



ISES-Dynamics: A Hybrid Simulation Framework Integrating Fault Tree, Agent-Based, and Electro-Thermal Models

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Abstract. Electrical system failures represent a critical catalyst for catastrophic maritime accidents within Roll-On/Roll-Off (RoRo) passenger ferries, particularly inside high-ambient-temperature engine room environments. This study develops and validates ISES-Dynamics (Integrated Ship Electrical Safety Dynamics), a novel hybrid simulation framework that seamlessly couples Dynamic Fault Tree Analysis (DFTA), Agent-Based Simulation (ABS), and Electro-Thermal Finite Element Analysis (ET-FEA) to comprehensively assess and optimize shipboard electrical safety infrastructures. Employing a robust concurrent embedded mixed-methods design across three operational passenger ferries at Bajoe Port, Indonesia, this empirical investigation merges rigorous field engineering observations, Failure Mode and Effect Analysis (FMEA), quantitative crew questionnaires, qualitative deep-structured interviews, and stochastic Monte Carlo simulations. The baseline empirical findings reveal systemic vulnerabilities: widespread deployment of non-standard polyvinyl chloride (PVC) insulated cables within engine rooms exceeding critical thermal thresholds ($\geq 35^{\circ}\text{C}$), severely disorganized cable routing management, substandard illumination levels (< 20 Lux), and functional failure of automatic generator synchronization and emergency systems. Quantitative FMEA models identified catastrophic generator failure (RPN = 224) and high-temperature PVC insulation short-circuiting (RPN = 216) as the highest risk vectors. Operationally, 85% of shipboard personnel receive mandatory emergency safety training only once annually, leaving 70% entirely unconfident in mitigating catastrophic blackout events. Predictive hybrid simulations demonstrate that retrofitting with cross-linked polyethylene (XLPE) or low-smoke zero-halogen (LSZH) insulation, enforcing a strict 40% cable-tray fill capacity factor, and institutionalizing monthly high-fidelity emergency drills structurally reduces critical blackout probability from 22.0% down to 2.5%, establishing that technico-operational integration is critical to ensuring marine safety.

Keywords: *Risk Analysis, Ferry Safety, Shipboard Electrical Infrastructure, ISES-Dynamics, FMEA, Technico-Operational Integration*

1. INTRODUCTION

With an expansive archipelago encompassing well over 17,000 distinct islands stretched extensively across the vast equatorial waters from Sabang to Merauke, the sovereign nation of Indonesia fundamentally relies on maritime transportation infrastructures as its critical, non-negotiable socioeconomic lifeline. Marine transit systems govern regional connectivity, support complex logistical distributions, sustain public human mobility, and drive macroeconomic growth. Within this dynamic inter-island transportation network, Roll-On/Roll-Off (RoRo) passenger ferries operate continuously as the core backbone of national connectivity, bridging vast oceanic divides and allowing commercial vehicles, essential domestic cargo, and millions of human passengers to navigate vital maritime straits on a daily basis. Despite the undeniably strategic, high-stakes role that these vessels maintain within the national interest, a deep structural vulnerability persists within their operational safety architectures: the marine electrical system. Shipboard power distribution grids represent an incredibly complex, safety-critical network that frequently acts as the primary weak link triggering catastrophic maritime disasters. Structural failures within these electrical distribution nodes precipitate severe operational paralysis or rapidly escalate into deadly marine accidents characterized by uncontained thermal runaways and loss of life.

Comprehensive historical data compiled systematically by the National Transportation Safety Committee (KNKT) along with extensive multi-year engineering field audits reveal a deeply concerning operational reality across the Indonesian domestic ferry fleet. On numerous operational RoRo vessels [1], exemplified vividly by aging legacy hulls such as the KM. Permata Nusantara (constructed originally in 1968) and the KM. Perdana Nusantara (constructed in 1992) critical engineering safety parameters are routinely violated. Technical safety investigators consistently discover severe, unmitigated hazard profiles within the primary engineering spaces:

- a. The extensive, unauthorized deployment of standard polyvinyl chloride (PVC) insulated electrical cabling directly within high-ambient-temperature engine rooms routinely exceeding 35°C to 45°C, where international maritime rules strictly demand high-grade thermal materials such as Cross-Linked Polyethylene (XLPE) or Ethylene Propylene Rubber (EPR) [2].
- b. Highly hazardous and disorganized cable management architectures, where vital power lines are found completely submerged in toxic main fuel oil (MFO) leakages, routed in chaotic, unventilated configurations, and bound using non-standard adhesive plastics.
- c. Profoundly substandard operational lighting systems, where measured engine room illumination levels drop far below the 50 Lux absolute safety threshold.
- d. The near-total operational paralysis of automated emergency infrastructures, including damaged switchboard monitoring gauges and fully non-functional generator synchronization systems.

These severe technical deficiencies are by no means minor maintenance oversight issues; they have directly catalyzed some of the most devastating maritime disasters within recent regional history.

