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Integrated Fire Safety Model for Ship Engine Rooms

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***Abstract*—** Engine room fire remains a major safety concern in commercial shipping because it may originate from the interaction of fuel leakage, lubricating oil, hot surfaces, electrical faults, ventilation conditions, and delayed emergency response. Although international regulations and shipboard safety procedures have established minimum requirements for fire prevention and firefighting, fire incidents in engine rooms continue to occur. This situation indicates that compliance with technical standards alone is not sufficient to ensure effective fire safety readiness. This paper aims to develop an integrated fire safety model for ship engine rooms by linking technical readiness, managerial implementation, and human capability into one conceptual framework. The study uses an integrative literature review and conceptual model development approach. Relevant maritime regulations, peer-reviewed studies on ship engine room fires, fire detection and suppression systems, safety barriers, human factors, and organizational safety theory were reviewed and synthesized. The results show that effective fire prevention and suppression depend on the combined performance of three dimensions. Technical readiness reduces ignition probability and supports early detection and suppression. Managerial implementation ensures that inspections, maintenance, procedures, drills, and supervision function consistently. Human capability strengthens hazard recognition, communication, coordination, decision-making, and emergency response. The proposed model demonstrates that engine room fire safety should be managed as a socio-technical system rather than as a purely technical issue. This model provides a practical framework for shipping companies, maritime education institutions, and safety regulators to improve fire safety readiness in ship engine rooms.

Keywords— engine room, fire safety, firefighting, maritime safety, safety management, ship fire, socio-technical system.

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I. INTRODUCTION

Engine room fire remains one of the most critical safety threats in commercial shipping because it develops in a machinery space where fuel systems, lubricating oil systems, electrical installations, hot surfaces, ventilation flows, rotating equipment, and human operations interact continuously under confined conditions. Unlike open-space fire scenarios, an engine room fire may escalate rapidly because combustible fluids, high-temperature components, oxygen supply, and complex machinery arrangements exist within the same operational environment. When ignitions occur, the consequences are not limited to local equipment damage. Fire may disable propulsion, interrupt electrical generation, reduce steering and auxiliary system reliability, endanger crew members, delay cargo operations, and create secondary environmental or economic losses. Recent maritime fire studies emphasize that ship fires are characterized by high fire load, rapid spread, difficult suppression, and severe consequences for personnel and property, while specific engine room studies consistently identify fuel leakage, hot-surface ignition, delayed detection, and ineffective emergency response as major risk pathways [1]–[5].

The engine room is therefore not merely a technical compartment but a critical safety node in the whole ship system. Its failure may compromise vessel manoeuvrability, cargo continuity, port arrival schedules, emergency preparedness, and the wider reliability of maritime transport. This problem is particularly important for commercial vessels operating under tight schedules, ageing machinery, variable maintenance quality, and diverse crew competency levels. Studies on ship machinery spaces show that the initial causes of fire are often related to pressurized fuel leakage, lubricating oil release, deteriorated pipe connections, thermal insulation failure, electrical overheating, and inadequate control of ventilation during early fire development [6]–[9]. Experimental and simulation-based studies further show that air velocity, ventilation layout, smoke stratification, and thermal conditions significantly influence flame behaviour and smoke movement in marine engine room environments [10], [11]. These findings confirm that engine room fire is not a random event, but the result of interacting technical weaknesses within a high-risk machinery system.

International maritime regulations have established a strong normative foundation for shipboard fire safety. SOLAS requires fire protection, fire detection, fixed fire-extinguishing arrangements, containment measures, and emergency preparedness, while STCW and IMO model courses define minimum competency standards for engineering officers and shipboard personnel involved in fire prevention and firefighting operations [12]–[14]. In principle, these instruments should create an

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internationally consistent safety baseline. However, the continued occurrence of machinery-space fires indicates that regulatory compliance alone does not guarantee operational readiness. A ship may possess approved fire detection systems, fixed CO_2 installations, portable extinguishers, insulation materials, emergency procedures, and certified crew members, while still remaining vulnerable when maintenance is weak, inspections are superficial, drills are formalistic, or crew members cannot make timely decisions under emergency pressure [15]–[17]. This creates a major practical problem: the presence of safety equipment and documents does not always represent the real ability of a ship to prevent, detect, control, and suppress an engine room fire.

Previous research has made significant contributions to the understanding of engine room fire, but the current literature remains fragmented. One group of studies focuses on technical risk mechanisms, including fire risk assessment, fuzzy fault tree analysis, domino effects, ship power system vulnerability, and quantitative modelling of fire escalation in machinery spaces [2], [3], [6], [18]. These studies are valuable because they explain how fire may start and propagate through technical subsystems. Another group of studies examines detection and suppression technologies, including smoke sensors, fire image detection, deep-learning-based recognition, CO_2 systems, water mist suppression, and early fire identification in complex shipboard environments [4], [5], [19]–[21]. A third group of studies investigates ventilation effects, hot-surface ignition, smoke diffusion, and flame behaviour under different airflow conditions [9]–[11]. Although these technical studies improve understanding of specific hazards and control systems, most of them remain subsystem-oriented and do not sufficiently explain how technology interacts with management practice and crew capability during actual ship operations.

Human and organizational studies provide another important perspective. Research using the Human Factors Analysis and Classification System, fuzzy fault tree analysis, bow-tie analysis, and safety barrier approaches demonstrates that engine room fires are also shaped by unsafe acts, inadequate supervision, poor communication, ineffective training, weak safety culture, and degraded organizational barriers [15], [16], [22], [23]. These studies shift the explanation of fire accidents from isolated component failure to socio-technical interaction. However, many of them are retrospective and focus on accident causation after the event has occurred. They identify why accidents happened, but they do not always provide a forward-looking readiness model that can guide prevention, training, inspection, and operational evaluation before an accident occurs. As a result, shipping companies and maritime education institutions still lack an integrated framework that connects technical readiness, managerial implementation, and human capability into one practical model for engine room fire safety.

The research problem addressed in this article emerges from this gap between formal compliance, technical studies, and operational readiness. Current fire safety practices often evaluate shipboard preparedness through separate indicators, such as equipment availability, regulatory documentation, crew certification, maintenance records, or drill completion. These indicators are necessary, but they are insufficient when treated independently. An engine room may have reliable detection equipment, but the system may fail to produce effective safety outcomes if alarms are ignored, maintenance is delayed, or the crew does not understand the correct response sequence. Similarly, a vessel may conduct regular drills, but those drills may not improve emergency capability if they do not simulate realistic communication, ventilation shutdown, fuel isolation, fixed system release, and personnel accountability scenarios. Therefore, the central problem is not simply whether ships have fire safety components, but whether those components function as an integrated readiness system [17], [22]–[25].

The scientific gap of this study is threefold. First, existing engine room fire studies are rich in technical detail but limited in integrative explanation. They explain fuel leakage, hot surfaces, detection, suppression, ventilation, and fire spread, yet they often do not connect those elements with maintenance discipline, procedural control, emergency leadership, and crew decision-making [2], [5], [10], [19]. Second, human-factor and barrier studies explain organizational weakness and unsafe behaviour, but they frequently remain accident-analysis oriented rather than readiness-model oriented [15], [16], [23]. Third, maritime education and competency standards are often discussed separately from engineering risk models, even though crew competence is the bridge between technical systems and emergency performance [12]–[14], [22]. These gaps show the need for a conceptual model that is academically coherent, operationally useful, and educationally relevant.

The novelty of this article lies in developing an Integrated Fire Safety Model for Ship Engine Rooms that combines three interdependent dimensions: technical readiness, managerial implementation, and human capability. Technical readiness refers to the condition and reliability of fuel systems, lubrication systems, hot-surface insulation, electrical installations, ventilation control, detection systems, and suppression equipment. Managerial implementation refers to inspection quality, maintenance discipline, written procedures, emergency drill realism, supervision, documentation, reporting, and safety culture. Human capability refers to knowledge, situational awareness, communication, teamwork, leadership, compliance, and decision-making during both routine prevention and emergency response. By integrating these dimensions, the model moves beyond equipment-based safety assessment and offers a socio-technical explanation of why formally compliant ships may still experience weak fire readiness [1], [15], [18], [23], [25].

