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Mooring-Line Entrapment and Load Redistribution During Berthing: A Case-Informed OPTIMOOR Assessment of Mona Manx

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ABSTRACT

Mooring-line entrapment presents a hazard distinct from conventional rope parting: tensioned lines can recoil suddenly when released from berth structures, with a potentially large vertical trajectory. This study examines the fatal Mona Manx mooring accident at Puerto Ventanas, Chile, through documentary casualty analysis, a two-scenario OPTIMOOR mooring-load comparison, and exploratory expert ratings of operational risk factors. The Marine Accident Investigation Branch established that an aft spring line became entrapped near a berth fender and released as the vessel manoeuvred astern, fatally striking the second officer on 26 August 2021. The computational comparison reports two loaded lines at 73.8 under a case-informed arrangement, compared with 35.5 and 35.3 under a modified arrangement, reductions of 51.9% and 52.2%, respectively. The output force unit, strength-reference denominator, scenario settings, and compatibility of the reported steel-wire model with the casualty's high-strength copolymer rope were not established; the results therefore indicate within-model sensitivity rather than validated accident mechanics. Expert ratings rank organisational, individual and environmental considerations at 100, 87 and 60 on the study's reported scale, values that are not additive percentages of causation. A layered safety response prioritising master–pilot information exchange, prohibition of unauthorised engine-driven repositioning, fender-entrapment checks, three-dimensional recoil awareness, and disciplined communications follows from the combined technical and investigation findings. The analysis illustrates the value of case-informed scenario testing while demonstrating the need for transparent rope characterisation and model validation before quantitative safety limits are inferred.

Keywords: mooring-line entrapment; OPTIMOOR; spring-line recoil; mooring safety; human factors

1. Introduction

Berthing and mooring are safety-critical ship–shore operations because a vessel is restrained by a system of ropes, winches, fairleads, bollards and fenders while environmental forces and ship movement continue to affect the line leads (Sholihin et al., 2017; Villa et al., 2017). Unequal pretension, changes in ship position, and mechanical interaction with berth fittings may redistribute load between simultaneously deployed lines (Kery, 2018; Thorenz & Schulze, 2021). The resulting risk is not limited to line overload or parting. A line can acquire substantial stored elastic energy while caught on a fixed structure and then release without warning; its recoil can cross deck levels that personnel may mistakenly regard as safe (Swenson, 1983). The design of a safe mooring arrangement therefore requires simultaneous consideration of hardware, operating procedures and crew positioning (IMO, 2020b, 2020a; OCIMF, 2018).

The fatal accident on the bulk carrier Mona Manx at Puerto Ventanas on 26 August 2021 provides a direct demonstration of this risk (Hasanspahić et al., 2023; Zhao et al., 2023). During a manoeuvre approximately 30 m astern to align the vessel with terminal loading equipment, the port aft spring line became trapped, probably in way of a fender, and then released. Its upward movement struck the second officer, who had positioned himself near the ship's side to monitor the line (Hasanspahić et al., 2023). The Marine Accident Investigation Branch (MAIB, 2024) identified interacting procedural, physical and communication shortcomings, including a manoeuvre under the vessel's own power that contravened terminal guidance and a missing task-specific toolbox briefing.

Numerical mooring tools can inform decisions about line tensions and redistribution when a configuration or operating condition changes (Asmara et al., 2026), demonstrating the importance of vessel-specific wind and current coefficients in OPTIMOOR analyses (Kamis et al., 2026). Engineering treatments of mooring systems similarly show the sensitivity of loading to line properties, geometry and operational conditions (Mujeeb-Ahmed et al., 2021; Pillai et al., 2022). Yet a numerical comparison cannot, on its own, establish the cause of a fatal accident or the kinematics of a released rope (Hao, 2024). These outcomes depend on the validity of input data and whether the software represents the physical mechanism of interest (Pascoletti et al., 2019).

The present study integrates three connected inquiries (Piskoty et al., 2017; Torres-Zúñiga, 2024). First, it describes the Mona Manx accident and its berth-interface hazard using the official investigation record. Second, it examines how two reported mooring configurations differ in their modelled line-load indicators. Third, it organises expert-reported organisational, individual and environmental concerns into actionable controls (Fan & Yang, 2023; Hennø & Schøyen, 2024; Vidmar et al., 2020). The purpose is to illuminate the interaction between load sharing and shipboard operational risk without equating a simplified scenario comparison with reproduction of the fatal recoil event.

2. Literature Review

2.1 Mooring-system mechanics and operational loads

A moored ship is governed by the combined response of hull loads and restraint forces generated by ropes, terminal equipment and fenders (Zwijnsvoorde et al., 2019). The analysis of mooring systems typically requires line force–extension behaviour, lead angle, water level, pretension, external loading and boundary conditions (Menteş & Yetkin, 2022). An increase in load on one line does not imply equal distribution across the remaining lines: depending on fairlead and bollard geometry, some lines can carry relatively high forces while other lines remain slack (Trubat et al., 2019). The engineering treatment of mooring arrays emphasises this coupled behaviour and the importance of consistent component definitions (Yang et al., 2026).