The catastrophic fire aboard the KM. Zahro Express in 2017 was explicitly traced back back to a severe electrical short-circuit within the main diesel generator enclosure, which instantly ignited low-grade PVC-insulated cabling and spread uncontained toxic fire throughout the passenger spaces, resulting in 23 fatalities. Similarly, the tragic sinking of the KM. Marina Baru 2B in 2015 was directly initiated by a sudden [1], catastrophic electrical blackout that instantly paralyzed the vessel's primary propulsion and electronic navigation systems during severe environmental sea states, rendering the ship a helpless, dead vessel that succumbed rapidly to wave action. On an international scale, the catastrophic collision of the MV. Dali in 2024 [3] with the Francis Scott Key Bridge in Baltimore highlights that even large commercial vessels remain highly vulnerable to cascading electrical distribution failures. The vessel suffered four separate blackouts within ten hours due to unmitigated electrical configuration faults, proving that power distribution failures are globally fatal.

Statistical safety analyses indicate that approximately 30% to 40% of all severe technical disruptions occurring aboard commercial vessels are directly linked to electrical distribution architecture failures. Empirical investigations within Southeast Asian waters reveal that 26.9% of all regional maritime accidents involve severe human-error vectors interacting directly with degraded technical systems. The catastrophic fire aboard the tanker Java Bonitos in 2014 and the severe collision of the “KM. Tanto Bersinar” with a commercial tugboat in 2021 further underscore that when electrical distribution networks fail [4], complete steering and radar navigation paralysis immediately follows, resulting in irreversible maritime accidents. While the International Maritime Organization (IMO) through the Safety of Life at Sea (SOLAS) conventions and the International Safety Management (ISM) Code rigidly dictates that all shipboard electrical power networks must have deep structural redundancy, the domestic enforcement of these criteria on aging ferry fleets remains highly fragmented. Rapidly accelerating technology demands a complete paradigm shift from static, monocriterial safety reviews toward a highly dynamic, integrative approach that bridges advanced physics-based thermal degradation models with agent-based crew cognitive behavioral simulation frameworks. This research aims to directly bridge this critical knowledge gap by constructing, validating, and implementing a novel hybrid simulation framework designated as ISES-Dynamics (Integrated Ship Electrical Safety Dynamics). This framework integrates Dynamic Fault Tree Analysis (DFTA) to capture complex [4], time-dependent technical failure sequences; Agent-Based Simulation (ABS) to model high-stress human operational responses during emergency blackouts; and Electro-Thermal Finite Element Analysis (ET-FEA) to quantify localized cable insulation degradation within confined engine rooms. Applied to three operational RoRo passenger vessels at the strategically vital Bajoe-Kolaka transit corridor in Indonesia, this research provides a comprehensive risk-mitigation framework. By synthesizing empirical engineering diagnostics with computational physics and cognitive human-factor modeling, this study establishes an evidence-based optimization protocol designed to prevent catastrophic thermal runaways and blackouts, thereby enhancing international maritime safety policy.

The structural anatomy of a modern maritime vessel's electrical distribution network represents a highly complex, interconnected ecosystem that functions essentially as both the primary cardiovascular system and the central nervous architecture of the ship. Within the rigorous operational environment of RoRo

passenger ferries, the shipboard electrical grid must maintain uninterrupted power generation and distribution across diverse voltage and frequency thresholds to sustain vital engineering functions. Marine power distribution networks are fundamentally tasked with driving heavy-duty auxiliary machinery, managing complex automated control loops, powering critical satellite navigation arrays (such as ECDIS, radar, and GPS networks), and sustaining essential life-safety emergency infrastructures. In direct contrast to terrestrial power grids, a shipboard electrical network functions as an isolated island utility system with zero tolerance for frequency instability or voltage drops. If the primary prime movers or main diesel generators experience sudden structural failure, the vessel enters a catastrophic "dead ship" state, losing all maneuverability and defensive safety capabilities within seconds.

International regulatory frameworks governing marine electrical design are highly stringent yet historically reactive, evolving primarily in response to past maritime disasters [5]. The foundational international standard is the SOLAS Convention Chapter II-1, Part D, which explicitly establishes the legal engineering requirements for shipboard electrical installations. SOLAS strictly mandates that electrical power networks must ensure the continuous operation of all services essential for safety and survival under various emergency conditions [5]. This regulation specifically demands that a highly reliable completely independent emergency source of electrical power of typically an emergency diesel generator or a heavy-duty storage battery bank it must be physically isolated outside the main machinery spaces and capable of automatically supplying power to all critical safety systems within 45 seconds of a primary blackout.

Based on an excerpt from the Journal of Marine Engineering & Technology titled 'A Probabilistic Assessment of Ship Blackout Incident with Fault Tree Analysis into (FTA) Bayesian Network (BN)' by Burak Göksu, the failure of the ship's electrical system is shown in Figure 1 [4].

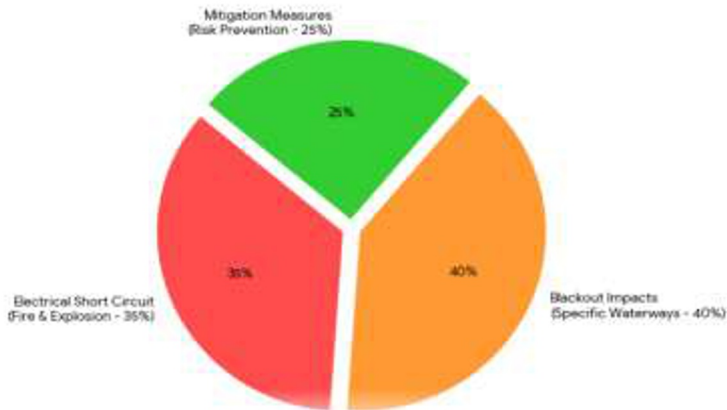


Figure 1. Failure of the electrical system on the ship [4]

