The NRC's verification and validation framework provides a proven template that could be adapted for maritime applications.



Across defense, aerospace and nuclear power, HPMs have matured from research tools into practical engineering tools. These industries use HPMs to evaluate staffing levels, assess automation concepts, optimize operator interfaces and identify performance risks long before systems reach operational testing. The challenges now emerging in maritime operations include reduced crewing, increasing automation and remote vessel supervision. These challenges are the types of opportunities HPMs were developed to address.

For maritime, the nuclear lesson is less about the modeling tool and more about credibility: HPM adoption requires explicit verification, validation and defined limits of use. Without a structured verification and validation (V&V) process, HPM outputs are difficult to defend in design reviews, regulatory submissions or safety cases. Establishing a maritime-specific V&V framework is a prerequisite for HPMs to be accepted as engineering evidence.

Taken together, these examples show that HPMs are not speculative tools. They are established engineering methods whose relevance increases when systems become more automated, staffing becomes leaner and assurance expectations become more demanding.

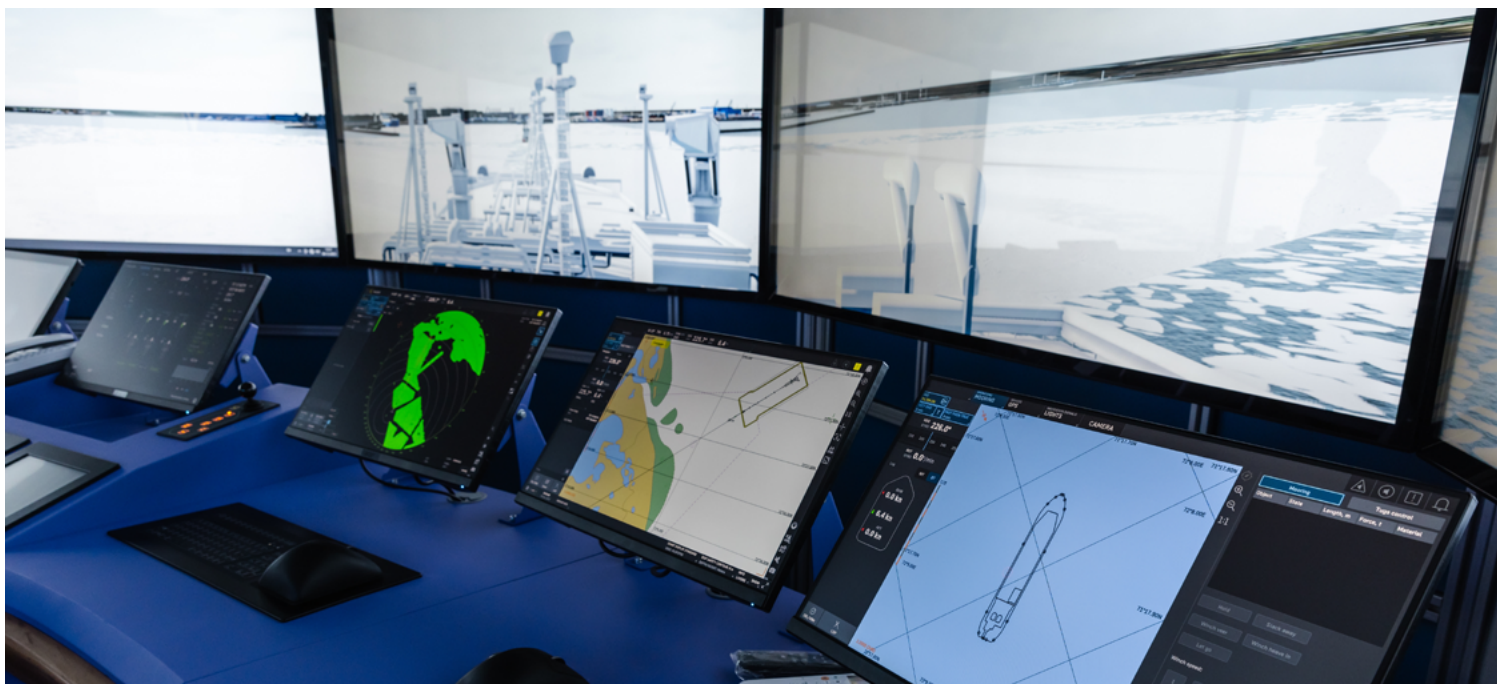
WHY MARITIME NEEDS HPMS NOW

Maritime automation is not just adding new equipment to the bridge; rather, it is fundamentally changing the role of the human operator. As vessels become increasingly automated, operators are shifting from direct control to supervisory oversight, where they must monitor automated systems, maintain situational awareness, detect anomalies and intervene when automation reaches its limits.

This transition introduces well-known human factors challenges, including automation complacency, reduced situational awareness, skill degradation, automation surprise and vigilance loss during extended monitoring periods. These risks emerge from the interaction between human operators and complex systems and cannot be adequately assessed through checklists or expert opinion alone. They require a systematic approach that predicts how people will perform under realistic operational conditions.