Design-stage standards and operational procedures serve different functions. The IMO (2020a) guidance on mooring arrangements focuses on occupational safety, equipment selection and ergonomics, whereas the IMO (2020b) addresses inspection and maintenance of equipment, lines and tails. OCIMF (2018) further sets out a ship–shore management framework that differentiates ship-design minimum breaking load from line-design break force and operating limitations. A numerical utilisation value cannot be interpreted against these standards unless its denominator and line-certification basis are explicit (Cajiao et al., 2025; Hennø & Schøyen, 2024).

Research on cable incidents has highlighted risks from insufficient configuration control and operational oversight (Gao et al., 2021). Offshore mooring investigations provide useful demonstrations of load redistribution and redundancy but are not direct validations of shipboard quay-side operations. For example, the multiple-leg offshore analysis by Hao et al. (2025) concerns floating wind-turbine systems, for which anchoring, wave response and restraint configuration differ from a bulk carrier berthing alongside a fendered jetty. Consequently, such studies inform the rationale for scenario comparison but do not justify transplanting numerical limits to the Mona Manx case.

2.2 Entrapment, snap-back and three-dimensional recoil

Snap-back is often taught as the recoil associated with a line parting under tension. However, a rope can also recoil when its path is temporarily constrained by a fender, fixed fitting or other obstruction (Bitting, 1982). In the latter case, an intact line may be stretched while diverted from its natural lead, and its subsequent release can move the span rapidly in a direction that is not captured by a flat deck plan (Roccia et al., 2025). The MAIB (2024) concluded that the entrapped aft spring on Mona Manx rose approximately 9 m in less than one second. This is a different physical sequence from the fatigue fracture or progressive failure of a rope.

The injury mechanism places operational significance on safe observation positions. A crew member may move to the deck edge to see the line or fender clearance, while simultaneously entering the line of fire created by its potential release (Zhao et al., 2023). A hazard assessment must therefore identify possible rope paths around fittings, vertical and lateral recoil trajectories, and locations of supervisors, winch operators and assistants (Zhao et al., 2023). Generic painted snap-back zones alone cannot establish that a position is free from risk under all line leads and berth geometries (Branch, 2024; Forum, 2018).

2.3 Human reliability, maintenance and ship–shore coordination

Human performance in mooring work is shaped by more than individual attention. The interaction of organisational instructions, crew numbers, role allocation, lighting, communication channels, workload and equipment condition can determine whether a developing hazard is recognised and controlled (Macrae, 2009; Singh et al., 2023). A recent maritime risk study by Tekeli et al. (2026) applied an uncertainty-sensitive Bayesian framework to cargo-operation mooring hazards and identified the importance of environmental and mooring-arrangement factors; its probability estimates should not be transferred to a different ship or terminal without case-specific calibration.

Maintenance and inspection remain a prerequisite because in-service rope properties may deviate from nominal new-line strength, and degraded fairleads or winch controls can create additional mechanical risks (Burton, 1987). The IMO (2020b) provides the framework for periodic inspection, maintenance and line replacement. In the Mona Manx investigation, however, the immediate accident pathway concerned an entrapped line suddenly released under tension rather than a confirmed material break. Maintaining the distinction prevents preventive strategies from focusing exclusively on rope strength at the expense of task planning and hazard recognition.

The master–pilot exchange is a further interface between shipboard and terminal risk controls. It should communicate restricted manoeuvres, intended mooring sequence, loading-arm alignment requirements, tug use, local fender hazards and emergency stopping criteria (Surinov et al., 2025). The failure to communicate an alongside engine-use restriction in the Mona Manx operation illustrates how an otherwise routine positional correction can create an unplanned line-handling task (Branch, 2024).

2.4 Case-informed simulation and evidence limits

Scenario modelling is valuable for isolating potential influences when the assumptions are transparent (Gende et al., 2019). In a berth mooring context, simulations may compare line tensions at different vessel positions, external-force inputs, line arrangements, or pretensions. OPTIMOOR has been applied to wind- and current-coefficient analysis (Matakis, 2010), while broader reliability research illustrates the dependence of line performance on operating and structural conditions (Putra et al., 2021).

It is important to distinguish a reported maximum line-load output from a validated dynamic simulation of entrapment, local contact, unloading or elastic recoil (Hayes & Fletcher, 2024). The latter would require suitable line constitutive properties, contact and release mechanics, temporal integration, and benchmark observations (Carbonell et al., 2022; Pastewka et al., 2025). In the present case, a two-scenario line-load comparison can establish a conditional difference in reported numerical results (Ciceri et al., 2026; Gerasimov & Lorenzis, 2019). It cannot establish a line-failure probability, an injury trajectory, or a counterfactual claim that an alternative manoeuvre would necessarily have prevented the accident.