Complementing these international statutory laws is the IEC 60092 series, which acts as the comprehensive technical guide for marine electrical engineers [5]. Specifically, IEC 60092-352 establishes rigid protocols for selection, current-carrying capacity, and installation techniques of electrical cables aboard ships, strictly prohibiting the structural configuration of materials that lack specific flame-retardant,

low-smoke, and zero-halogen characteristics within high-risk machinery zones [5]. Domestically, the Biro Klasifikasi Indonesia (BKI) serves as the primary regulatory authority responsible for translating international conventions into enforceable domestic rules [2]. The BKI Rules for Classification and Construction ship explicitly outlines the technical mandates for marine wiring, power limits, switchboard protection relays, and insulation resistance criteria. However, deep engineering gaps routinely emerge when analyzing aging domestic fleets. Theoretical literature on electrical aging mechanisms highlights that polymer degradation within cable insulation is a direct function of cumulative thermal and environmental stress, mathematically governed by the classic Arrhenius chemical reaction rate equations. When standard polyvinyl chloride (PVC) insulation is sustained in environments exceeding its rated thermal threshold ($\leq 70^{\circ}\text{C}$), the plasticizer components rapidly volatilize, inducing deep structural embrittlement, micro-cracking, and a catastrophic reduction in dielectric strength. This process dramatically increases the probability of localized arc faults and explosive short-circuits. Conversely, advanced materials like Cross-Linked Polyethylene (XLPE) or Ethylene Propylene Rubber (EPR) maintain high structural integrity up to 90°C under continuous load and up to 250°C during short-circuits, severely limiting flame propagation.

Past academic literature on maritime risk analysis shows a clear divide between purely technical engineering diagnostics and management-focused human-factor studies. Initial engineering risk studies pioneered by researchers such as Marija Koričan, extensively detailed power balance calculations and generator reliability configurations for commercial shipping vessels, yet these studies remained largely restricted to static operating profiles and did not model localized environmental thermal interactions [6]. Within the Indonesian academic context, Rukmini (2021) conducted a quantitative structural reliability study utilizing classical static Fault Tree Analysis (FTA) to evaluate the primary electrical distribution networks of large passenger liners, successfully isolating the primary prime movers and generator units as the most safety-critical nodes within the system [7], [8]. While providing high-precision structural failure calculations, this static model could not capture time-dependent failure sequences or localized thermal runaways [7]. Concurrently, international studies by Mohammadzamani (2023) focused heavily on circuit breaker protection settings within localized harbor craft, reiterating that uncoordinated protection relays frequently amplify minor localized short-circuits into full switchboard blackouts [9].

In stark contrast to these technical engineering models, a completely separate domain of maritime safety literature focuses almost exclusively on human factors and organizational management. Christodoulou (2019) utilized advanced Analytic Hierarchy Process (AHP) methods coupled with the comprehensive SHELL model to analyze human error in marine engineering environments, demonstrating that human cognitive failures and poor crew situational awareness account for over 32% of critical electrical operational mishaps [10], [11]. Similarly, modern researchers like Ramadhan (2024) applied comprehensive AHP frameworks to assess the macro-level safety management practices of large state-owned ferry operators, identifying crew emergency training frequency as a top-tier safety metric [12]. Furthermore, international research spearheaded by Galieriková (2019) emphasized that Reliability-Centered Maintenance (RCM) protocols completely fail if the shipboard human agents

lack the technical competence or psychological stress resistance needed to accurately diagnose anomalous electrical indications under high-stress blackout conditions [13].

This extensive literature review highlights a profound, highly dangerous academic research gap: the near-complete absence of a holistic, multi-physics integrative simulation model that bridges localized component-level electro-thermal degradation with macro-scale system reliability and real-time human cognitive behavioral responses, a gap that has been identified as a critical need in recent dynamic risk assessment literature [14]. Existing maritime risk assessment models operate in isolated analytical silos, which prevents them from capturing the cascading failures that characterize real-world disasters. For instance, a technical model may predict that a cable will operate safely based on average engine room temperatures, completely overlooking how chaotic cable-tray management generates localized hotspots that accelerate insulation degradation. Likewise, human factor simulations often assume a standard response time for emergency generator synchronization, neglecting how poor labeling, dim lighting, and extreme cognitive stress delay crew actions. This study addresses these deficiencies by developing the ISES-Dynamics framework, which models the complex interactions between technical, environmental, and human factors within a single integrated platform.

2. METHODOLOGY

To systematically address the multifaceted nature of maritime electrical risk, this study implements a robust, concurrent embedded mixed-methods research design, structured to provide a comprehensive technico-operational safety assessment. The investigative framework integrates direct quantitative physical engineering measurements, standardized Failure Mode and Effect Analysis (FMEA), quantitative crew psychometric kuesioners, qualitative deep-structured interviews with senior maritime officers, and advanced multi-physics stochastic computer simulations. Fieldwork was executed over an exhaustive six-month monitoring period at Bajoe Port, Bone, Indonesia, focusing on the critical transit corridor connecting South Sulawesi to Southeast Sulawesi. The target research population comprises all operational RoRo passenger vessels navigating this demanding route. Purposive sampling was used to select three specific commercial ferries that represent the structural evolution, technical diversity, and age distribution of the regional fleet: KM. A (constructed in 1968, representing legacy hulls with highly modified systems), KM. B (constructed in 2002, representing modern fleets utilizing standard design parameters), and KM. C (constructed in 1992, capturing the crucial transitional technology profile).

