Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p24055-cd

Systemic Human Factors Analysis of Hydrogen Fuel Supply in Maritime Operations: Integration Concept of STPA, SLIM, and BN

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The adoption of alternative fuels such as hydrogen introduces complex safety challenges in maritime operations, making the integration of human factors essential. Human performance, seafarer capability to operate novel equipment, and interactions with emerging automation significantly influence operational safety. In addition, the unique properties of hydrogen present occupational hazards that heighten risks during shipboard operations. Therefore, human factors must be a central element in analyzing the safety of hydrogen-powered ships. Furthermore, most of the studies still utilise the linear accident causation method, which will neglect the complex socio-technical relationship between the human as the operator, control logic, and the components. Therefore, the adaptation of the novel technologies of hydrogen in the ship should be analyzed in a systemic approach. This study conducts a safety analysis of hydrogen-fuel supply in maritime operations by applying the System-Theoretic Process Analysis (STPA) to identify potential unsafe human actions and their interactions with other system components. These unsafe actions and loss scenarios are then linked to relevant human Performance Shaping Factors (PSFs), enabling a structured understanding of the human contribution to system risks. To provide a quantitative assessment, Bayesian Networks (BN) and the Success Likelihood Index Method (SLIM) are integrated to estimate the probability of human control action within the systems. The findings of this study will support the evaluation of human performance in operating emerging hydrogen technologies on ships and inform the development of regulatory measures and training programs. Ultimately, the results aim to bridge safety gaps and strengthen the safe implementation of decarbonisation strategies in the maritime sector.

Keywords: Hydrogen, STPA, SLIM, BN, decarbonization

1. Introduction

Hydrogen is emerging as one of the cleanest alternative fuels due to its zero emissions, which is aligned with the goal of net-zero emissions of maritime transportation in 2050 (Alavi-borazjani, Adeel, and Chkoniya 2025). However, hydrogen also poses hazards such as fire and explosion due to its narrow flammability range and higher burning velocity (Jeong et al. 2025). Moreover, the cryogenic features of hydrogen will lead to embrittlement if there is a leakage (Park et al. 2025). With those hazardous properties of hydrogen both in LH_2 and CH form, the safety and prevention of the hazards and risks of the hydrogen operation are essential.

The current risk analysis landscape for hydrogen as a maritime fuel generally follows two complementary directions. The first focuses on preventing system failures that may lead to hazardous conditions such as leaks or loss of containment. The second addresses the consequences once a leak occurs, examining dispersion behaviour and the likelihood of subsequent fire or explosion. For the first focus, several method that have been utilised in hydrogen risk analysis, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) to analyse the general risks of hydrogen-powered ships (Berkehan and Emre 2026), safety barriers in hydrogen bunkering (Tamburini et al. 2024), Failure Modes Effect and Analysis (FMEA) for marine propulsion system (Wang et al. 2025), hydrogen bunkering with dynamic reliability (Choi and Jeong 2026). Bayesian Network (BN) has also been utilized in hydrogen risk analysis in the maritime sector for hydrogen fuel system leakage (Li et al. 2025), leakage from the fuel cells (Kang et al. 2025). Meanwhile, for the second focus, Computational Fluid Dynamics (CFD) is the main method, since it emphasises the LH_2 and CH dispersion analysis (Qin et al. 2026).

Across the existing literature, two key gaps remain. First, the majority of the studies still rely on linear, event-chain risk methods, even though shipboard hydrogen operations are expected to be highly automated and mediated through extensive sensors, alarms, and HMIs. This creates a socio-technical system where risk emerges from human–automation interaction, feedback, and control authority, not only from isolated technical failures, yet current approaches often lack the detail needed to analyse these interaction-driven deficiencies. Second, despite the continued importance of the human element in decarbonisation, human performance in hydrogen operations is underexamined in current risk analyses. Given that human factors remain a major contributor to maritime accidents, uncertainty around human performance is likely to be a significant contributor to risk in decarbonized operations.