This integrated perspective is important because engine room fire safety is determined by interaction rather than isolation. Technical defects create the initial hazard, managerial weaknesses allow the hazard to persist, and human limitations may prevent timely interruption of escalation. Conversely, strong technical systems reduce ignition probability, effective management maintains system reliability, and competent crew members improve early recognition, tactical response, and escalation control. The proposed model therefore treats fire safety readiness as a mediating mechanism that links the three input dimensions to effective prevention and suppression outcomes. In this sense, the model contributes not only to maritime fire safety theory, but also to practical shipboard safety management, inspection design, emergency training, and maritime education curriculum development [3], [16], [20], [22], [24].

II. LITERATURE REVIEW

A. Engine Room Fire as a Socio-Technical Safety Problem.

Engine room fire is widely recognized as one of the most severe fire scenarios in maritime operations because the engine room contains dense arrangements of machinery, pressurized fuel systems, lubrication systems, electrical components, hot surfaces, and ventilation flows. In this environment, fire may develop through direct contact between leaked flammable fluids and ignition sources such as exhaust manifolds, turbochargers, boilers, overheated electrical panels, or insufficiently insulated machinery surfaces. Recent studies on ship fire risk emphasize that shipboard fires are associated with high fire load, rapid spread, difficult suppression, and severe operational consequences, while engine-room-specific studies show that the machinery space remains a major source of fire risk due to the interaction of fuel, heat, oxygen, and human activity [1]–[3], [6], [7], [26]. Therefore, engine room fire should not be understood only as a technical malfunction, but as a socio-technical safety problem involving equipment reliability, operational discipline, crew response, and organizational control.

Previous research has shown that machinery-space fires often follow a chain of causation beginning with leakage, abnormal heat exposure, ignition, delayed detection, ineffective isolation, and escalation. Fire risk assessment studies in ship engine rooms indicate that diesel oil, heavy fuel oil, lubricating oil, and electrical faults are among the dominant sources of ignition and escalation. Kang et al. reported that fire risk in a ship power system under engine room fire conditions can be modelled through fuzzy fault tree analysis and expert comprehensive evaluation, while Zhang et al. emphasized that fire-induced domino effects may occur when one failed unit affects neighbouring units within a complex engine room arrangement [2], [3]. These studies are important because they explain that engine room fire is dynamic rather than static. A minor leakage event may become a major casualty when detection, isolation, ventilation control, and suppression do not operate within a limited response window [2], [3], [6], [18].

B. Technical Readiness in Engine Room Fire Safety

Technical readiness refers to the physical and functional condition of systems that prevent ignition, detect early fire development, suppress fire growth, and support safe emergency response. In the context of ship engine rooms, this dimension includes fuel-line integrity, lubricating oil system condition, hot-surface insulation, electrical installation reliability, ventilation control, fire detection systems, fixed extinguishing systems, portable firefighting appliances, and emergency shutdown arrangements. Studies on ship engine room fire risk consistently show that fuel leakage and hot-surface ignition are among the most critical technical pathways [2], [3], [6], [7]. A risk assessment of ship power systems under engine room fire conditions found that fuel leakages from diesel supply tanks and heavy fuel oil tanks are major accident contributors, confirming that fuel system integrity must be treated as a primary technical priority [3]. Therefore, effective fire prevention begins with controlling the physical sources of ignition and combustible release before they enter the escalation pathway.

Ventilation is another critical element of technical readiness because it has a dual function in engine room safety. Under normal operating conditions, ventilation maintains temperature, removes fumes, and supports machinery operation. During fire events, however, uncontrolled ventilation may supply oxygen, intensify flame spread, influence smoke movement, and reduce suppression effectiveness. Research on ship ventilation and fire incidents shows that ventilation design and control strategy can influence both fire development and smoke distribution [9]–[11]. Studies on engine room fire-induced domino effects also demonstrate that fire development is time-dependent and influenced by automatic detection, human detection, and suppression reliability [2]. This means that ventilation control cannot be separated from detection and suppression systems. A technically ready engine room must therefore have not only adequate ventilation capacity, but also reliable procedures and equipment for shutdown, isolation, and smoke control during emergency conditions.

Fire detection technology has received increasing attention in recent maritime safety research. Traditional systems such as smoke detectors, heat detectors, and flame detectors remain essential, but complex engine room environments may create limitations due to high temperature, vibration, oil mist, air turbulence, and visual obstruction. Recent studies have explored sensor fusion, image-based detection, deep learning, and intelligent monitoring to improve detection speed and accuracy in shipboard environments [4], [5], [19], [26], [27]. Zhang et al. developed a deep-learning-based fire detection approach for ship engine rooms and noted that the complex internal environment of engine rooms creates difficulties for traditional detection methods [4]. More recent reviews of ship fire detection technologies also show a research shift from conventional sensors toward intelligent methods, especially vision-based and deep-learning models [26]. However, detection technology alone cannot guarantee safety if alarm response, maintenance, and emergency decision-making remain weak.

Suppression readiness is equally important because the success of fire control depends on whether fixed and portable systems can be activated correctly and effectively under emergency conditions. CO_2 systems, water mist systems, foam systems, portable extinguishers, and emergency shutdown arrangements are designed to interrupt the fire triangle by reducing oxygen, cooling surfaces, isolating fuel, or suppressing flames. Experimental studies on water mist systems indicate their potential effectiveness in engine room fire suppression, while research on CO_2 systems highlights the importance of correct system design, integrity, and operational procedures [20], [21]. Nevertheless, suppression systems may fail to produce the intended safety outcome if nozzles are clogged, valves are poorly maintained, crew members are unfamiliar with release procedures, or ventilation is not isolated before system activation. This confirms that technical readiness must be evaluated through actual system functionality rather than mere equipment availability.

C. Managerial Implementation and Safety Management

Managerial implementation refers to the way technical fire safety requirements are translated into daily operational practice through inspection, maintenance, supervision, documentation, reporting, emergency drills, and safety culture. The International Maritime Organization has established fire protection requirements through SOLAS and competency requirements through STCW and IMO Model Courses, but the existence of regulations does not automatically guarantee operational readiness [12]–[14]. IMO fire protection guidance emphasizes fire protection, fire detection, and fire extinction as key components of ship safety, while contemporary maritime fire research notes that incidents may persist despite regulatory improvements when operational controls are weak [12], [14], [28]. Therefore, management systems are needed to ensure that equipment, procedures, and crew competence remain functional under real conditions.

Inspection and maintenance are central components of managerial implementation because they determine whether technical systems remain reliable throughout the vessel's operation. Fire safety deficiencies commonly observed in ships include fuel leaks, oil-soaked insulation, defective fire pumps, clogged fire-extinguishing arrangements, ventilation problems, and poorly maintained firefighting appliances [28], [29]. These problems are not purely technical; they reflect weaknesses in maintenance discipline, reporting culture, resource allocation, and supervisory control. In this sense, a vessel may be formally compliant during documentation review but practically unsafe during emergency response. Literature on ship fire risk evaluation also shows that fire risk should be evaluated using multiple indicators because fire occurrence and escalation depend on the combined effects of causes, severity, system reliability, and response capacity [24], [30]. Thus, managerial implementation acts as the bridge between regulatory intention and operational safety performance.

Emergency drills are another key managerial mechanism because they transform written procedures into practical response capability. Fire drills that are repetitive, predictable, or merely formal may produce compliance records without improving actual emergency performance. Effective drills should test hazard recognition, alarm interpretation, communication flow, machinery isolation, ventilation shutdown, boundary cooling, use of portable extinguishers, preparation for fixed-system release, personnel accountability, and command coordination. Human-factor studies of engine room fires show that inadequate training, poor supervision, weak communication, and unsafe acts contribute significantly to fire-explosion accident formation [15], [16]. Therefore, emergency drills should not be evaluated only by frequency, but also by realism, learning value, crew participation, and corrective action after identified weaknesses.

Safety culture influences how consistently the crew and management treat small abnormalities before they become major accident precursors. A weak safety culture may normalize small oil leaks, damaged insulation, temporary repairs, delayed maintenance, blocked access to firefighting appliances, incomplete reporting, or superficial inspection records. Conversely, a strong safety culture encourages early reporting, preventive maintenance, procedural discipline, and shared awareness of fire hazards. Studies on fire prevention and mitigation onboard passenger ships emphasize that maritime fire safety requires attention to socio-technical aspects, including technology, organization, human behaviour, and monitoring systems [28]. This supports the argument that engine room fire safety should not rely only on equipment installation, but should be embedded in a broader safety management system that continuously monitors, corrects, and learns from operational conditions.