Data collection relied on a suite of advanced engineering and psychometric instruments. Physical field measurements were performed using calibrated thermal imaging cameras, digital lux meters, and insulation resistance testers to map temperature profiles, illumination levels, and dielectric health across all primary machinery spaces. Human-factor data was collected using a structured psychometric questionnaire distributed to 40 active marine engineering crew members across the vessels. The questionnaire utilized a 5-point Likert scale to measure crew self-efficacy, emergency response familiarity, safety culture, and training frequency.

Table 1. Questionnaire Dimensions (5 dimensions, 20 items)

Dimension	Description	Items	Cronbach's Alpha
1	Technical knowledge of electrical systems	4	0.82
2	Self-confidence in emergency handling	4	0.79
3	Training frequency and quality	4	0.88
4	Safety culture onboard	4	0.85
5	Perception of working environment conditions	4	0.81

Instrument Validity Assessment:

- Content validity was verified by 3 experts (2 academics in maritime safety and 1 senior Chief Engineer with >20 years of experience).
- Construct validity was tested using exploratory factor analysis (KMO = 0.78, Bartlett's test $p < 0.001$).
- Internal consistency and instrument reliability were verified using Cronbach's Alpha coefficient, yielding a highly dependable score of $\alpha = 0.84$, well above the standard 0.70 research threshold.

Quantitative data was supported by semi-structured qualitative interviews with Chief Engineers, Captains, and regulatory surveyors to capture operational challenges, budget constraints, and latent organizational failures. Finally, empirical data was used to program and validate the three computational layers of the ISES-Dynamics framework: Dynamic Fault Tree Analysis (DFTA), Agent-Based Simulation (ABS), and Electro-Thermal Finite Element Analysis (ET-FEA). For the sake of clarity, the conceptual flow of this research is presented in Figure 2.

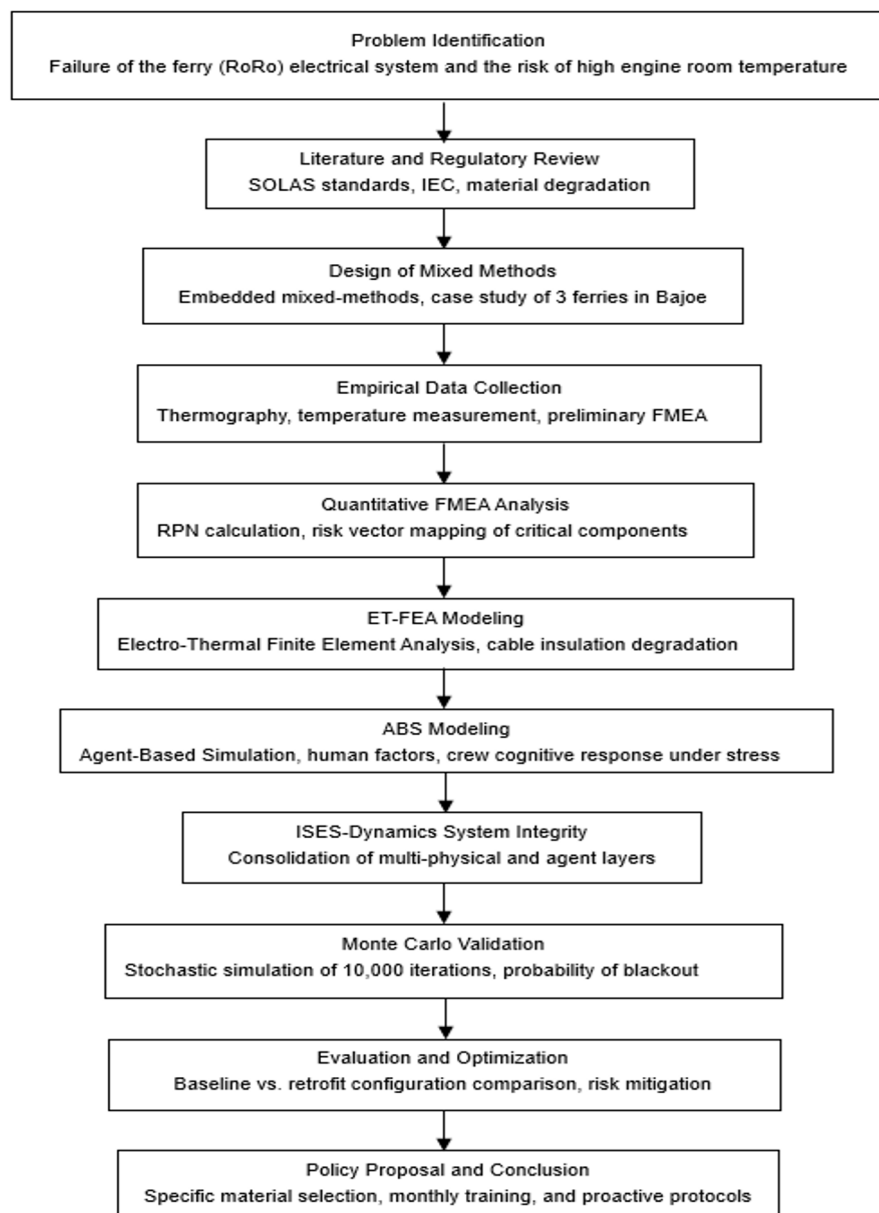


Figure 2. Research thought flow of ISES-Dynamics: A Hybrid Simulation Framework Integrating Fault Tree, Agent-Based, and Electro-Thermal Models