To address the limitations of linear, event-chain risk models, System-Theoretic Process Analysis (STPA) offers a systemic alternative that treats safety as a control problem (Leveson and Thomas 2018). Rather than focusing only on component failures, STPA identifies how accidents can emerge from unsafe interactions among humans, automation, procedures, and the physical process, and it frames prevention in terms of enforcing system safety constraints. STPA has been increasingly applied in the maritime domain, even in the hydrogen hazard identification (Sumon et al., 2024), and recent studies have also explored ways to quantify STPA outputs to support risk-informed decision making. However, within maritime applications, quantification is still underdeveloped: some STPA-based quantitative studies tend to reduce unsafe control actions to a single dominant causal factor, which conflicts with the systemic principles of system theory. Consequently, a more explicitly systemic approach is needed to quantify the loss-scenario pathways that lead to unsafe control actions.

To address these gaps, this study proposes a conceptual risk assessment approach for hydrogen maritime operations that explicitly represents the human role within the socio-technical control structure. STPA is applied to identify hazards and safety constraints, and to define unsafe control actions as failures to enforce those constraints under specific operational contexts. Success Likelihood Index Method (SLIM), integrated with a Bayesian Network (BN), is then used to quantify the likelihood of inadequate human supervisory control given performance shaping factors and operational context.

2. Material and Methods

2.1. *General Framework*

This study consists of two main methods. The first method, which is STPA, has the objective of conducting hazard identification in the risk management process. The system boundaries, such as losses, accidents, and hazards, were obtained, and the system control structure, which comprises of controller, actuator, control actions, and feedback, was determined. After that, the Unsafe Control Actions (UCA) of the control actions were derived. Then, the loss scenarios, as the last step of STPA, which is based on a human controller model of cognitive aspects of information processing, mental model processing, and the decision-making process, were formulated.

The second method is to integrate the SLIM method with the results from STPA, which is the loss scenario. To conduct that, each scenario is mapped with the Performance Shaping Factors (PSF) that are associated with it. In this study, only the direct PSFs that are related to the scenario were examined. After that, the SLIM-BN model can be generated by mapping each PSF to the scenarios, then the SLIM calculation will be conducted to determine the likelihood of scenario mechanism, and then the probability of human inadequate control action with the systemic context can be estimated. Since this study only performs the concept of the integration method, the quantitative aspect with real data is not covered.

2.2. *STPA*

In this study, STPA was selected because it is well-suited to identifying hazards that arise from interactions within complex systems, not only from individual component failures (Gomola and Bouwer Utne 2024). The shipboard hydrogen distribution arrangement can be considered a complex socio-technical system: it is remotely operated and relies on multiple sensors, alarms, and HMIs, where human–automation coordination and trust directly influence how control actions are taken (Sumon et al. 2024). As a result, system deficiencies are unlikely to be explained by a single failed component alone; they more often emerge from unsafe interactions, inadequate feedback, or mismatches between system behaviour and the operator's understanding of the system state.

2.3. *SLIM*

The Success Likelihood Index Method (SLIM) is one of the human reliability analysis methods that has been utilised due to insufficient real accident data or resources (Tekeli et al. 2024). SLIM was first proposed by Embrey et al. (1984), with the method being based on the analysis of human error in task-based activities, with the influence of PSFs' relevance and rating, which is based on expert judgment. SLIM has the advantage when it is used for specific and detailed scenarios, which are suitable for STPA analysis (Kayisoglu, Gunes, and Bal 2022).

The first step of the SLIM is to estimate the Success Likelihood Index (SLI) by calculating the weight of PSFs (W) to the task and the rating of the PSF to the task (R), based on the expert's value, by Eq.1. Then the Human Error Probability (HEP) in logarithmic terms can be calculated by Eq.2, while the value of a and b can be determined by two tasks with highest and lowest SLI.

$$SLI = \sum_{i=1}^{N} Wi \,.\, Ri \qquad (1)$$

$$Log\,(HEP) = a\,SLI + b \qquad (2)$$

2.4. *SLIM-BN*

SLIM-BN was proposed by Abrishami et al. (2020) to deal with a common weakness of conventional SLIM: it often treats human failure events as independent, even when they share the same PSFs, and it handles PSF ratings as fixed values even though, in practice, they are uncertain. BN helps because it can represent these dependencies explicitly and carry uncertainty through the model (Abrishami et al. 2020). As new information becomes available, such as better evidence about PSF conditions or operational observations, the model can be updated using Bayesian inference, and sensitivity analysis can be used to highlight which PSFs are more significant to the PSFs.