These drivers also intersect with the maritime industry's primary operational governance framework: the Safety Management System (SMS). The International Safety Management (ISM) Code requires maritime companies to establish an SMS covering hazard identification,





risk assessment, safe operating procedures, adequate manning, emergency preparedness and continuous improvement. HPMs can strengthen these processes by providing scenario-specific workload predictions, supporting procedure evaluations and helping identify human performance risks before incidents occur.

Framing HPMs as strengthening existing SMS processes, rather than creating new ones, may be the most practical path to adoption.

THE QUESTIONS ARE GETTING HARDER

The design and operational questions facing the maritime industry are becoming more complex:

- **How many vessels can a remote operator supervise?** The answer depends on traffic density, automation reliability, alarm frequency, communication delays and human cognitive limits.
- **Can bridge crews be reduced without increasing risk?** The answer depends on task demands, timing, workload distribution and the crew's ability to manage concurrent activities.
- **Will a new bridge display improve performance?** The answer depends on how effectively operators can locate, interpret and act on critical information.
- **Can an operator regain situational awareness quickly enough during a takeover from an autonomous system?** The answer depends on how information is presented, the complexity of the situation and the time available to respond.

Answering these questions also requires defining what “acceptable” performance looks like for each situation. Research across multiple industries has shown that there is no single workload threshold above which all operators fail and below which all operators succeed. Human operators adapt their strategies, reprioritize tasks and adjust their approach to maintain performance across a range of workload conditions, until the limits of their flexibility are reached, and performance degrades sharply. This means that workload limits should be set based on the criticality of the task being evaluated. A safety-critical function such as collision avoidance demands a more conservative threshold than a routine administrative task. HPMs support this approach by allowing analysts to apply different performance criteria to different parts of the operational scenario and evaluate the consequences quantitatively.

These questions cannot be answered reliably through intuition alone; they require structured evidence generated through established methods. HPMs provide a means to generate evidence early in the design process, when changes remain practical and affordable.



THE REGULATORY ENVIRONMENT IS EVOLVING

Emerging frameworks for Maritime Autonomous Surface Ships (MASS) increasingly emphasize the ability of human operators, whether aboard the vessel or ashore, to maintain situational awareness, respond effectively and assume control when required [IMO, 2026].

The challenge is not recognizing the importance of the human element; it is demonstrating that human performance requirements have been met. HPM offers a structured, repeatable and defensible method for generating evidence and evaluating alternative designs before entering service.

Organizations that can support design and operational decisions with quantitative human performance data will be better positioned than those relying solely on qualitative assessments and expert judgment.

As assurance frameworks develop, stakeholders may increasingly need to demonstrate not just that a system functions technically, but that operators can monitor it, understand it and intervene effectively under realistic conditions. Specifically, emerging evidence expectations may include demonstrations of takeover capability within defined time windows, workload acceptability across the range of credible operating conditions, situational awareness support under degraded or high-traffic scenarios, staffing sufficiency during abnormal and emergency conditions and alarm management performance under realistic alarm loads. HPMs provide a structured method for generating this evidence across far more scenarios and conditions than simulator trials alone can practically cover. Organizations that establish HPM capabilities now will be better positioned to meet these expectations as regulatory and classification frameworks mature.

THE COST OF GETTING IT WRONG

Human-system integration problems are among the most expensive and disruptive deficiencies to correct after deployment. A bridge layout issue discovered during sea trials, a manning concept that proves unsustainable in operation or an automation design that creates unexpected operator workload can require costly redesigns, retraining and operational workarounds.

HPMs allow these risks to be identified when they are still inexpensive to address. Modifying a task model or evaluating an alternative staffing concept during design takes days. Redesigning hardware, procedures or operational concepts after deployment can take months and cost millions.

WHAT MARITIME ALREADY HAS

The maritime industry is not starting from zero. Rather, many of the building blocks needed to support HPM already exist across industry guidance, research programs and operational practice.

- Human-centered design guidance: Frameworks such as the ABS Guidance Notes on Ergonomic Design of Navigation Bridges provide established principles for function allocation, workload management, situational awareness and bridge design.
- Maritime human factors research: European initiatives including CASCADE, CyClaDes and FAROS have explored cognitive modeling, crew-centered design, human reliability and the human implications of increasing automation.
- MASS-focused studies: Academic and industry research continues to advance understanding of seafarer workload, cognitive demands, remote operations and human-system interaction in MASS concepts.
- Modeling tools and prototypes: Open-source tools such as SimManning have demonstrated the feasibility of applying discrete-event simulation and other modeling methods to maritime manning and workload assessments.

As maritime systems become more automated, more connected and more dependent on human oversight, the ability to predict human performance before implementation will become increasingly valuable. HPM provides a practical way to make those predictions and reduce risk before it reaches the bridge, the operations center or the fleet.

- Transferable methods from other industries: Task-network models, workload prediction methods, cognitive architectures and attention-allocation models have been successfully applied in defense, aerospace and naval operations and are readily adaptable to commercial maritime applications.

These efforts demonstrate that the underlying concepts, methods and tools are already available. However, what remains absent is a cohesive framework that integrates them into a practical maritime methodology.