3. Methods

3.1 Design and source hierarchy

The study used a case-informed, mixed-evidence design combining documentary casualty analysis, a two-condition OPTIMOOR comparison and thematic interpretation of three maritime professionals' reported expert ratings. The MAIB (2024) investigation was the primary source of casualty facts. The numerical and expert-rating findings were treated as distinct forms of evidence: they were not used to overwrite the factual accident record or infer causal certainty. The structured interpretation proceeded through case chronology, physical-hazard identification, scenario-output comparison, expert-factor classification and integrated operational recommendations.

3.2 Case setting and incident chronology

Mona Manx was an Isle of Man-registered bulk carrier of 199.90 m length overall and 35,606 gross tonnage. On 26 August 2021 it approached Puerto Ventanas Site 3 port side alongside. The weather was fine and clear, with a south-easterly Beaufort force 2 wind and approximately 0.7 m south-westerly swell. The berth included protruding

fenders that could entrap a line passing between the ship and shore. Two assisting tugs were used to hold the ship alongside (MAIB, 2024).

Table 1. Chronology of the Mona Manx operation reconstructed from the MAIB (2024) investigation. Times are UTC −4.

Time (local)	Verified operational event
07:36	Anchor weighing began; pilot boarded and participated in master–pilot exchange.
08:18	The ship was turned and brought parallel to Site 3 with tug assistance.
08:30	First aft spring fast to shore; port requested a 30 m astern adjustment.
08:32:42	Engine set dead slow astern with mooring lines deployed; vessel reached approximately 0.5 kn.
08:35:50	Engine brought to stop as positional adjustment neared completion.
08:36:11	Second officer stood near ship-side rail observing aft spring.
08:36:31	Entrapped spring suddenly released and recoiled upward, fatally striking second officer.

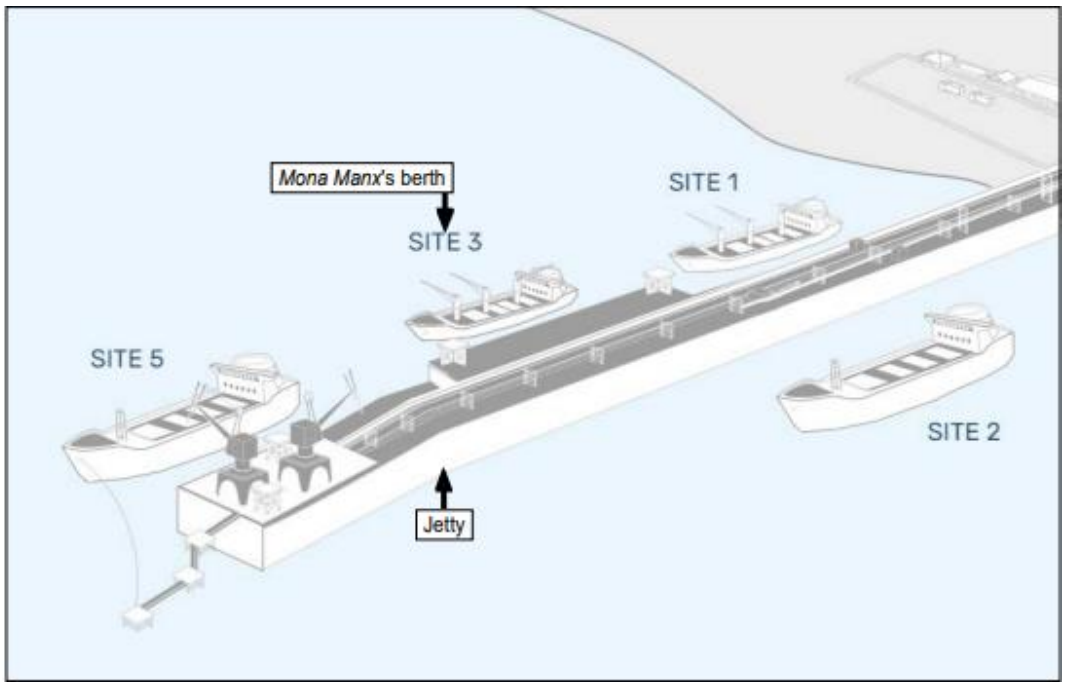


Figure 1. Puerto Ventanas Site 3 location. Reproduced in the case study from Puerto Ventanas S.A. / MAIB (2024).