3. Case Studies and Results

3.1. *System Boundaries and Definitions*

For the STPA in this study, the system is based on the hydrogen fuel distribution system, adopted from EMSA (2025), which is depicted in Figure 1. The system boundary is set around the shipboard LH_2 fuel storage and distribution arrangement associated with the Tank Connection Space (TCS). Safety and protective functions within the boundary include the Pressure Relief Valves (PRV) and vent line routing to the vent mast, the TCS ventilation arrangement (to maintain a safe atmosphere within the enclosure). Interfaces at the boundary include hydrogen input from the bunkering manifold and hydrogen delivery to consumers (treated as downstream demand outside the detailed process dynamics), while the analysis focuses on how control and feedback within the TCS, venting, and isolation functions interact to prevent releases, trapped hydrogen, and unsafe discharge conditions.

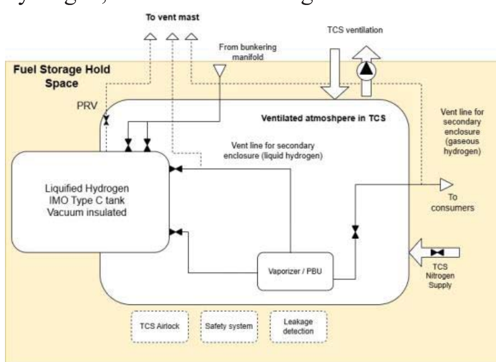

Fig. 1. The diagram of the fuel distribution system in a hydrogen-powered vessel(EMSA 2025)

3.2. *STPA Process*

3.2.1. *Losses, Accidents, Hazards and System Constraints*

The loss in the system is categorised as the consequences to the people, vessels, environmental damage, as the hydrogen explosion can harm the environment, and major operational disruption.

In STPA, a hazard is defined as an unsafe system state, a condition that exists when safety constraints are not enforced, rather than a generic label for an accident outcome. By contrast, the "hazards" listed in the EMSA report often describe accident/incident events or accident precursors (e.g., fire/explosion, gas-freeing incidents) rather than the underlying hazardous system states. For this reason, in the present study, the EMSA hazard list is re-interpreted at the accident level in the STPA hierarchy, such as: (1) Hydrogen fire in or near TCS area, (2) Explosion and overpressure in TCS area, (3) High-pressure jet fire from piping and valve rupture, (4) Vent mast flame, (5) Major loss of containment of LH_2, (6) Rupture of piping/component due to trapped-volume overpressure. Meanwhile, the hazards in the system are explained in Table 1. To counteract the hazards, there are several system safety constraints that should be adhered to prevent any hazardous circumstances, which are stated in Table 2.

Table 1. Hazardous condition in the hydrogen fuel distribution system

Hazardous condition ID	Hazards description	Relationship with accidents
H-1	A flammable LH_2 mixture exists in the TCS or a connected enclosed space	A-1, A-2
H-2	Uncontrolled hydrogen release into a confined region	A-1. A-2, A-5
H-3	Hydrogen release routed to an unsafe discharge location, forming a hazardous jet cloud.	A-3, A-1, A-2
H-4	Trapped cryogenic volume exists without an effective relief path	A-3, A-5, A-6
H-5	Hydrogen is discharged via the vent mast under the condition is not assured.	A-4
H-6	The fuel distribution system operates with invalid, unavailable, or misleading safety information.	A-1, A-2, A-3. A-4, A-5

Table 2. System constraints to be enforced by systems

System constraint ID	Systems constraints
SC-1	The system should restrict the formation or persistence of a flammable hydrogen mixture in the TCS or enclosed spaces.
SC-2	The system should prevent uncontrolled hydrogen release into confined regions.
SC-3	The system shall ensure that any hydrogen release or discharge is routed only to a verified safe discharge.
SC-4	The system shall prevent trapped cryogenic volumes without an effective relief path.
SC-5	The system shall ensure vent discharge occurs only under conditions where safe dispersion and ignition are assured.
SC-6	The system shall maintain the availability, integrity, validity, and usability of safety-critical information (status of the systems)