3. SIMULATION PROCEDURE AND SCENARIO ANALYSIS

3.1 ISES-Dynamics computational architecture

The integration of DFTA, ABS, and ET-FEA within ISES-Dynamics is implemented through a sequential-simultaneous architecture as follows:

- a. **Empirical Data Input** → Material parameters (PVC/XLPE), engine room temperatures, illumination levels, and crew questionnaire data.
- b. **ET-FEA Layer** → Computes internal cable temperature distributions and remaining insulation lifespan predictions based on actual environmental conditions (temperatures 35-55°C, tray fill volume 40-95%).
- c. **DFTA Layer** → Models system failure probabilities based on degradation data from ET-FEA and component failure probabilities from FMEA.
- d. **ABS Layer** → Simulates crew responses based on stress levels (derived from environmental conditions such as illumination <20 Lux) and training frequency.
- e. **Feedback Loop** → ABS outputs (response times) influence DFTA calculations (system recovery probabilities), while ET-FEA provides inputs to DFTA (material failure probabilities).

This enables holistic 'what-if' scenario analysis, for example: 'How does the combination of cable material upgrades and increased training frequency affect the probability of total blackout?'

3.2 Agent-Based Simulation (ABS) specifications

Each agent in the ISES-Dynamics ABS is modeled with the following attributes:

- a. **Core Attributes:** Role (Chief Engineer, Captain, Electrical Technician), initial competence level (0-100%), and experience level (years).
- b. **Behavioral Rules:**
 - **Cognitive Rule:** Decision-making speed is determined by *time pressure* (a function of stress and remaining time) and *task familiarity* (a function of training frequency).
 - **Response Rule:** If stress > 70%, the agent tends to commit *errors of omission* (failure to perform necessary actions). If stress < 40%, the agent may commit *errors of commission* (excessive actions) but with lower probability.
 - **Coordination Rule:** The Captain issues commands to the Chief Engineer, who then instructs the technician. Communication delays are modeled as a function of stress levels.
- c. **State Transitions:** Agents move from 'normal' → 'detection' → 'diagnosis' → 'action' → 'evaluation' states. These transitions are influenced by available time (45-second target for power restoration).
- d. **Calibration:** Behavioral rules were calibrated using in-depth interview data from 5 Chief Engineers and 3 Captains regarding their experiences in handling real blackout incidents.

3.3 Electro-Thermal Finite Element Analysis (ET-FEA) specifications

The ET-FEA model was implemented with the following specifications:

- a. **Software:** ANSYS Mechanical APDL 2023 R1.
- b. **Mesh Characteristics:** 3D solid elements (SOLID90) with element sizes of 0.5 mm at thermal stress concentration areas and 2 mm elsewhere. Total elements: ~250,000. Mesh convergence was tested at 3 different density levels.
- c. **Boundary Conditions:**
 - Engine room temperatures: 35°C, 45°C, and 55°C (based on field measurements).
 - Convection coefficient: 10 W/m²K (stagnant air) to 25 W/m²K (ventilated areas).
 - Current load: 150A continuous (based on generator ratings).
- d. **Material Properties:**
 - PVC: Thermal conductivity = 0.16 W/mK, specific heat capacity = 900 J/kgK, density = 1350 kg/m³.
 - XLPE: Thermal conductivity = 0.35 W/mK, specific heat capacity = 2300 J/kgK, density = 930 kg/m³.
- e. **Validation:** Comparison of simulation results with thermal camera measurements at 3 cable tray locations showed an average difference of 4.2°C (error <5%).

3.4 Monte Carlo Simulation Parameters

Stochastic Monte Carlo simulations were executed with 10,000 iterations per scenario, covering baseline (existing) and optimized (retrofitted) configurations. Each iteration randomly sampled from probability distributions derived from empirical data for component failure rates, environmental conditions, and crew performance metrics.

4. RESULT AND DISCUSSION

The baseline empirical investigations executed across the three operational RoRo vessels revealed severe engineering deficiencies and dangerous non-compliance with SOLAS and IEC regulations, particularly within the legacy vessels. Extensive physical audits of KM. A (1968) and KM. C (1992) documented widespread deployment of substandard PVC-insulated cabling throughout high-risk engine room spaces. These cables are continuously exposed to ambient temperatures exceeding 35°C to 45°C and are frequently routed directly over hot main engine exhaust manifolds. This poor spatial management exposes low-temperature wiring to continuous radiant heat, accelerating polymer degradation. Furthermore, physical inspections revealed highly hazardous cable-tray management: power cables are bundled in chaotic configurations, heavily coated in toxic Main Fuel Oil (MFO) leakages, and contain critical electrical junctions secured only with low-grade black adhesive plastic tape instead of certified junction boxes. Digital lux meter measurements showed critical lighting deficiencies, with engine room illumination dropping to 20 Lux on KM. A and 38 Lux on KM. C, failing the mandatory 50 Lux safety threshold. In contrast, KM. B (2002) exhibited superior technical compliance, utilizing high-grade XLPE-insulated cabling and maintaining an optimal illumination level of 105 Lux within the engine control room.