3.3 Mooring configuration and material characterisation

The comparative model described a vessel placed parallel to a straight quay, with fairleads connected to shore bollards and a pair of forward and aft spring lines acting as primary longitudinal restraints. Its stated nominal line length was 220 m and diameter 68 mm. The model entry identified the material as steel wire. By contrast, the investigation recorded that the actual aft spring was a high-strength copolymer line of the same nominal length and diameter, with a new-line breaking load of 745 kN, installed in 2019 (MAIB, 2024). These are different constitutive materials; sharing line dimensions does not imply equivalent stiffness or energy storage. The two material descriptions are therefore kept distinct, and the reported numerical results are not claimed to replicate the documented spring line's mechanical response.

Table 2. Case facts and comparative-model assumptions. The distinction is important when interpreting strength utilisation and recoil mechanics.

Parameter	Documented casualty	Reported comparative model
Vessel	Mona Manx; LOA 199.90 m	Generic bulk-carrier berth arrangement based on Mona Manx
Aft spring material	High-strength copolymer	Steel wire (listed model parameter)
Aft spring length	220 m	220 m

Parameter	Documented casualty	Reported comparative model
Diameter	68 mm	68 mm
New-line minimum breaking load	745 kN	Not established
Line elasticity / damping	Not fully characterised in study	Not established
Mooring lead	Fender-interaction risk at Site 3	Quay bollards and fairleads, no independently verified entrapment contact model
Environmental and numerical settings	Fine/clear, southeast F2; southwest swell 0.7 m	Full scenario vectors, solver mode/time step and repetitions not reported

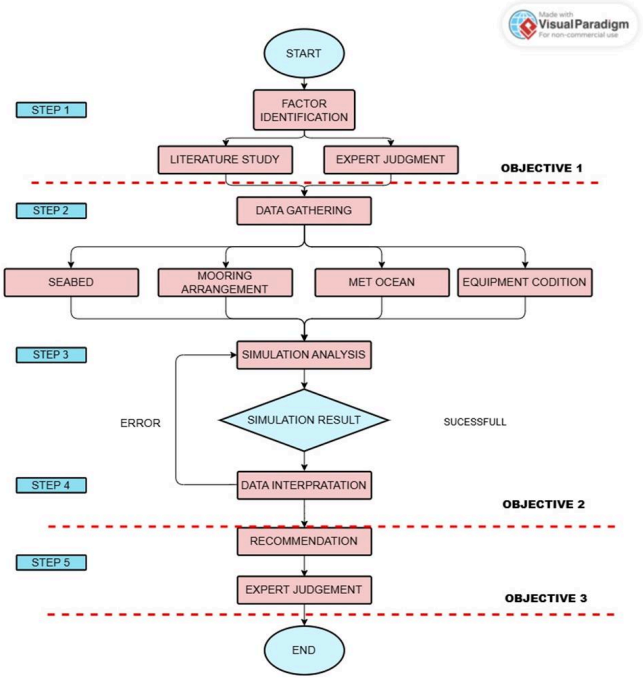


Figure 2. Sequential framework integrating factor identification, the OPTIMOOR comparison, interpretation and risk-control recommendations.

3.4 Numerical scenario definitions

Two nominal conditions were assessed. Scenario A, described as the case-study configuration, retained the mooring arrangement and operational influences associated with the along-berth repositioning; Scenario B, described as a comparative condition, reduced or removed the specified vessel-engine movement influence while maintaining the general line arrangement. The reported model included lines labelled 11–14. The output summary provides two slack lines and two loaded lines per scenario. Line force was tabulated as 73.8 for each active case-condition line and as 35.5 and 35.3 for the two active comparative-condition lines.

Because the saved OPTIMOOR project files, solver configuration and load-unit definition were not available, neither the precise handling of propulsion effects nor constancy of line pretension, contact geometry, environmental coefficients or time history could be verified. The output therefore constitutes a reported two-condition comparison, not a fully reproducible engine-effect experiment. In particular, nothing establishes that the model explicitly resolves the transient trapping/release of a copolymer rope under a fender.