D. Human Capability and Crew Competence

Human capability is the third major dimension of engine room fire safety because crew members are responsible for recognizing abnormal conditions, interpreting alarms, isolating hazards, operating firefighting equipment, communicating with the bridge, coordinating emergency teams, and making time-critical decisions. STCW and IMO Model Courses define minimum competency standards for engineering officers, including knowledge of machinery operation, emergency procedures, fire prevention, and firefighting [13], [14]. However, formal certification does not always represent actual emergency competence. In real fire situations, crew members must combine technical knowledge, situational awareness, communication, teamwork, leadership, and decision-making under stress. This makes human capability a practical operational variable, not merely an administrative qualification.

Human-factor studies provide strong evidence that unsafe acts, inadequate supervision, organizational influence, and preconditions for unsafe behaviour contribute to engine room fire and explosion accidents. Uğurlu et al. applied a hybrid HFACS and fuzzy fault tree model to analyse engine-room fire-explosion accidents and showed that human and organizational factors can be structured hierarchically to explain accident formation [15]. Similar research using HFACS and safety barrier approaches indicates that training, supervision, coordination, procedural compliance, and communication are essential variables in preventing fire escalation [16], [22], [23]. These findings show that human capability is not separate from technical readiness. Even advanced detection and suppression systems require crew members who can interpret signals, act correctly, coordinate actions, and avoid procedural errors during high-pressure situations.

Communication and leadership are particularly important during the early stage of engine room fire response. Delayed or unclear communication may result in incorrect assessment of fire location, late ventilation shutdown, inappropriate extinguishing media selection, unsafe entry into smoke-filled spaces, or delayed activation of fixed suppression systems. Team coordination is also essential because engine room fire response involves multiple simultaneous actions, including alarm confirmation, fuel isolation, boundary cooling, evacuation, bridge communication, and preparation of firefighting teams. Studies on maritime risk and barrier analysis show that accident prevention depends on the integrity of preventive and mitigative barriers, including human barriers such as awareness, decision-making, and leadership [22], [23], [31]. Therefore, crew capability must be assessed in relation to realistic emergency tasks rather than only through theoretical knowledge.

E. Integrated Fire Safety Model and Research Position

The literature indicates that technical, managerial, and human dimensions have often been studied separately, although actual engine room fire safety depends on their interaction. Technical studies explain ignition pathways and control mechanisms; managerial studies explain maintenance, inspection, drills, and safety culture; human-factor studies explain unsafe acts, communication failure, supervision weakness, and decision-making limitations [2], [3], [15], [16], [22], [24], [28]. However, the main weakness of the existing literature is that many studies remain focused on one subsystem, one method, or one accident-analysis perspective. This creates a practical limitation for shipping companies and maritime education institutions because they require an operational model that can connect fuel leakage, hot-surface insulation, detection, suppression, maintenance, procedures, and crew competence within one coherent framework.

An integrated model is needed because engine room fire develops through a sequence of interacting failures. Technical defects create ignition potential, managerial weaknesses allow hazards to remain uncorrected, and human limitations reduce the ship's ability to interrupt escalation. Conversely, strong technical readiness reduces the probability of ignition, strong managerial implementation sustains system reliability, and strong human capability improves recognition, communication, and response quality. Recent research on comprehensive ship fire risk evaluation and integrated risk frameworks supports the use of multi-indicator and multi-method approaches because ship fire risk is complex, uncertain, and influenced by both causal and consequence-related factors [24], [30], [32]. Therefore, the present article positions its contribution in the development of an integrated socio-technical model that is conceptually grounded and operationally applicable.

III. METHOD

This study employed an integrative literature review combined with conceptual model development to formulate an Integrated Fire Safety Model for Ship Engine Rooms. This design was selected because engine room fire is a multidimensional maritime safety problem that cannot be explained adequately by a single technical variable, a single human factor, or a single regulatory requirement. Integrative literature review is suitable for synthesizing theoretical, empirical, technical, and regulatory sources in order to generate a broader conceptual understanding of a complex phenomenon [33]–[35]. In this study, the method was used not only to summarize previous research, but also to reorganize fragmented findings on fire risk, technical systems, safety management, and crew capability into one operational framework for engine room fire safety [1]–[3], [15], [17], [22].

The methodological position of this article is conceptual-analytical rather than experimental or survey-based. Therefore, the study did not collect primary data from ships, crew members, shipping companies, or training institutions. Instead, it relied on secondary scientific and normative sources, including peer-reviewed journal articles, international maritime regulations, IMO competency standards, and foundational safety theory. This approach is appropriate because the objective of the article is to develop a conceptual model that explains how technical readiness, managerial implementation, and human capability interact in engine room fire prevention and response [12]–[14], [33], [34]. The method follows the principle that a literature review can function as a research methodology when it is systematic, transparent, critically organized, and directed toward theory or model development [34], [35].

The review process was structured into five main stages: problem formulation, literature identification, literature screening, thematic synthesis, and conceptual model construction. The first stage defined the review problem as follows: how can existing maritime fire safety studies, regulations, and safety theories be integrated into a practical model for ship engine room fire safety? This problem formulation guided the selection of literature and ensured that the review remained connected to the title and objective of the article. The second stage identified relevant literature on ship engine room fire, machinery-space fire, fire detection, fire suppression, ventilation, fire risk assessment, human factors, safety barriers, safety culture, and maritime competency standards [2]–[6], [15], [16], [20], [22], [24].

The literature search focused on reputable academic databases and scholarly indexing platforms commonly used in engineering and maritime safety research. The main sources included Scopus-indexed journals, ScienceDirect, SpringerLink, MDPI journals, Taylor & Francis, Wiley Online Library, IEEE Xplore, Google Scholar for supplementary tracking, and official IMO publications for regulatory documents. The search emphasized recent studies published between 2019 and 2025 in order to ensure that the review reflected current developments in maritime fire risk assessment, intelligent fire detection, water mist suppression, ventilation effects, and socio-technical safety analysis [2]–[5], [20], [24], [26], [30]. Older references were included only when they had strong foundational value, such as organizational accident theory, STCW, SOLAS, IMO Model Courses, and established integrative review methodology [12]–[15], [33].

The search strategy used combinations of maritime, technical, managerial, and human-factor keywords. The main keywords included "ship engine room fire," "machinery space fire," "marine engine room fire risk," "ship fire detection," "ship fire suppression," "water mist engine room," "CO_2 fire extinguishing ship," "ventilation ship fire," "fire risk assessment ship," "bow-tie fire safety," "HFACS engine room fire," "maritime safety management," "crew competency firefighting," and "socio-technical safety model." Boolean operators were applied to combine concepts, for example "ship engine room fire" AND "risk assessment," "machinery space fire" AND "human factors," and "ship fire detection" AND "deep learning." This strategy was designed to capture both technical and non-technical dimensions of engine room fire safety [4], [5], [15], [16], [19], [22].

The inclusion criteria were established before the final synthesis. Sources were included when they met at least one of the following conditions: they directly examined ship engine room fire or machinery-space fire; they discussed fire detection, fire suppression, ventilation, fuel leakage, hot-surface ignition, electrical ignition, or fire risk assessment in maritime contexts; they analyzed human factors, safety barriers, organizational accidents, safety management, or safety culture related to shipboard emergencies; or they provided international regulatory and competency requirements relevant to engine room fire prevention and firefighting [2], [3], [12]–[16], [20]–[24]. These criteria ensured that the literature used in the study was directly connected to the article title, objective, and proposed integrated model.

The exclusion criteria were also applied to improve the relevance and quality of the review. Sources were excluded when they discussed fire safety in non-maritime contexts without clear transferability to ship engine rooms, when they focused only on general occupational safety without connection to shipboard operations, when they lacked academic credibility, when they duplicated arguments already represented by stronger sources, or when they did not provide clear relevance to technical readiness, managerial implementation, or human capability. Conference papers, reports, and web-based materials were used only as supporting references when peer-reviewed journal sources or official IMO documents were insufficient. This screening approach follows the principle that review-based studies should clearly explain why sources are included or excluded in order to improve transparency and trustworthiness [34], [35], [37].

After screening, the selected literature was grouped into four evidence categories. The first category consisted of international maritime regulations and competency standards, including SOLAS, STCW, and IMO Model Courses, which define minimum requirements for fire protection, emergency preparedness, and engineering officer competence [12]–[14]. The second category consisted of technical and engineering studies on ignition mechanisms, fire risk assessment, detection systems, suppression systems, ventilation, and machinery-space hazards [2]–[5], [18]–[21], [24], [26], [30]. The third category consisted of human-factor and organizational safety studies, including HFACS, bow-tie, safety barrier, and socio-technical accident analysis [15], [16], [22], [23]. The fourth category consisted of methodological and theoretical literature supporting integrative review and conceptual model development [33]–[35].