3.2.2. Safety Control Structure

Figure 2 illustrates the control structure of the system. Since the LH_2 distribution is fully operated, the human operator team is operating from the remote-control center in the vessel, mainly in the engine control room. The human operator mainly controls the system through the Central Control Unit (CCU), and it transmits the control action to the physical equipment, such as valves, bunkering manifold, vaporizer, ventilation, PRV and vent mast. The feedback is given via the internal and external sensors within the internal control system, and when there is an unconformity, leakage, high pressure, or high concentration of H_2, the sensors will automatically generate an Alarm to send the feedback to the Human operator team. The operator team is also responsible for executing manual Emergency Safety Devices (ESD) activation if the CCU is in the failure mode, to automatically close all the valves during the fuel distribution process.

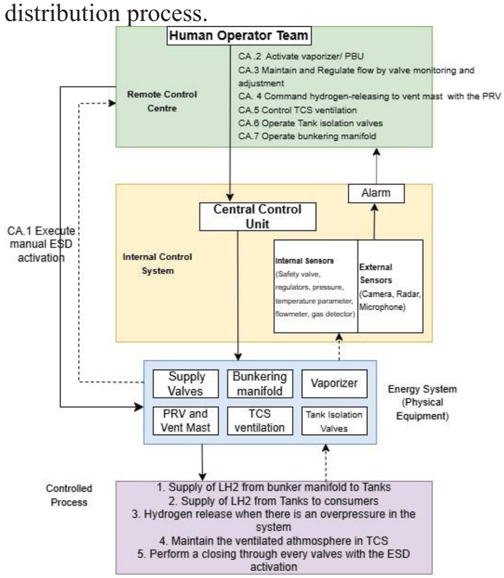

Fig. 2. The safety control structure of the system

3.2.3. Unsafe Control Actions (UCA)

Based on the STPA guidelines, the UCAs are the conditions under which the control action fails to enforce the safety constraints. There are four types of UCA, which are not providing, providing causes a hazard, too early or too late, and stopping too soon, or applied too long. UCAs should be formulated as context-dependent failures of safety-constraint enforcement, grounded in the system's operational mode and state. This approach supports a socio-technical control perspective by explicitly capturing how interactions between human operators, automation, procedures, and process dynamics shape risk during hydrogen operations. Table 3 shows an example of the UCAs from CA1.

Table 3. The Unsafe Control Actions for CA1 (Execute manual ESD activation)

Control action	Not providing causes hazards	Providing causes a hazard	Too early, too late, out of order	Stopped too soon, applied too long
CA 1 (Execute manual ESD activation)	(UCA 1.1) ESD is not initiated during the central control unit failure during the abnormal conditions (rising pressure, trapped volume, leakage), allowing continued operation in an unsafe state (H-1,2,4,6)	(UCA 1.2) Manual ESD initiation is executed within the safe condition of H2 concentration, creating a trapped volume in the valve and piping system	(UCA 1.3) Manual ESD initiation is delayed due to an inappropriate decision threshold to rely on automatic ESD or manual activation, allowing escalation before a safe condition is achieved	(UCA 1.4) ESD status is cleared before all hazards are eliminated, enabling re-entry into unsafe conditions

3.2.4. Loss Scenarios of UCA

According to the STPA Handbook, loss scenarios can be developed in two main ways. The first type explains why an unsafe control action occurs, focusing on the controller's process model, control logic or decision-making, and the feedback provided by sensors. The second type explains why a control action is not executed or not executed as intended, with emphasis on the control path, actuator behaviour, and the response of the controlled process. As this study focuses on human influence within the system, the analysis concentrates on the first type of loss scenarios, which capture how human understanding, decision-making, and feedback interpretation contribute to unsafe control actions.