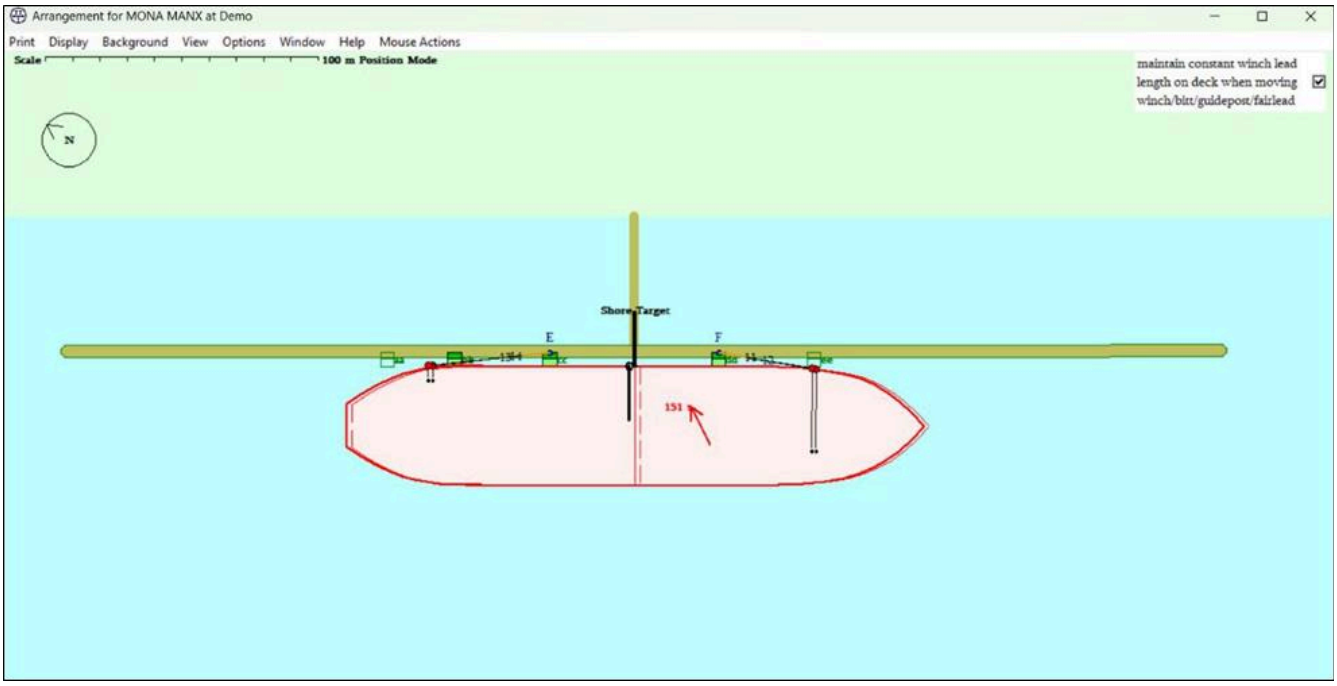


Figure 3. OPTIMOOR berth and spring-line arrangement adopted for the comparative analysis.

3.5 Quantitative interpretation

The modelled change in a reported line-load value was calculated as $\Delta L\,(\%) = \frac{L_A - L_B}{L_A} \times 100$, where L_A and L_B denote a comparable numerical output from Scenario A and Scenario B in the same force units. This relative calculation does not depend on an independent choice of force unit, provided the two scenario outputs are commensurate. By contrast, the strength-utilisation ratio $U\,(\%) = \frac{100L}{\mathrm{MBL}}$ requires a confirmed force unit, a reference breaking load for the modelled line, and compatible force definitions. The source table's 60%, 29% and 28% labels are therefore reported but not independently certified as breaking-load utilisation.

The official new-line MBL of 745 kN corresponds to approximately 75.97 metric tonnes-force. If a result such as 73.8 were expressed in kilonewtons, its direct ratio to 745 kN would be 9.9%. If it instead denoted tonnes-force, the ratio would be approximately 97.2%. Neither conditional interpretation establishes the program's actual output unit, and neither is used to infer operational acceptability.

3.6 Expert-factor interpretation

Three maritime professionals provided judgements organised into organisational, individual and environmental factors. The reported outputs were 100, 87 and 60, respectively. Under a percentage-of-total causal attribution method these values would need to sum to 100, which they do not. They are therefore interpreted as comparative expert rating indices on the reported scale rather than percentages of accident causation. Raw scores, interview transcripts, question wording, aggregation procedure, inter-rater agreement and consent records were not available; thematic conclusions are consequently exploratory. Themes were organised around risk planning, communication, equipment readiness, competence, fatigue controls and the physical environment, consistent with qualitative thematic grouping approaches (Braun & Clarke, 2006).

4. Results

4.1 Casualty mechanism and conditions

The primary investigation established a multi-stage accident mechanism: the vessel was repositioned astern under its own power with spring lines deployed; a slack aft spring became entrapped around a berth fender; the line tensioned as ship position changed; the trapped portion suddenly came free; and the stored energy drove a rapid vertical recoil. The line rose about 9 m in less than a second and struck the second officer. The MAIB found that the repositioning manoeuvre conflicted with the port's procedure, was not covered by a task-specific toolbox talk, and was not adequately evaluated for entrapment or vertical-recoil risks (MAIB, 2024). These verified observations concern an intact released line, not a confirmed line-fracture event.

4.2 Modelled line-load comparison

Table 3. Reported OPTIMOOR outcomes. The identifiers of the two active lines in Scenario B are ambiguous across the original figure and tabulation and are not reassigned here.