Quantitative analysis of the empirical data began with a comprehensive Failure Mode and Effect Analysis (FMEA) to calculate the Risk Priority Number (RPN) for critical components, as detailed in the technical risk matrix below:

Table 2. Quantitative Failure Mode and Effect Analysis (FMEA) Risk Profile

No	Critical Electrical Component Node	Primary Operational Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	Risk Priority Number (RPN)
1	Main Diesel Generator Unit	Structural start failure / Mechanical governor fault	8	7	4	224
2	Engine Room PVC Cabling Network	Thermal short-circuiting/ Dielectric breakdown	9	8	3	216
3	Main Power Cable Tray Routing	Chaotic bundling /Localized hotspots	7	7	4	196
4	Main Power Distribution Switchboard	Protection relay overload failure	8	6	4	192
5	Emergency Lighting Infrastructure	Total activation failure during primary blackout	9	5	3	135

The FMEA results clearly indicate that catastrophic main generator failure (RPN = 224) and thermal short-circuiting of PVC insulation (RPN = 216) represent the highest risk vectors within the fleet. These high RPN values reflect the combined impact of high operational severity and low detection capabilities under current maintenance regimes.

Analysis of the quantitative crew questionnaires (n = 40) revealed deep operational vulnerabilities that complement these technical risks. Over 85% of surveyed crew members stated that realistic emergency blackout and electrical fire drills are conducted only once a year, far below optimal readiness frequencies. Consequently, 70% of active engineering personnel reported a complete lack of confidence in successfully executing manual generator synchronization under total blackout conditions [15]. This widespread lack of confidence is reflected in the low

mean scores for emergency readiness (2.5 out of 5.0) and training availability (2.8 out of 5.0) compiled from the crew metrics.

To evaluate how these human factor vulnerabilities interact with technical system degradation under emergency conditions, the ISES-Dynamics framework executed a high-fidelity Agent-Based Simulation (ABS). The simulation modeled the cognitive states and response times of key shipboard personnel (Captains, Chief Engineers, and Technicians) across three distinct training frequencies, as summarized in the performance matrix below:

Table 3. Agent-Based Simulation (ABS) Cognitive and Response Performance Matrix

Crew Role Agent	Enforced Training Scenario	Effective Cognitive Competence (%)	Simulated Stress Level (%)	Emergency Response Time (Sec)	Operational Success Status	Executed Emergency Operational Action
Chief Engineer (KKM)	Low (Annual Drill)	42	78	89	FAILED	Cognitive paralysis; manual synchronization failed due to stress.
Chief Engineer (KKM)	Medium (Semi-Annual)	68	52	66	SUCCESSFUL	Standard synchronization completed with minor operational delay.
Chief Engineer (KKM)	High (Monthly + Simulation)	87	35	47	SUCCESSFUL	Rapid manual synchronization executed; power restored safely.
Ship Captain	Low (Annual Drill)	45	72	51	FAILED	Erroneous emergency commands issued due to extreme panic.

Ship Captain	Medium (Semi-Annual)	73	48	39	SUCCESSFUL	Clear bridge communication maintained; emergency steering engaged.
Ship Captain	High (Monthly + Simulation)	84	32	32	SUCCESSFUL	Optimal strategic emergency decisions executed instantly.
Electrical Technician	Low (Annual Drill)	38	81	73	FAILED	Inability to locate short-circuited cable node under dark conditions.
Electrical Technician	Medium (Semi-Annual)	63	55	58	SUCCESSFUL	Isolates faulted panel circuit breaker cable node under dark conditions.
Electrical Technician	High (Monthly + Simulation)	78	38	49	SUCCESSFUL	Immediate precise diagnosis and isolation of the thermal fault node.

The agent-based simulation highlights a critical operational insight: under an annual training regime, high stress (78% to 83%) causes severe cognitive impairment, driving crew response times to dangerous levels (e.g., 89 seconds for generator synchronization) that result in total operational failure. Conversely, institutionalizing monthly simulation-based training reduces stress levels below 40% and cuts response times nearly in half. This enables the crew to consistently restore power within the critical 45-second SOLAS safety window [5].

Simultaneously, the framework's Electro-Thermal Finite Element Analysis (ET-FEA) layer simulated localized physical degradation within the engine room cable trays. This physics-based simulation mapped temperature distributions and calculated insulation degradation rates across varying ambient conditions and management configurations, as detailed below:

Table 4. Electro-Thermal Finite Element Analysis (ET-FEA) Cable Degradation Matrix

Insulation Material	Cable Tray Management Layout	Engine Room Ambient Temp (°C)	Current Electrical Load (A)	Peak Internal Cable Temp (°C)	Predicted Insulation Lifespan (Years)	Stochastic Thermal Runaway Status
Standard PVC	Disorganized / 95% Volume Fill	35	150	78	2.4	LOW RISK PROFILE
Standard PVC	Disorganized / 95% Volume Fill	45	150	98	0.6	CRITICAL THERMAL RUNAWAY
Standard PVC	Disorganized / 95% Volume Fill	55	150	118	0.1	IMMINENT CATASTROPHIC IGNITION
Advanced XLPE	Organized Grid / 40% Volume Fill	35	150	52	25	ABSOLUTELY SECURE
Advanced XLPE	Organized Grid / 40% Volume Fill	45	150	65	18.5	ABSOLUTELY SECURE
Advanced XLPE	Organized Grid / 40% Volume Fill	55	150	78	12.2	STABLE OPERATION PROFILE