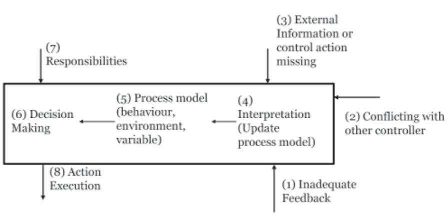

Fig. 3. The proposed human controller model with several control flaws

To generate the causal factors of loss scenarios, this study developed a framework to generate scenarios of human controller based on human information processing cognitive factors such as receiving information, interpretation and update the process model, decision making, and action execution and with the addition of systemic control aspects such as, conflict with other controllers, external information missing, conflicting responsibilities, and inadequate feedback, which is illustrated in Figure 3.

In this study, the UCA 1.1 will be selected as the example, and the details of the scenarios (S1-UCA1.1) are: *During an abnormal condition indicating hydrogen release (e.g., leak/LOC alarms or rising concentration), the operator team does not recognise that the CCU has not executed the ESD command. Because the HMI provides ambiguous confirmation and the team expects automatic ESD to function, they maintain the process model "ESD active / system safe," delaying manual escalation and allowing the hazardous state to continue.*

3.3. *Integration of STPA and SLIM-BN*

3.3.1. General Approach

The purpose of integrating STPA and SLIM in this study is to quantify the likelihood that the human control action fails to enforce the relevant safety constraints under a defined socio-technical operating context (*P(H-UCA$_i$))*.

The methodological challenge is that SLIM is traditionally task-based, whereas STPA frames safety in terms of control and feedback within a socio-technical system. To bridge this gap, each UCA is reformulated as a conditional human control failure event tied to an explicit control responsibility and triggering conditions. For example, for the UCA1, the event is defined as: failure to initiate and sustain an ESD-driven safe state when safety-critical triggering conditions exist, such as leakage, overpressure, under-degraded automation or CCU failure.

In this study, a two-stage quantification strategy is adopted in which STPA loss-scenario mechanisms are quantified first**,** and the UCA likelihood is then derived from those mechanisms. These STPA loss scenarios are then used to justify which PSFs are relevant and to support PSF weighting; SLIM is applied at the loss-scenario level to estimate *P(S$_k$)*, the conditional likelihood of the loss scenario mechanism being present given the PSFs and operational context. The resulting scenario likelihoods are subsequently combined within a Bayesian Network to estimate *P(H-UCA$_i$)* by modelling how one or more loss-scenario mechanisms can produce the unsafe control action as a failure to enforce the safety constraint.

3.3.2. Loss Scenarios to SLIM PSFs

The likelihood of human control action failure is derived through STPA loss scenarios, particularly those reflecting human information-processing and cognitive mechanisms, which can be influenced by PSFs in a manner consistent with SLIM's underlying concept. While any PSF could theoretically affect human performance, this framework treats PSFs as contextual influences whose impact on UCA occurrence (or human control action failure) is realised through the specific loss-scenario mechanisms, rather than if all PSFs directly influence every UCA.

In this case, there are 9 SLIM PSFs that are selected based on the remote operation of the hydrogen fuel supply in ship operations. The PSFs also compared and elicited from other SLIM studies, especially those that are related to LNG (Tekeli et al. 2024) and autonomous vehicles (Liao, Chen, and Quiao 2024), which will have a similar context to this study's operation. The 9 PSFs are: (1) Human-System Interface (HMI); (2) Human-automation trust; (3) Organizational and procedure; (4) Training and competence; (5) Time pressure; (6) Workload, complexity, and stress; (7) Working condition; (8) Coordination and communication; (9) Remote operation and situational awareness limitation.

The next step is to associate the scenario with the PSFs to determine the PSFs that are related to the loss scenario. In this step, the expert judgment will be needed to assess the relevance level of the PSFs to the scenarios. Table 4 shows an example of determining the PSFs that are related to the scenarios with reasoning.

Table 4. The example of associating the PSFs with the scenarios

Scenarios	PSFs	Reasoning
(S1-UCA1.1)	PSF1, PSF9, PSF2, PSF8	The scenario is driven by the information given to the operator with the Human-machine interface and automation.