Maritime lacks a common approach for selecting modeling methods, establishing model credibility, validating predictions, defining acceptable use cases, incorporating HPM results into design reviews and decision-making. Establishing that framework would allow the industry to move beyond isolated studies and toward the systematic use of HPMs as an engineering and assurance tool.

Such a framework would not require inventing new modeling techniques. Rather, it would adapt proven practices from defense, aerospace and nuclear power to the unique operational, regulatory and safety challenges of the maritime domain.

A PATH FORWARD

A phased approach is recommended to integrate HPM into maritime design and operations. While the industry already possesses many of the technical building blocks, broader adoption will require common practices, shared resources and a clear understanding of where HPMs can provide the greatest value. As the industry moves toward adoption, HPMs should be integrated into existing safety management processes rather than treated as a standalone method. Organizations can begin by mapping HPM outputs to specific SMS processes: workload and error-likelihood data into risk assessments, task timing into procedure evaluations and performance risk identification into continuous improvement cycles.

1. ADOPT HPMS AS A DESIGN-SUPPORT METHOD

HPMs should be used as a quantitative complement to established human factors engineering practices. Rather than replacing task analysis, ergonomic assessments, or simulator testing, HPMs extend these methods by providing predictive insights early in the design process.

Priority applications include:

- Manning and staffing analysis
- MASS remote operations center design
- Bridge and control room display evaluation
- Function allocation between humans and automation
- Procedure development and assessment
- Human reliability analysis
- Integrated system validation

2. ESTABLISH A VERIFICATION AND VALIDATION FRAMEWORK

For HPM outputs to be trusted and used in design, operations and decision-making, the industry will need a structured approach to model verification and validation. Experience from defense, aerospace and nuclear power demonstrates that model credibility depends on clearly defining a model's intended use, verifying that it has been correctly implemented and validating its predictions against empirical data where appropriate.

Developing maritime-specific guidance for HPM verification and validation will be an important step toward broader adoption and acceptance.

3. DEVELOP MARITIME-SPECIFIC RESOURCES

Broader adoption will require a common set of maritime resources that support model development, calibration and validation, including:

- Task libraries: Standardized representations of bridge, engine room, cargo and remote operations tasks
- Scenario templates: Representative operational scenarios that enable consistent and repeatable analyses
- Referent databases: Collections of workload, timing, performance and human reliability data that support model calibration and validation

These shared resources would reduce development effort, improve consistency and increase confidence in model results across the industry.

4. APPLY HPMS TO MASS ASSURANCE

Evidence from HPMs can help demonstrate that human operators, whether aboard ships or ashore, can maintain situational awareness, manage workload and execute effective intervention when required.



HPMs can provide quantitative evidence supporting the design and evaluation of remote operations centers, takeover procedures, alarm management concepts, staffing levels and human-automation interfaces across a range of operating conditions.

CONCLUSION

HPM is not a new technology. It is a mature and proven methodology that has been used for decades in defense, aerospace and nuclear power to evaluate human-system performance, reduce design risk and support critical engineering decisions.

Today, the maritime industry faces many of the same challenges that drove HPM adoption in those sectors: increasing automation, evolving operator roles, reduced manning and growing expectations for demonstrating human-system performance before deployment. The modeling methods, tools and validation practices needed to address these challenges already exist. What has been missing is a maritime-specific framework that brings them together into a coherent and practical approach.

The opportunity for applying HPM applications in the maritime industry is significant. HPMs can help maritime stakeholders evaluate staffing concepts,

design human-centered systems, assess automation strategies and identify performance risks long before they appear in sea trials or operational service. Not all HPM applications are equally mature or equally ready for maritime adoption. A tiered approach can help organizations prioritize:

NEAR-TERM, PRACTICAL STARTING POINTS:

- Manning and staffing analysis
- Bridge and control room workload evaluation
- Procedure assessment under normal and emergency conditions

MEDIUM-TERM APPLICATIONS:

- Interface and alarm management assessment
- Remote operator workload distribution and multi-vessel supervision analysis

LONGER-TERM AND ADVANCED APPLICATIONS:

- Situational awareness prediction using attention-based models
- Takeover readiness evaluation for complex autonomous operations
- Knowledge-based decision modeling using cognitive architectures



Starting with near-term applications allows the industry to build experience, develop maritime-specific resources and establish credibility before progressing to more complex modeling approaches. By moving critical human factors questions earlier in the design process, HPMs can reduce uncertainty, lower development costs and improve the safety and effectiveness of future maritime systems.

The maritime industry's challenge is no longer recognizing that the human element matters. The challenge is evaluating it early enough, rigorously enough and consistently enough to influence design before risk becomes expensive to correct. HPM offers a practical way to do that.

This white paper represents a first step toward establishing a maritime-specific framework. ABS invites shipowners, operators, designers, technology developers, regulators, researchers and classification societies to participate in building a maritime HPM capability that is credible, practical and fit for purpose. The industry's most important future decisions will increasingly depend not only on what technology can do, but on how people perform when working with it. HPM provides a means to evaluate that interaction before those decisions become costly to change.



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