The analytical process used thematic synthesis. Each source was read and coded according to recurring concepts related to engine room fire safety. The initial codes included fuel leakage, lubricating oil leakage, hot surfaces, electrical faults, ventilation, detection, suppression, maintenance, inspection, drills, supervision, documentation, safety culture, training, communication, leadership, teamwork, decision-making, and regulatory compliance. These codes were then grouped into three higher-level analytical dimensions: technical readiness, managerial implementation, and human capability. This thematic grouping was used because previous literature shows that engine room fire is shaped by the interaction of physical hazards, organizational controls, and crew performance rather than by a single isolated factor [2], [3], [15], [16], [22].

Technical readiness was operationalized as the condition and reliability of physical systems that prevent ignition, support early detection, and enable effective suppression. This dimension includes fuel system integrity, lubrication system condition, hot-surface insulation, electrical installation reliability, ventilation control, fire detection systems, fixed extinguishing systems, portable firefighting equipment, and emergency shutdown arrangements [2]–[5], [18]–[21]. Managerial implementation was operationalized as the ability of the shipboard and company safety management system to maintain technical reliability and procedural readiness through inspection, maintenance, drills, supervision, reporting, documentation, and safety culture [12], [15],

[16], [22], [28]. Human capability was operationalized as the crew's ability to recognize hazards, interpret alarms, communicate effectively, coordinate actions, lead emergency response, comply with procedures, and make decisions under pressure [13]–[16], [22].

The synthesis was conducted through comparative interpretation across the three analytical dimensions. First, technical studies were examined to identify how fires begin and how physical control systems function. Second, management and regulatory sources were examined to identify how those technical systems should be maintained, inspected, documented, and practiced. Third, human-factor studies were examined to identify how crew members influence prevention, initial response, and escalation control. The findings from these three streams were then compared to identify convergence, contradiction, and complementarity. This comparative process made it possible to develop an integrated explanation of why ships may remain vulnerable to engine room fire even when regulatory requirements and firefighting equipment are formally present [1]–[3], [15]–[17], [22].

Conceptual model development was carried out after the thematic synthesis. The model was constructed by positioning technical readiness, managerial implementation, and human capability as input dimensions that jointly influence fire safety readiness. Fire safety readiness was then conceptualized as a mediating condition consisting of hazard identification, early detection, initial response quality, and escalation control. The final outcome of the model is effective prevention and suppression of ship engine room fire. This conceptual construction follows the logic of integrative review, in which fragmented findings from prior studies are reorganized into a new framework that has explanatory and practical value [33],[34]. In this study, the model is intended to support maritime safety management, shipboard inspection, emergency training, and maritime education curriculum development.

To improve methodological transparency, the study also applied source triangulation. Regulatory documents were used to establish normative safety and competency requirements. Technical studies were used to explain fire initiation, propagation, detection, and suppression mechanisms. Human-factor and organizational studies were used to explain why safety systems may fail despite formal compliance. Methodological literature was used to guide the structure of the integrative review and strengthen the reliability of the synthesis [12]–[16], [22], [33]–[35]. This triangulation reduced dependence on a single type of evidence and allowed the final model to reflect both engineering and socio-technical dimensions of engine room fire safety.

The quality of evidence was assessed qualitatively based on relevance, recency, source credibility, and contribution to model development. Priority was given to peer-reviewed journal articles published in reputable journals such as *Journal of Marine Science and Engineering*, *Ocean Engineering*, *Safety Science*, *Fire Technology*, *Sensors*, *Fire*, and *Reliability Engineering & System Safety*. Regulatory sources from IMO were treated as authoritative normative references even when their publication dates were older, because they remain central to international maritime safety compliance [12]–[14]. Foundational theoretical and methodological sources were retained when they provided essential conceptual support for accident theory, integrative review, or review transparency [15], [33]–[35].

This study has methodological limitations. First, it does not present primary empirical data from onboard observation, interviews, questionnaires, or accident investigation records collected by the authors. Second, the analytical weights assigned to technical readiness, managerial implementation, and human capability should be understood as conceptual interpretation rather than statistical measurement. Third, the proposed model has not yet been validated through field testing on specific vessel types. However, these limitations are consistent with the conceptual objective of the article. The model developed in this study should therefore be treated as an evidence-based framework that is ready for future empirical validation using shipboard surveys, expert judgment, accident case analysis, simulation, or mixed-method maritime safety research [33]–[35].

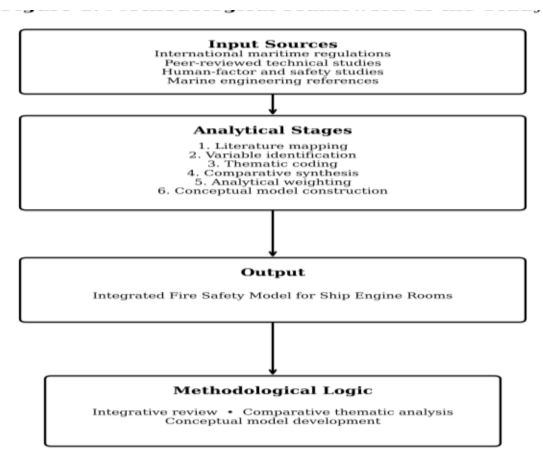

Figure 1. Methodological Framework of the Study

The methodological process of this article may be summarized through Fig. 1, which links input sources, analytical stages, and final conceptual output. The validity of the analysis was strengthened through triangulation of source categories. Regulatory documents established what safe engine room fire management should look like [4]–[7]; technical studies explained how fire hazards emerge and how engineering controls function [1]–[3], [8]–[14], [17]–[20]; and human-factor studies clarified why hazard escalation continues despite formal safety systems [15], [16], [20]. Analytical reliability was also supported by consistent coding against the same three core dimensions.

Although this article does not use primary field data, it follows scholarly ethics by clearly distinguishing between literature-based analytical findings and primary empirical findings. The study does not claim onboard survey results or experimental outcomes that were not actually conducted. Instead, it presents a valid conceptual synthesis supported by peer-reviewed sources and international standards. The methodological contribution of the article lies in its ability to connect fragmented maritime fire studies into a single operational framework that is systematic, transparent, visually interpretable, and ready for future empirical validation

IV. Results and Discussion

This section presents the results of the integrative literature review and discusses their implications for the development of an Integrated Fire Safety Model for Ship Engine Rooms. The findings are organized according to the three analytical dimensions established in the method section: technical readiness, managerial implementation, and human capability. These dimensions are then integrated into a conceptual model that explains how engine room fire safety is formed through the interaction of physical systems, organizational control, and crew performance. Since this study is conceptual and literature-based, the analytical results should not be interpreted as primary statistical findings from onboard surveys or experiments. Instead, the numerical values presented in this section represent structured analytical weights derived from the intensity, recurrence, and explanatory relevance of themes identified in the reviewed literature [33]–[35].

A. Overview of the Synthesized Evidence

The review shows that engine room fire is consistently explained in the literature as a multi-causal and dynamic safety problem. Technical studies emphasize leakage, hot surfaces, electrical faults, ventilation effects, detection limitations, and suppression reliability as dominant fire-related variables. Human-factor and organizational studies emphasize unsafe acts, weak supervision, poor communication, inadequate training, procedural non-compliance, and degraded safety barriers. Regulatory documents provide the normative baseline for fire protection, detection, suppression, emergency preparedness, and engineering competency. When these sources are compared, a clear pattern emerges engine room fire safety cannot be explained by one dimension alone. Fire may begin from a physical technical defect, but its escalation is strongly influenced by managerial control and human response.

To make the synthesis more transparent, the reviewed evidence was classified into four source categories: regulatory standards, technical engineering studies, human-factor and safety-barrier studies, and methodological or conceptual references. Each category contributed differently to the model. Regulatory sources established what should be achieved; technical studies explained how fire develops and how systems work; human-factor studies explained why formal safety arrangements may fail in practice; and methodological sources supported the integrative review and model-building process. Table 1 summarizes the contribution and limitation of each evidence category.