Model output	Scenario A: case-informed	Scenario B: modified
Slack-line status	Two lines reported slack	Two lines reported slack
Loaded-line output 1	73.8 (unit unconfirmed)	35.5 (unit unconfirmed)
Loaded-line output 2	73.8 (unit unconfirmed)	35.3 (unit unconfirmed)
Reported strength indicator	60% for each loaded line	29% and 28% for loaded lines
Change relative to 73.8	Reference	51.9% and 52.2% lower, respectively

Both conditions show pronounced nonuniformity: the two loaded spring-line outputs carry the reported demand while two other lines are slack. The maximum indicator falls from 73.8 to 35.5, equivalent to a relative reduction of 51.9%, while the other active-line indicator falls to 35.3, a reduction of 52.2%. This illustrates the numerical model's sensitivity to a modified operating condition or input configuration. It does not quantify the amount of load transmitted through an entrapped spring at the accident instant and does not establish that propulsion caused the entire numerical difference.

The stated percentage-of-strength readings (60% versus approximately 29%) move in the same direction as the raw indicators, but their denominator remains unverified. Given the MAIB's documented line MBL of 745 kN and the model's conflicting steel-wire entry, a definite strength margin or overload determination cannot be made from this comparison alone.

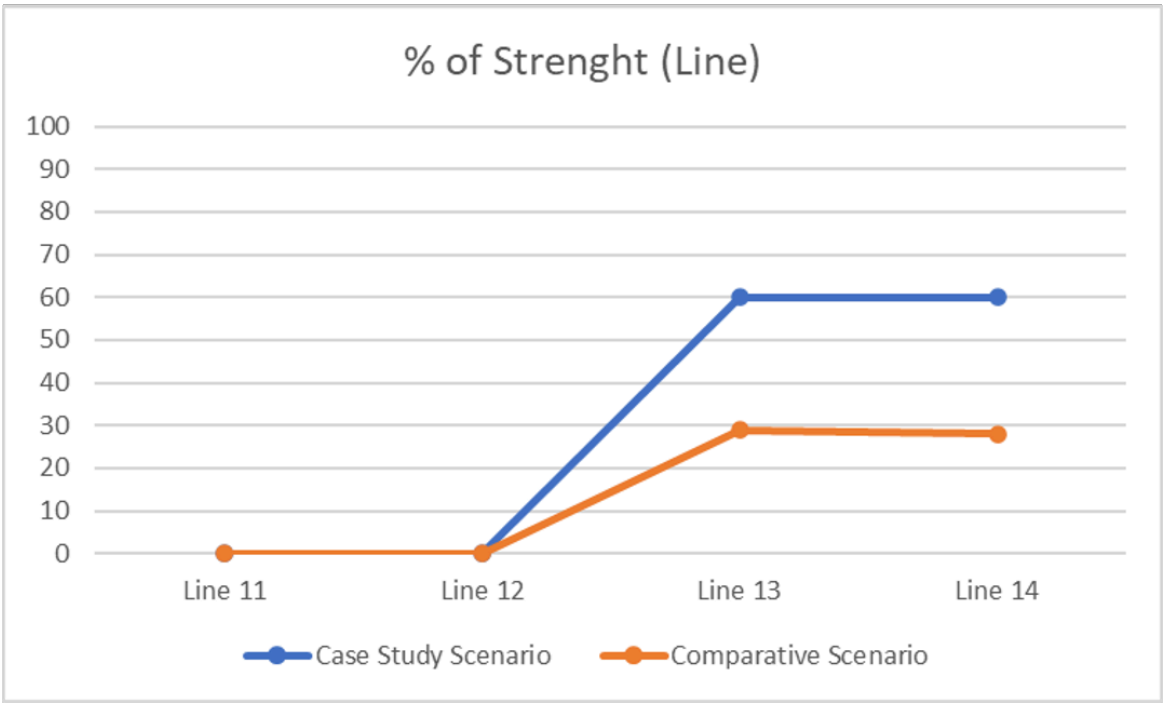


Figure 4. Reported percentage-of-strength comparison between case-informed and modified scenarios. Percentages are model labels and have not been independently validated.

4.3 Expert perceptions of contributing factors

The expert summary rated organisational factors highest (100), followed by individual factors (87) and environmental factors (60). These non-additive values indicate priority as perceived by the consulted professionals. Organisational concerns comprised the quality of planning, master–pilot and bridge–deck communication, equipment inspection, readiness checks and clearly defined authority to stop work. Individual concerns included training, competence maintenance, potential fatigue, role clarity and attention during critical line-handling tasks. Environmental concerns encompassed noise, lighting, distraction and operational conditions at the berth.

These findings do not mean that organisational circumstances caused 100% of the accident. The official investigation establishes specific interacting system failures, while the expert scores offer an additional practical prioritisation of improvement measures.