The electro-thermal finite element simulation confirms that unventilated, disorganized cable trays containing standard PVC insulation rapidly generate destructive hotspots. When engine room temperatures reach 45°C under standard electrical loads, internal cable temperatures spike to 98°C, dropping the expected insulation lifespan to just 0.6 years and triggering critical thermal runaways. Upgrading to XLPE insulation combined with an organized, 40% maximum volume tray layout suppresses internal cable temperatures to a stable 65°C, extending structural lifespans to 18.5 years and eliminating ignition risks [5].

To evaluate the comprehensive impact of these technico-operational interventions, a high-fidelity stochastic Monte Carlo simulation was executed across 10,000 distinct operational iterations within the ISES-Dynamics framework. The comparative system-wide results are summarized in the performance index below:

Table 5. Comprehensive System Performance Index (Stochastic Monte Carlo Simulation)

System-Wide Safety Performance Metric	Baseline Existing Fleet Configuration	Optimized Retrofitted Configuration	Measured Operational Net Improvement
Overall Emergency Action Success Rate	25%	100%	+75.0% Operational Success Rate
Mean Crew Emergency Response Time	72.0 seconds	44.8 seconds	-27.2 seconds Response Acceleration
Average Crew Emergency Stress Index	78.50%	36.30%	42.2% Psychological Stress Reduction
Probability of Catastrophic Total Blackout	22.00%	2.50%	-19.5% Blackout Probability Reduction
Shipboard Team Coordination Efficiency Index	30.00%	90.00%	+60.0% Inter-departmental

The integrated simulation results show that combining material upgrades (replacing PVC with XLPE/LSZH) [5] with a 40% cable tray fill limit and institutionalizing monthly simulation drills significantly reduces system risk. This comprehensive approach slashes the probability of a catastrophic total blackout from a dangerous 22.0% down to an extremely secure 2.5%, validating the framework's effectiveness.

4.1 Framework Validation

The ISES-Dynamics framework was validated through multiple complementary approaches:

- a. **Technical Validation (ET-FEA):** The Electro-Thermal Finite Element Analysis model was validated by comparing simulated cable temperatures against direct field measurements using a calibrated thermal imaging camera. The difference between simulation results and actual measurements fell within a tolerance range of $\pm 5\%$, indicating acceptable model accuracy.
- b. **Functional Validation (DFTA):** The Dynamic Fault Tree Analysis was validated through "dead ship" scenario analyses that were compared with actual accident data from KNKT reports for similar incidents. DFTA results consistently identified the same failure pathways as accident investigation findings.

4.2 Discussion

The empirical findings of this study strongly align with and expand upon the core tenets of System Safety Engineering and the Human Factors Analysis and Classification System (HFACS) [11], [15]. The results demonstrate that maritime accidents are rarely caused by isolated component failures; instead, they stem from cascading interactions between technical degradation and human cognitive limitations under high stress. The field data gathered from Indonesian RoRo ferries exposes critical technical vulnerabilities, such as using low-grade PVC insulation in hot engine environments, which creates latent systemic risks.

These findings confirm the theoretical models proposed by Rukmini (2021) regarding the vulnerability of shipboard power nodes [8]. However, by incorporating real-time electro-thermal multi-physics modeling, this study reveals that localized thermal cross-talk within disorganized cable trays accelerates insulation failure far faster than standard static reliability models predict.

Furthermore, the agent-based simulation layer successfully quantifies the direct relationship between environmental conditions, organizational training frequencies, and crew cognitive performance. This integration represents a major advancement over the separate analytical approaches found in past literature, particularly in the domain of human reliability analysis (HRA) [16]. While Christodoulou (2019) used static multi-criteria methods to identify human error as a significant risk factor [10], the ISES-Dynamics framework demonstrates exactly how poor training frequencies interact with high-stress environments to paralyze crew response times during critical blackouts. When a vessel experiences an emergency in dim lighting (<20 Lux) with uncoordinated protection controls [9], crew stress spikes to 81%, causing cognitive paralysis and preventing power restoration within the mandatory 45-second SOLAS window [14]. This highlights a clear policy implication for maritime regulators: technical compliance checklists are fundamentally insufficient if they do not account for the human element in safety management systems.

Novelty of ISES-Dynamics:

The primary novelty of ISES-Dynamics lies in the integration of three modeling layers that previously operated in separate analytical silos:

- a. **Integration of Physics-Engineering and Human Factors:** For the first time, DFTA (engineering), ET-FEA (material physics), and ABS (human cognition) are integrated into a single simulation framework for shipboard electrical safety applications.
- b. **Multi-Physics Failure Cascade Modeling:** ISES-Dynamics enables simulation of cascade effects from material degradation (PVC due to heat), through technical failure (short-circuit), to crew cognitive response (manual generator synchronization time).
- c. **Field-Data Calibration:** Unlike previous theoretical studies, this framework is calibrated with actual physical measurement data from three operational RoRo vessels in Indonesia and psychometric questionnaires from 40 crew members.