Table 1.
Quality and Contribution of Evidence Sources

Evidence Category	Main Contribution	Main Limitation	Role in the Integrated Model
Maritime regulations and competency standards	Define minimum requirements for fire protection, detection, suppression, emergency response, and crew competence	Normative and not based on specific shipboard field data in this study	Establishes regulatory baseline for fire safety readiness
Technical engineering studies	Explain ignition mechanisms, fuel leakage, hot-surface exposure, ventilation effects, detection, and suppression	Often subsystem-specific and not fully integrated with human and managerial factors	Defines technical readiness variables
Human-factor and safety-barrier studies	Explain unsafe acts, supervision weaknesses, communication problems, training gaps, and barrier degradation	Often retrospective and accident-analysis oriented	Defines human capability and managerial implementation variables
Methodological and conceptual studies	Support integrative review, thematic synthesis, and conceptual model development	Do not provide direct fire accident data	Strengthens transparency and logic of model construction

Interpretive note: Table 1 shows that the strength of this study does not come from one single source type, but from the triangulation of regulatory, technical, organizational, and methodological evidence. This triangulation supports the development of an integrated model rather than a subsystem-specific explanation.

The quality appraisal indicates that the reviewed literature provides strong conceptual and technical support for model development. However, the evidence also has limitations. Many technical studies focus on specific components, such as detection systems, water mist suppression, ventilation, or fire risk modelling. Meanwhile, human-factor studies often focus on accident causation after an event has occurred rather than on readiness before the event. This confirms the central research gap of the article: existing studies explain important parts of engine room fire safety, but they rarely combine those parts into one operational model that can be used by shipping companies, maritime educators, and regulators.

B. Technical Readiness as the First Dimension of Fire Safety

The first major finding is that technical readiness remains the most visible and direct determinant of engine room fire risk. The reviewed literature consistently identifies fuel leakage, lubricating oil leakage, hot surfaces, electrical faults, ventilation problems, delayed detection, and suppression limitations as the most important technical variables. These variables form the physical pathway through which fire begins and develops. In most engine room scenarios, fire does not appear suddenly without precursors. It usually develops through a chain beginning with combustible release, contact with an ignition source, delayed recognition, insufficient isolation, and escalation.

Fuel system integrity is the most critical technical issue because pressurized fuel leakage may produce spray, mist, or vapour that can ignite rapidly when exposed to hot surfaces. Hot surfaces such as exhaust manifolds, turbochargers, boilers, and poorly insulated machinery components create an ignition environment that is difficult to eliminate completely during ship operation]. Lubricating oil leakage creates an additional combustible load and can intensify fire spread after ignition. Electrical faults also remain important because short circuits, overloaded panels, poor insulation, and overheating components may become ignition sources in confined machinery spaces. These technical findings confirm that engine room fire prevention must begin with systematic control of leakage, insulation, electrical reliability, and abnormal heat exposure.

Ventilation has a dual role in engine room fire safety. During normal operation, it supports machinery cooling, air circulation, and safe working conditions. During fire, however, uncontrolled ventilation may supply oxygen, accelerate flame spread, influence smoke movement, and reduce the effectiveness of fixed extinguishing systems. This dual role makes ventilation a strategic technical variable. A technically ready ship must not only have adequate ventilation capacity, but also reliable ventilation shutdown and isolation procedures during emergency response. Detection and suppression systems are also essential because they determine whether an initial fire can be identified and controlled before it becomes a major casualty.

TABLE 2.
TECHNICAL READINESS VARIABLES AND THEIR FIRE SAFETY FUNCTIONS

Technical Variable	Fire Safety Function	Risk if Weak	Model Implication
Fuel system integrity	Prevents leakage, spray, and mist formation	Rapid ignition when fuel contacts hot surfaces	Primary prevention barrier
Lubricating oil system condition	Reduces additional combustible load	Faster fire growth and spread	Secondary prevention barrier
Hot-surface insulation	Reduces ignition probability	Direct ignition pathway after leakage	Critical ignition control
Electrical installation reliability	Prevents sparks, overheating, and short circuits	Secondary ignition source	Electrical hazard control
Ventilation control	Regulates oxygen supply and smoke movement	Increased flame spread and suppression difficulty	Escalation control mechanism
Fire detection system	Supports early warning and hazard recognition	Delayed initial response	Early response trigger
Fixed and portable suppression systems	Controls or extinguishes fire growth	Uncontrolled escalation	Mitigation and damage control

Interpretive note: Table 2 demonstrates that technical readiness is not a single variable. It is a system of preventive, detective, and mitigative controls. Its contribution to the integrated model lies in reducing ignition probability and supporting early intervention.

The technical dimension contributes directly to the proposed model because it explains how engine room fire physically begins and how engineering controls interrupt the fire pathway. However, technical readiness alone is not enough. A fire detection system may be installed but poorly maintained. A CO_2 system may be available but not correctly prepared for activation. Insulation may exist but may be damaged by vibration, heat, age, or poor maintenance. Portable extinguishers may be present but inaccessible or unsuitable for the fire class. Therefore, the technical dimension must be connected to managerial implementation and human capability. This is the first key contribution of the integrated model: it prevents technical variables from being interpreted as independent safety guarantees.

C. Managerial Implementation as the Second Dimension of Fire Safety

The second major finding is that managerial implementation determines whether technical fire safety systems remain functional in real ship operations. This dimension includes inspection quality, maintenance discipline, emergency drills, documentation, reporting, supervision, and safety culture. The reviewed literature indicates that many shipboard safety weaknesses are not caused by the absence of equipment, but by the poor implementation of maintenance, inspection, and emergency procedures. In other words, managerial implementation transforms formal compliance into operational readiness.

Inspection is the first managerial barrier because it identifies abnormal conditions before they become accident precursors. In the engine room, inspection should detect fuel leakage, oil accumulation, damaged insulation, abnormal temperatures, electrical defects, blocked access, alarm malfunction, poor housekeeping, and ventilation problems. If inspection becomes superficial, repetitive, or documentation-oriented, small defects may remain hidden until they interact with other hazards. Maintenance discipline is equally important because fire pumps, sensors, extinguishers, valves, dampers, alarms, CO_2 systems, water mist systems, and shutdown mechanisms require continuous functional reliability. Weak maintenance creates false readiness: the ship appears compliant, but its systems may fail when needed.

Emergency drills are the practical bridge between procedures and actual response. A written procedure does not guarantee that crew members can perform coordinated actions under stress. Effective drills should test fire alarm confirmation, engine room communication, ventilation shutdown, fuel isolation, boundary cooling, portable extinguisher use, fixed-system preparation, evacuation, personnel accountability, and command decision-making. If drills are predictable or formalistic, they may produce records but not competence. The literature on human factors and accident causation shows that weak training, poor supervision, and ineffective communication may significantly increase the probability of escalation in engine room fire events.

TABLE 3.
MANAGERIAL IMPLEMENTATION VARIABLES AND THEIR SAFETY ROLES

Managerial Variable	Operational Role	Risk if Weak	Contribution to Integrated Model
Inspection quality	Detects abnormalities before escalation	Hidden hazards remain uncorrected	Converts hazard awareness into prevention
Maintenance discipline	Sustains equipment and system reliability	Fire systems fail during emergency	Maintains technical readiness
Emergency drill realism	Tests actual response capability	Crew response becomes slow or fragmented	Strengthens preparedness
Documentation and reporting	Records hazards, defects, and lessons learned	Near misses are not translated into improvement	Builds safety memory
Supervision	Reinforces procedural compliance	Unsafe routines become normalized	Prevents barrier erosion
Safety culture	Shapes preventive attitude and reporting behaviour	Small deviations become accepted practice	Supports continuous readiness

Interpretive note: Table 3 shows that managerial implementation is the enabling layer of the integrated model. It determines whether technical systems remain reliable and whether emergency procedures become operationally meaningful.

The contribution of managerial implementation to the integrated model is that it explains why formally compliant ships may still be unsafe. Compliance may show that a ship has required systems and documents, but readiness depends on whether those systems and documents work in practice. A ship with advanced detection systems but weak maintenance may still suffer delayed warning. A ship with complete emergency procedures but unrealistic drills may still experience confusion during fire response. A ship with certified engineers but poor safety culture may tolerate oil leaks, insulation damage, or incomplete reporting. Therefore, managerial implementation acts as the organizational mechanism that sustains or weakens technical readiness and human capability.

D. Human Capability as the Third Dimension of Fire Safety

The third major finding is that human capability is not merely a supporting factor, but a core determinant of engine room fire safety. Crew members are the actors who observe abnormalities, interpret alarms, report hazards, isolate systems, operate firefighting equipment, communicate with the bridge, coordinate emergency teams, and make decisions under pressure. In this context, competence should not be understood only as certification. It should be understood as demonstrated operational capability during prevention and emergency response.