3.3.3. SLIM to BN modelling

The process modelling of SLIM to BN is similar to the approach that has been published by (Abrishami et al. 2020; Biočić et al. 2024). However, in this study, we modified the BN model by adding another layer of scenarios as the child node of the PSFs rather than the SLI of the UCA. This layer will provide a comprehensive systemic detail on which PSFs directly influence the scenarios. Therefore, it will benefit the users or stakeholders to see which PSFs should be the focus to improve the safety level of the operation. The probability of scenario mechanism *P(S$_k$)* can be calculated by assessing the SLI of the scenarios based on the weight of the PSFs, which is based on expert judgment as per Eq(1-2).

Then, after the likelihood of the scenario is obtained, the *P(H-UCA$_i$)* can be generated by using Noisy-OR Max of BN (Waskito et al. 2025). The expert judgment will be needed to assess the strength of scenario mechanisms on human control failure. The fuzzy set theory will be used to quantify linguistic value and reduce bias between experts. After that, the *P(H-UCA$_i$)* can be obtained. Figure 4 shows the complete model of the scenarios and the PSFs that lead to UCA 1.1.

Since this study only offers the concept, the detailed calculation will be performed when the data from experts, the scenarios, and UCAs are well documented.

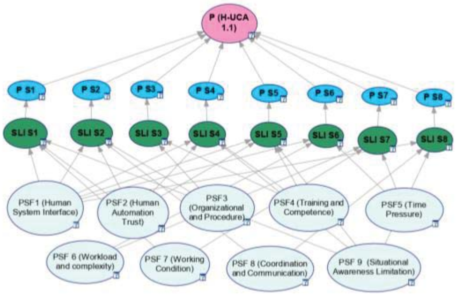

Fig. 4. The SLIM-BN method for UCA 1.1

4. Discussion

Based on STPA's results show that STPA can identify the unsafe human actions and scenarios within the complex system that consists of automation, sensors, and novel technologies. In this study, the hydrogen distribution system has been analysed, and the results indicated that the failure of the control actions is not a singular failure or component or human, but also within the interaction of the systems.

In terms of the performance of a human controller or operator, the proposed control flaws scenario based on human information processing, inadequate feedback, conflicting information and commands can enrich the possible scenarios that can lead to unsafe human control action that does not enforce the safety constraints. Consequently, there will be a humongous number of scenarios that can be developed, which can lead to the demand for risk quantification to help with assessing which scenarios that more likely or of greater significance to human control action error.

However, this approach also has some drawbacks, especially in the process of converting UCA into the SLIM-based analysis; sometimes it can be directed or tend towards the singular human error, such as operator execution error, or situational awareness error, which contradicts the systemic aspect of STPA. To overcome this weakness, it is important to keep in mind that the human control action failure to enforce the safety context is based on the system and event, not based on singular human error. Moreover, this approach is considered tedious and requires a high number of work hours and also involves several experts to assist with the validation of the model and the quantification part of SLIM-BN.

The future studies will be focused on attempting the quantification process by gathering data from expert judgment, and then, the sensitivity analysis of BN will be performed to assess the significance of PSFs to particular scenarios.

5. Conclusion

As hydrogen fuels are introduced into maritime transport, higher-consequence hazards and uncertainty in complex, tightly coupled fuel systems make it essential to adopt risk assessment approaches that capture system interactions and explicitly consider human performance. To address this need, this study develops an integrated STPA–SLIM–BN framework to estimate the likelihood of inadequate human supervisory control in enforcing safety constraints during remotely operated hydrogen fuel distribution. STPA is used to identify hazards, unsafe control actions, and loss scenarios centred on the remote control centre, demonstrating that unsafe control actions arise from unsafe interactions, inadequate feedback, and conflicting control rather than isolated human or equipment failures. These loss scenarios are then linked to performance shaping factors and quantified using SLIM–BN, providing a scenario-informed estimate of constraint-enforcement failure likelihood and supporting more transparent identification of risk drivers in hydrogen fuel operations. This study will be beneficial for improving the methodology in determining human performance in complex systems and the unknown risks of maritime decarbonization.

Acknowledgement

The authors would like to extend their gratitude to the Indonesia Endowment Fund for Education (LPDP), the Ministry of Finance, Republic of Indonesia, for generously providing the financial support for this research project in the form of a doctoral fellowship.

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