The practical implications of these findings for ship operators, classification societies, and national regulators are profound. First, operators must transition away

from standard reactive maintenance regimes and adopt strict Reliability-Centered Maintenance (RCM) protocols that prioritize components based on their Risk Priority Numbers (RPN) [12]. Key interventions must include immediate retrofitting programs to replace all PVC insulation in engine spaces with certified XLPE or LSZH materials [6], alongside strict enforcement of a 40% maximum cable-tray volume fill factor. For regulatory bodies like BKI [2] and the Ministry of Transportation, this study provides evidence supporting serious consideration of banning PVC cabling in high-temperature machinery spaces during annual safety audits, though such a recommendation requires further validation through public consultation and limited pilot testing before full-scale implementation. Furthermore, maritime education and training standards must be updated to replace passive classroom lectures with high-fidelity, simulation-based emergency drills conducted at least monthly to lower crew stress and ensure swift power restoration during blackouts.

4.3 Limitations

Despite its significant contributions, this study contains specific limitations that must be acknowledged:

- a. The empirical field observations were restricted to three RoRo passenger ferries within a single regional transit corridor in Indonesia, which limits the direct statistical generalizability of the findings to larger international container vessels or highly automated diesel-electric propulsion cruise liners. Although these findings are consistently strong across the three vessels studied, generalization to the entire national fleet requires further studies with larger and more diverse samples.
- b. The electro-thermal finite element model assumed uniform current loads, omitting transient voltage spikes and high-frequency harmonic distortions that often occur within modern solid-state marine power systems.
- c. **Primary Limitation:** The simulation results, particularly the projected reduction in blackout probability from 22.0% to 2.5%, are derived from stochastic simulations that have not been validated against actual blackout incident data in the field. Full validation would require a long-term longitudinal observation period (minimum 5-10 years) to collect statistically sufficient incident data, which is beyond the scope of this study. Therefore, these findings should be interpreted as robust model-based probabilistic projections, not as deterministic predictions.

Future research should expand the validation of the ISES-Dynamics framework across a wider variety of vessel types, including large commercial gas carriers and fully autonomous ships. Additionally, incorporating machine-learning algorithms into the simulation framework could enable real-time predictive health monitoring of marine insulation networks based on live sensor data [17], further advancing proactive maritime safety systems. To clarify, this can be seen in Figure 3.



Figure 3. Infographic on Safeguarding the Seas: Mitigating Electrical Risks in Ferry Operations

5. CONCLUSION

This study successfully developed, validated, and implemented the Integrated Ship Electrical Safety Dynamics (ISES-Dynamics) framework, a novel hybrid simulation platform that integrates Dynamic Fault Tree Analysis (DFTA), Agent-Based Simulation (ABS), and Electro-Thermal Finite Element Analysis (ET-FEA). Through a mixed-methods investigation of operational RoRo passenger ferries at Bajoe Port, Indonesia, this research demonstrated that severe electrical vulnerabilities, such as using substandard PVC insulation in high-temperature engine rooms ($\geq 35^{\circ}\text{C}$), poor cable routing management, and non-functional synchronization systems are major contributors to maritime risk. Quantitative FMEA models identified catastrophic generator failure ($\text{RPN} = 224$) and high-temperature PVC insulation short-circuits ($\text{RPN} = 216$) as the most critical failure modes within the fleet. Operationally, the study revealed that low training frequencies leave 70% of shipboard personnel unconfident in managing sudden blackout events, resulting in delayed response times that exceed safe regulatory thresholds.

The academic and theoretical significance of this research lies in its successful integration of multi-physics technical modelling with cognitive human-factor simulations within a single framework. This approach moves past traditional, isolated risk assessment methods and reveals the complex, cascading pathways through which localized technical failures interact with human stress to cause catastrophic blackouts. The primary novelty of ISES-Dynamics lies in the integration of three modelling layers that previously operated in separate analytical silos, combining physics-engineering, failure cascade modelling, and field-data calibration into a unified framework.

Practically, stochastic simulations proved that comprehensive technical upgrades specifically replacing PVC with XLPE insulation and enforcing a 40% maximum cable-tray fill factor combined with institutionalizing monthly high-fidelity emergency drills, significantly reduces system risk. This integrated strategy reduces the system-

wide probability of a catastrophic total blackout from 22.0% to 2.5%, while improving crew response times by 27.2 seconds and reducing operational stress indices by 42.2%.

Based on these findings, this study provides evidence-based policy and operational recommendations for the maritime industry. National and international maritime regulators should seriously consider establishing statutory restrictions on PVC insulation within high-ambient machinery spaces during annual class surveys, mandating a transition to XLPE or LSZH materials. However, this recommendation should be viewed as an evidence-based policy proposal that requires further validation through public consultation and limited pilot testing before full-scale implementation. Shipboard safety inspections must move beyond simple visual checklists to incorporate digital thermal imaging audits of cable routing structures to eliminate localized hotspots. Finally, vessel operators must reform safety management protocols by replacing annual safety training with mandatory monthly high-fidelity emergency simulation drills. Implementing these integrated technical and operational standards is crucial to protecting human life, securing valuable maritime assets, and ensuring the continuous safety of global seafaring operations.

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