Human capability consists of several interrelated elements: technical knowledge, hazard awareness, situational interpretation, communication, teamwork, leadership, procedural compliance, and decision-making. Technical knowledge allows crew members to understand the relationship between fuel systems, lubricating oil systems, hot surfaces, ventilation, and ignition sources. Situational awareness helps the crew detect abnormal smell, smoke, temperature, leakage, vibration, or alarm patterns. Communication ensures that information moves quickly and clearly between the engine room, bridge, emergency team, and command structure. Leadership and teamwork are required because fire response involves simultaneous actions that must be coordinated within a short time window

The literature on HFACS and barrier analysis shows that unsafe acts, inadequate supervision, weak communication, and poor training contribute significantly to engine room fire and explosion accidents. These findings indicate that human error should not be treated simply as individual negligence. It often reflects deeper weaknesses in training, supervision, procedure design, workload, safety culture, and organizational learning. This is consistent with the socio-technical perspective used in this article. Human capability develops and functions within a system; it is strengthened by realistic drills, clear procedures, reliable equipment, and strong leadership.

The contribution of human capability to the integrated model lies in connecting technical systems and managerial procedures to real-time action. Fire detection does not suppress fire by itself. Procedures do not execute themselves. Suppression systems must be prepared, activated, and coordinated by trained personnel. Therefore, the integrated model positions human capability as a decisive dimension in early response and escalation control. Without capable crew members, even technically advanced and procedurally complete systems may fail to produce effective safety outcomes.

TABLE 4.
HUMAN CAPABILITY VARIABLES AND THEIR EMERGENCY FUNCTIONS

Human Capability Variable	Function in Fire Safety	Risk if Weak	Model Contribution
Technical knowledge	Supports understanding of fire causes and system interactions	Misinterpretation of hazards	Improves preventive awareness
Situational awareness	Identifies early abnormal conditions	Delayed recognition	Strengthens early detection
Communication	Transfers information rapidly and clearly	Confusion and delayed action	Supports coordinated response
Teamwork	Integrates multiple emergency actions	Fragmented response	Improves initial control
Leadership	Directs decisions under pressure	Tactical hesitation	Strengthens command effectiveness
Procedural compliance	Ensures correct emergency sequence	Unsafe or inconsistent actions	Reduces response error
Decision-making	Determines isolation, suppression, and evacuation actions	Escalation due to late or wrong decisions	Supports escalation control

Interpretive note: Table 3 shows that managerial implementation is the enabling layer of the integrated model. It determines whether technical systems remain reliable and whether emergency procedures become operationally meaningful

E. Analytical Weighting of the Three Dimensions

To clarify the relative explanatory contribution of the three dimensions, this study developed a comparative analytical weighting based on the reviewed literature. The weighting was derived from three interpretive criteria: frequency of appearance in the reviewed sources, explanatory strength in accident development, and operational relevance to prevention and response. This procedure does not represent inferential statistics, survey percentages, or experimental measurement. It is a structured conceptual statistic designed to make the literature synthesis more transparent and visually interpretable.

The analysis indicates that technical readiness carries the largest individual explanatory weight because most engine room fire scenarios begin with physical hazards such as leakage, hot surfaces, electrical faults, ventilation effects, and detection or suppression limitations. However, managerial implementation and human capability together represent the larger share of operational readiness because they determine whether technical hazards are detected, corrected, reported, and controlled. This finding is important because it challenges equipment-centered interpretations of fire safety. Fire prevention is not achieved only by installing systems; it is achieved by ensuring that systems are maintained, procedures are practiced, and crew members are capable of acting correctly.

TABLE 5.
COMPARATIVE ANALYTICAL WEIGHT OF FIRE SAFETY DIMENSIONS

Dimension	Main Components	Analytical Weight	Interpretation
Technical readiness	Fuel systems, lubrication systems, hot surfaces, electrical systems, ventilation, detection, suppression	45%	Explains physical ignition pathways and engineering controls
Managerial implementation	Inspection, maintenance, procedures, drills, reporting, supervision, safety culture	27%	Explains whether hazards are corrected or allowed to persist
Human capability	Knowledge, awareness, communication, teamwork, leadership, compliance, decision-making	28%	Explains how effectively the crew responds before escalation
Total	Integrated socio-technical readiness	**100%**	Fire safety depends on interaction among all three dimensions

Interpretive note: Table 5 should be read as conceptual analytical weighting, not as empirical statistical measurement. The table indicates that technical factors are dominant visible triggers, but managerial and human factors jointly account for most readiness conditions

For the revised manuscript, Figure 1 should present these weights in a simple full-width bar chart or pie chart. The figure should not be decorative; it must tell the story that engine room fire safety is not dominated by a single factor.

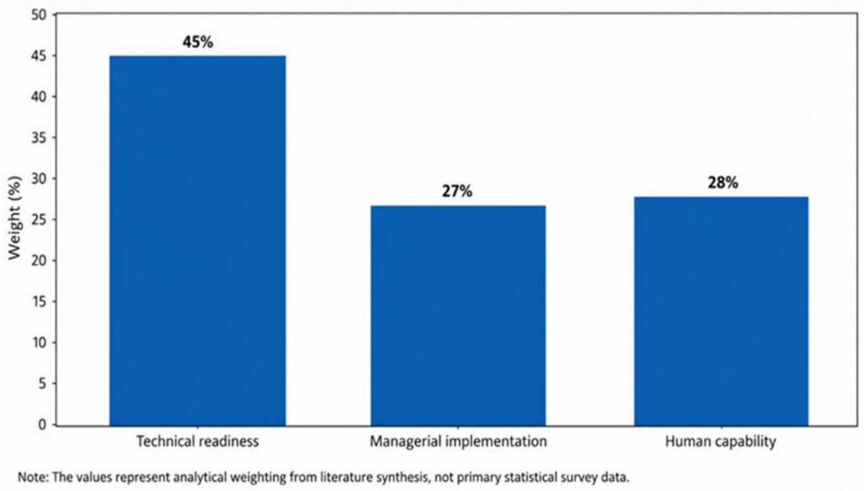

Figure 1. Comparative Analytical Weight of Engine Room Fire Safety Dimensions.

The chart should show technical readiness at 45%, managerial implementation at 27%, and human capability at 28%. A note should be added below the figure*: "The values represent analytical weighting from literature synthesis, not primary statistical survey data."* This note is important to prevent reviewer misunderstanding.

F. Causal Chain of Engine Room Fire Development

The synthesis also shows that engine room fire develops through a causal chain rather than through a single isolated cause. The typical chain begins with technical abnormality, such as fuel leakage, lubricating oil leakage, electrical overheating, or hot-surface exposure. This abnormality becomes dangerous when managerial controls fail to identify or correct it through inspection and maintenance. The hazard then escalates when detection is delayed, communication is unclear, ventilation control is late, fuel isolation is incomplete, or suppression is ineffective.

The revised manuscript should present this process as a full-width visual diagram. The recommended structure is:

Technical Abnormality → Ignition Potential → Detection Delay → Response Weakness → Escalation → Fire Consequence

Each stage should also show the relevant control barrier. For example, inspection and maintenance control technical abnormality; insulation and electrical reliability reduce ignition potential; detection systems and watchkeeping reduce detection delay; drills and communication improve response; suppression and ventilation control reduce escalation. This diagram will make the discussion more readable and demonstrate that the article does not merely list variables but explains how they interact dynamically.