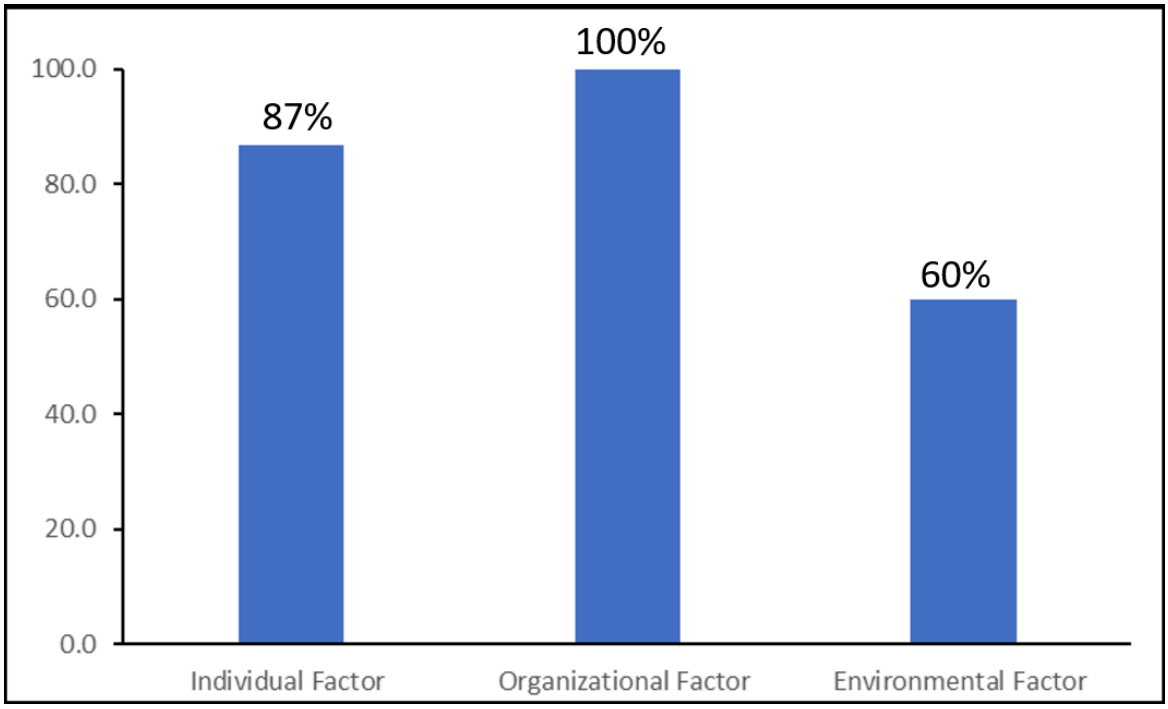


Figure 5. Exploratory organisational, individual and environmental expert-rating indices; values are not additive causal proportions.

5. Discussion

5.1 Interpreting the simulation against the accident record

The two-scenario numerical comparison suggests that altering an operational assumption can greatly change the reported forces on the active mooring lines. The finding is qualitatively consistent with the principle that load sharing depends on ship movement, line leads and the configuration of other restraints (Ma et al., 2019). Nevertheless, the accident cannot be reduced to this one load difference. The fatal event arose because the spring line took an abnormal route around a fender and then moved vertically after releasing, bringing its recoil trajectory into the second officer's position. An OPTIMOOR line-load output cannot independently reproduce this mechanism without a model of line contact, elasticity and three-dimensional recoil. This distinction also limits inferences from offshore line-failure studies, where restraint systems and loading regimes differ (Hao et al., 2025).

The material discrepancy has direct engineering significance. The real 68 mm high-strength copolymer spring is not interchangeable with an otherwise identically sized steel-wire line: the two have different force–elongation, hysteresis and energy-storage behaviour. Any safety analysis seeking to calculate the time course of rebound, contact force, or danger-zone extent must use the actual rope's certified properties and service condition. Accurate representation would also require the point of entrapment, fender geometry and a measured or otherwise constrained ship movement history.

5.2 Layered shipboard and terminal controls

First, the intended manoeuvre and restrictions on engine use must be communicated before the vessel is alongside. For Mona Manx, port control requested a 30 m position correction after an initial alignment; the MAIB (2024) observed that an alternative such as adjusting the shore loading arrangement or recovering deployed lines before a new manoeuvre was not systematically considered. The master–pilot exchange should therefore confirm terminal-specific restrictions, mooring-point availability, fender projections, movement limits and alternate positioning options.

Second, a change of plan with lines already deployed should trigger a pause and a task-specific risk assessment. Such a review should identify which lines will be slacked or tightened, how the vessel may move relative to fenders, who watches each line, when the winch operator must stop, and how a trapped line will be made safe without

creating an uncontrolled release. Explicit communications between pilot, bridge team, mooring stations, tugs and shore personnel are necessary. A single-channel congestion problem should be considered in the communications plan, with clear acknowledgement and stop-work conventions.