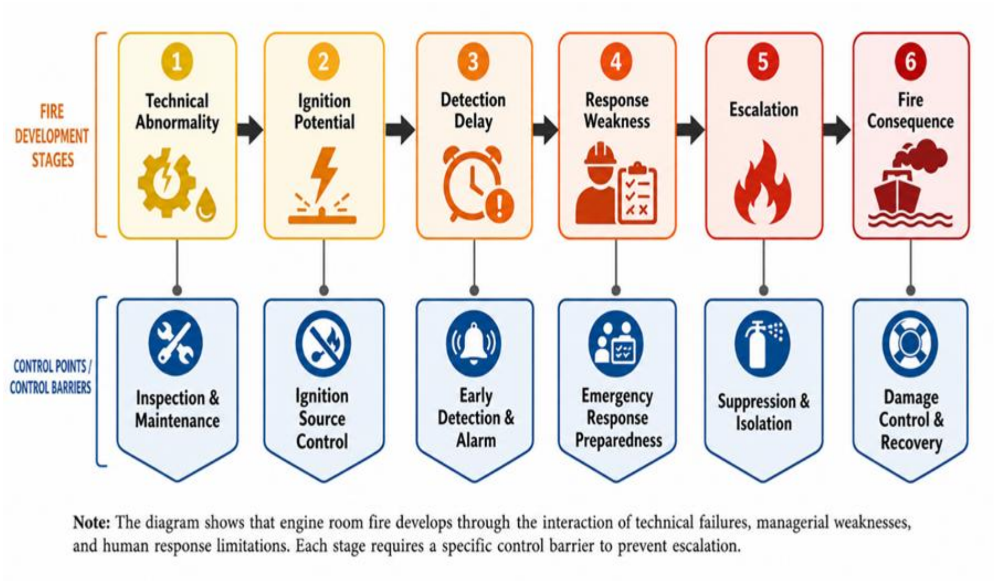

Figure 2. Causal Chain of Engine Room Fire Development and Control Points

This figure strengthens the novelty of the article because it visually links the three dimensions into one accident-development pathway. It also supports the argument that fire safety readiness must be evaluated across the full chain, from prevention to escalation control. A vessel may be weak at any point in this chain. If inspection is weak, hazards persist. If detection is weak, early warning fails. If communication is weak, response is delayed. If suppression is weak, escalation continues. The causal-chain figure therefore becomes an important bridge between the literature review and the final integrated model.

G. Layered Barrier Interpretation

The reviewed literature also supports the interpretation of engine room fire safety as a layered barrier system. Technical barriers include fuel containment, insulation, electrical protection, ventilation control, detection, and suppression. Managerial barriers include inspection, maintenance, procedures, drills, supervision, and reporting. Human barriers include awareness, communication, teamwork, leadership, and decision-making. A fire accident occurs when several barriers degrade at the same time or fail sequentially.

This barrier interpretation is useful because it explains why ships with formal compliance may still experience serious fire incidents. Compliance may confirm that barriers exist, but it does not guarantee that the barriers are strong, connected, or functional. For example, a fire detector may exist as a technical barrier, but if it is poorly maintained, the managerial barrier is weak. If the alarm is ignored or misunderstood, the human barrier is weak. If ventilation is not stopped before fixed-system activation, the technical and human barriers fail together. Therefore, the integrated model must evaluate not only the presence of barriers but also their operational reliability.

The revised manuscript should include a layered barrier diagram as a full-width figure. The recommended structure is:

Hazard Source → Technical Barrier → Managerial Barrier → Human Barrier → Fire Safety Readiness → Prevention/Suppression Outcome

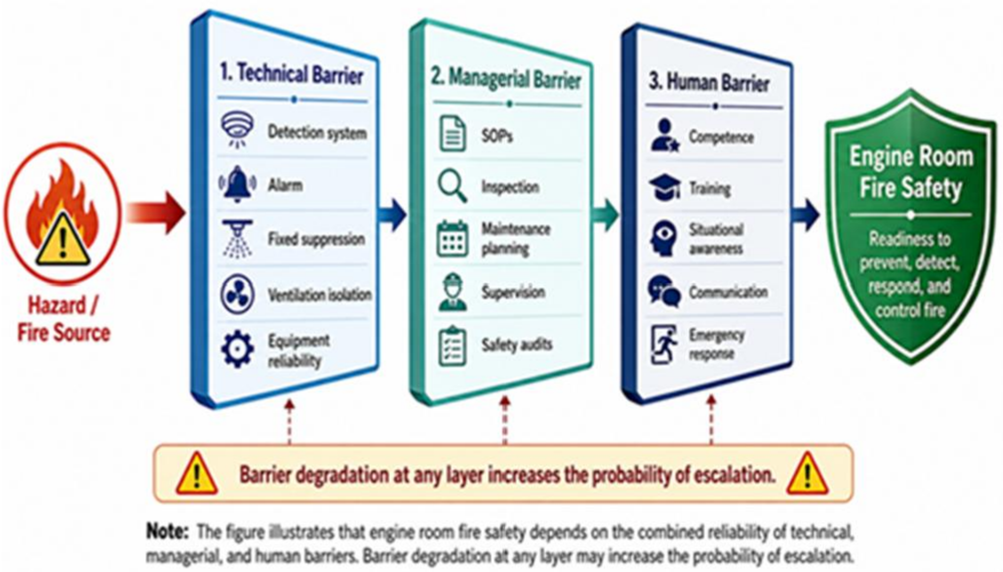

Figure 3. Layered Barrier Structure in Engine Room Fire Safety

This diagram helps the tables "tell a story." Table 2 explains technical variables, Table 3 explains managerial variables, Table 4 explains human variables, Table 5 explains analytical weight, and Figure 3 explains how all variables operate as barriers. This improves the presentation quality and responds directly to the editor's requirement that tables and figures be clear, full-width, and written fully in English.

H. Final Integrated Fire Safety Model

The final result of this study is the formulation of the Integrated Fire Safety Model for Ship Engine Rooms. The model consists of three input dimensions, one mediating readiness mechanism, and one final safety outcome. The input dimensions are technical readiness, managerial implementation, and human capability. These dimensions jointly influence fire safety readiness, which consists of hazard identification, early detection, initial response quality, and escalation control. The final outcome is effective prevention and suppression of engine room fire.

contribution lies in integrating fragmented maritime fire research into one operational framework. Previous studies have explained technical hazards, detection systems, suppression systems, ventilation effects, human factors, and safety barriers separately. The proposed model reorganizes these separate findings into a single socio-technical structure. It shows that technical systems reduce ignition probability, managerial systems maintain reliability and procedural consistency, and human capability determines the quality of real-time response.

TABLE 6.
STRUCTURE OF THE INTEGRATED FIRE SAFETY MODEL

Model Component	Main Elements	Function	Expected Safety Outcome
Technical readiness	Fuel integrity, lubrication control, insulation, electrical reliability, ventilation, detection, suppression	Reduces ignition and supports control	Lower probability of fire initiation
Managerial implementation	Inspection, maintenance, drills, supervision, reporting, safety culture	Maintains system reliability and procedural readiness	Stronger preventive control
Human capability	Knowledge, awareness, communication, teamwork, leadership, decision-making	Executes prevention and emergency response	Faster and more accurate response
Fire safety readiness	Hazard identification, early detection, initial response, escalation control	Mediates the three dimensions into action	Improved prevention and suppression
Final outcome	Reduced fire occurrence and reduced fire severity	Indicates model effectiveness	Safer engine room operation

Interpretive note: Table 6 clarifies that the integrated model is not a simple list of factors. It is a functional relationship among system condition, organizational practice, human performance, readiness mechanisms, and safety outcomes.

The final model should be presented as a full-width diagram. The left side should show the three input dimensions. The middle should show fire safety readiness. The right side should show effective fire prevention and suppression. Feedback arrows should be added from “incident reporting and learning” back to managerial implementation and human capability. This feedback loop is important because it shows that the model is not static. Engine room fire safety should improve continuously through reporting, evaluation, training, maintenance correction, and procedural revision.

Figure 4. Integrated Fire Safety Model for Ship Engine Rooms

I. Discussion of the Model Contribution

The integrated model contributes to maritime fire safety literature in three ways. First, it provides a socio-technical explanation of engine room fire safety. Instead of treating fire as a purely technical event, the model explains fire safety as the outcome of interaction among equipment, procedures, management, and crew action. This is important because machinery-space fires often begin with technical defects, but their severity depends on inspection, maintenance, communication, decision-making, and emergency coordination. Therefore, the model offers a broader explanation than equipment-based or accident-cause-based approaches.

Second, the model has practical value for shipping companies. It can be used as a basis for integrated engine room fire audits. Conventional inspections often focus on whether equipment exists and whether documents are available. The proposed model encourages a more complete audit approach by asking whether fuel systems are leak-free, insulation is intact, alarms are functional, extinguishing systems are maintained, drills are realistic, crew members understand emergency sequences, and communication pathways are effective. This makes the model useful for safety management systems because it connects physical inspection with procedural and human readiness.

Third, the model has educational value for maritime training institutions. Fire safety education should not only teach types of extinguishers, fire classes, or regulatory requirements. It should also train cadets and engineering officers to recognize machinery-space hazards, understand escalation pathways, communicate during emergencies, lead response teams, isolate systems, coordinate with the bridge, and make decisions under pressure. The model can therefore be translated into simulation scenarios, competency-based assessment, and integrated engine room emergency exercises.