Third, safe positions must be evaluated in three dimensions. A person above the mooring deck or behind a conventional marked area can remain within a possible vertical recoil path. During high-tension movements no one should enter an uncertain line-of-fire region to improve a visual angle. Where observation is difficult, the operation should be stopped and alternative monitoring or a different safe location established. The presence of fenders, protruding bollards, fixed ladders and guardrail openings should be included in a site-specific line-route assessment (MAIB, 2024; OCIMF, 2018).

Fourth, routine technical maintenance remains vital, but it cannot substitute for operational controls. The line management plan should document line strength, condition and retirement criteria alongside fairlead condition, winch settings and brakes. The IMO (2020b) provides an equipment inspection and maintenance framework; inspection records should be linked to the actual ropes in service so that subsequent model inputs do not adopt incorrect materials or breaking strengths.

5.3 Organisational, individual and environmental priorities

The expert ranking reinforces the MAIB's conclusion that this incident should not be read simply as an isolated judgement error by a crew member. Organisational measures include planning meetings, berth-specific instructions, bridge/deck/shore communications, a revised MPX checklist, periodic equipment inspection and formal stop-work triggers. Individual safeguards include competence-based training on recoil vectors, periodic mooring rehearsals, fatigue-awareness controls and ensuring that supervisors can observe the operation from verified safe locations. Environmental controls include lighting, noise management, slip and trip prevention, and monitoring weather and berth conditions.

Training scenarios should distinguish at least three hazard classes: a rope breaking under high tension; an intact rope suddenly releasing from a fixed object; and abnormal loading induced by repositioning or changes in ship-to-berth geometry. Crew briefings and simulator exercises should make clear that a visual line-of-fire risk can extend well above or outside a nominal two-dimensional snap-back marking. Because the expert scores are non-additive and derived from only three individuals, they are a planning aid, not a validated hierarchy of universal accident causes (Braun & Clarke, 2006).

5.4 Limitations and directions for validation

This study is bounded by a single fatal casualty and two numerical scenarios. The full OPTIMOOR setup, case environmental coefficients, vessel mass and loading condition in the program, detailed fairlead coordinates, fender contact model, time-step, solver mode and scenario replication are not available in a form that permits independent reproduction. Output tension units and percentages of strength are not traceable to a confirmed denominator. The source model's steel-wire specification also differs from the investigated copolymer line. The line-ID inconsistencies preclude detailed verification of individual-line load paths. Finally, the three-expert ratings lack disaggregated survey data and documented reliability measures.

Future research should reconstruct the validated incident geometry with the appropriate rope mechanical properties, contact and release dynamics, and measured vessel motion. A documented series of cases should vary slack, pretension, shore-fitting geometry, propulsion influence and environmental conditions independently. Numerical outputs should be verified against measured forces or qualified physical tests, followed by uncertainty analysis. Only then would it be appropriate to claim prediction of recoil trajectories, model validity or a specified reduction in casualty risk. Until such work is completed, the operational recommendations should be understood as risk-informed controls, not as quantified evidence of causal prevention.

6. Conclusion

The Mona Manx casualty demonstrates that mooring safety cannot be assessed solely by whether a line has adequate breaking strength. In this accident an entrapped, intact aft spring line released abruptly as the vessel manoeuvred astern, recoiling upward into an occupied shipboard position. The case-informed OPTIMOOR comparison reports that an altered configuration reduces two active-line output indicators from 73.8 to 35.5 and 35.3, reductions of approximately 51.9% and 52.2%. These conditional numerical differences do not replicate the physical release or establish independently verified line-strength margins. The exploratory expert ratings place organisational management concerns above individual and environmental considerations without measuring a causal percentage of the accident.

The combined evidence supports a layered approach to mooring risk management: terminal-specific master–pilot exchange; explicit restrictions and alternatives for repositioning alongside; renewed task-specific planning when line states change; monitoring for entrapment at fenders; three-dimensional recoil hazard awareness; reliable crew–shore communication; and verified equipment data in mooring simulations. These controls are directly relevant to berth safety, while quantitative evaluation of line loads and recoil hazard zones requires a more complete and independently validated modelling framework.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI-assisted technologies to support language editing, grammatical refinement, and improvements in readability. The authors subsequently reviewed and verified the content and take full responsibility for the accuracy, originality, and integrity of the published work.

Conflict of Interest

The authors declare that they have no known financial or non-financial competing interests that could have influenced the research presented in this manuscript.

Author Contributions

Data availability

Numerical findings, case chronology and expert-rating summaries are included in the article. Complete proprietary OPTIMOOR project settings, underlying expert responses and full simulation time histories are not available as part of the published evidence.

Ethics

The case analysis relies on a publicly available marine casualty investigation. The consent and ethical approval arrangements for the expert component are not reported.

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