The model also has regulatory implications. Regulators and port state control officers may use the integrated perspective to evaluate operational readiness beyond formal compliance. Equipment inventory and certification are necessary, but they are not sufficient indicators of safety performance. A more meaningful evaluation should include maintenance history, drill quality, crew familiarity, hazard reporting, corrective actions, and evidence of learning from near misses. In this way, the model supports a shift from document-based compliance to readiness-based safety evaluation.

J. Final Interpretation of Findings

The final interpretation of this study is that engine room fire safety depends on the simultaneous strength of technical readiness, managerial implementation, and human capability. Technical readiness explains how fire hazards physically emerge and how engineering systems can prevent or control them. Managerial implementation explains whether those systems remain reliable and whether procedures become actual practice. Human capability explains whether crew members can recognize, communicate, decide, and act effectively before escalation occurs. These three dimensions are inseparable.

The analytical weighting shows that technical readiness has the highest individual weight at 45%, but managerial implementation and human capability together account for 55% of the explanatory structure. This means that the majority of fire safety readiness depends on organizational and human conditions that support the technical system. Therefore, the most important implication of the study is that engine room fire safety should not be improved through isolated technical upgrades alone. It should be improved through integrated action: better equipment reliability, stronger maintenance and inspection systems, more realistic drills, clearer procedures, stronger safety culture, and higher crew emergency competence.

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V. Conclusion

This paper aimed to develop an integrated fire safety model for ship engine rooms by linking technical readiness, managerial implementation, and human capability into one conceptual framework. Based on the integrative literature review and conceptual model development, the study confirms that engine room fire safety cannot be explained only by the presence of firefighting equipment, regulatory compliance, or crew certification. Instead, effective fire prevention and suppression depend on the interaction of physical systems, organizational practices, and crew performance. The findings show that technical readiness is the first essential dimension of engine room fire safety. Fuel system integrity, lubrication system condition, hot-surface insulation, electrical reliability, ventilation control, fire detection systems, and suppression equipment directly influence the probability of ignition, early detection, and fire control. However, technical readiness alone is insufficient if the systems are not inspected, maintained, tested, and operated correctly.

The second dimension is managerial implementation. Inspection quality, maintenance discipline, emergency procedures, drill realism, supervision, documentation, reporting, and safety culture determine whether technical fire safety systems remain reliable in daily shipboard operations. This study shows that managerial weakness may create false readiness, where a vessel appears compliant but remains vulnerable during actual fire emergencies.

The third dimension is human capability. Crew knowledge, hazard awareness, communication, teamwork, leadership, procedural compliance, and decision-making are decisive in transforming technical systems and written procedures into effective emergency response. The model demonstrates that crew competence should be understood not only as formal certification, but also as practical capability to recognize hazards, coordinate action, isolate fire sources, and control escalation under pressure.

The main contribution of this paper is the proposed Integrated Fire Safety Model for Ship Engine Rooms. The model positions technical readiness, managerial implementation, and human capability as three interdependent input dimensions that jointly form fire safety readiness. This readiness is expressed through hazard identification, early detection, initial response quality, and escalation control. The final expected outcome is more effective prevention and suppression of engine room fires. Therefore, the novelty of this study lies in shifting the understanding of engine room fire safety from a fragmented technical issue to an integrated socio-technical readiness system.

This model has practical implications for shipping companies, maritime education institutions, and safety regulators. Shipping companies may use the model to design integrated engine room fire audits that evaluate not only equipment availability but also maintenance quality, drill effectiveness, crew response, and safety culture. Maritime education institutions may use the model to strengthen competency-based training through simulation, scenario-based learning, emergency communication exercises, and integrated engine room fire response assessment. Regulators and inspectors may use the model to evaluate operational readiness beyond documentation and formal compliance.

Since this study is conceptual and literature-based, the proposed model should be treated as an evidence-based framework that requires further empirical validation. Future studies should test the model using shipboard observation, expert judgment, questionnaire surveys, accident case analysis, simulation, and interviews with engineering officers and safety managers. Further validation across different vessel types, such as cargo ships, tankers, passenger ships, and offshore vessels, would strengthen the applicability and reliability of the model in real maritime operations.

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REFERENCES

[1] A. Alvarez, F. Pineda, and M. Martínez, "Machinery space fire casualty analysis in commercial ships," *WMU Journal of Maritime Affairs*, vol. 18, no. 4, pp. 567–584, 2019.

[2] H. Zhang, C. Li, N. Zhao, B. Q. Chen, H. Ren, and J. Kang, "Fire risk assessment in engine rooms considering the fire-induced domino effects," *Journal of Marine Science and Engineering*, vol. 10, no. 11, p. 1685, 2022, doi: 10.3390/jmse10111685.

[3] C. Li, H. Zhang, Y. Zhang, and J. Kang, "Fire risk assessment of a ship's power system under the conditions of an engine room fire," *Journal of Marine Science and Engineering*, vol. 10, no. 11, p. 1658, 2022, doi: 10.3390/jmse10111658.

[4] J. Zhu, J. Zhang, Y. Wang, Y. Ge, Z. Zhang, and S. Zhang, "Fire detection in ship engine rooms based on deep learning," *Sensors*, vol. 23, no. 14, p. 6552, 2023, doi: 10.3390/s23146552.

[5] H. Kim, J. Lee, and S. Park, "Smoke detection of marine engine room based on sensor fusion," *Journal of Marine Science and Engineering*, vol. 9, no. 8, p. 876, 2021.

[6] F. Khan, M. Yang, and R. Abbassi, "Risk evolution from causes to consequences of engine room fire hazards," *Safety Science*, vol. 115, pp. 191–202, 2019.

[7] J. Chen, Y. Zhang, and S. Wang, "Fire risk assessment of ship engine rooms based on fuzzy event tree analysis," *Journal of Marine Science and Engineering*, vol. 9, no. 4, p. 412, 2021.

[8] Y. Li, G. Chen, and L. Zhang, "A review of ventilation systems and fire incidents on ships," *Mathematical Modelling of Engineering Problems*, vol. 7, no. 4, pp. 615–623, 2020.

[9] Z. Wang, Y. Liu, and J. Chen, "Effects of ventilation system design on flame behavior and smoke characteristics for mitigating marine engine room fire hazards," *Ocean Engineering*, 2023.

[10] J. Li, H. Wang, and Q. Zhang, "Large-scale experimental investigation of the effect of mechanical ventilation on engine room fire behavior," *Fire Technology*, 2022.

[11] X. Liu, Y. Wang, and Z. Zhao, "Fire risk assessment in ship engine rooms considering system interaction," *Journal of Marine Science and Engineering*, vol. 10, no. 2, p. 245, 2022.

[12] International Maritime Organization, *International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended*. London, U.K.: IMO, 2010.

[13] International Maritime Organization, *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), 1978, as amended*. London, U.K.: IMO, 2017.

[14] International Maritime Organization, *Model Course 7.04: Officer in Charge of an Engineering Watch*. London, U.K.: IMO, 2015.

[15] U. Uğurlu, E. Yıldız, and O. Başar, "A hybrid model for human-factor analysis of engine-room fires on ships: HFACS-PVFFTA," *Ocean Engineering*, vol. 217, 2020.

[16] Y. Sun, J. Zhang, and G. Chen, "Human factors analysis of engine room fire accidents using HFACS," *Ocean Engineering*, vol. 215, 2020.

[17] M. Rahimi, R. Abbassi, and V. Garaniya, "Integrated fire safety framework for ship machinery spaces," *Journal of Marine Science and Engineering*, vol. 10, no. 6, p. 744, 2022.

[18] J. Wang, Z. Yang, and K. Li, "Fire risk assessment of ship power systems under engine room fire conditions," *Journal of Marine Science and Engineering*, vol. 8, no. 11, p. 879, 2020.

[19] R. Oliveira, J. Silva, and P. Costa, "Fire detection sensors for marine engine rooms: A review," *Sensors*, vol. 21, no. 15, p. 5021, 2021.

[20] J. Park, D. Kim, and S. Lee, "Experimental study on water mist fire suppression system in ship engine rooms," *Fire Technology*, vol. 57, no. 6, pp. 2815–2836, 2021.

[21] G. Chen, Y. Li, and H. Zhang, "Evaluation of CO_2 fire extinguishing systems effectiveness in ship engine rooms," *Journal of Marine Science and Engineering*, vol. 9, no. 7, p. 702, 2021.

[22] Y. Zhao, X. Wang, and Q. Liu, "Fire safety barrier analysis in ship machinery spaces using bow-tie method," *Journal of Marine Science and Engineering*, vol. 10, no. 9, p. 1216, 2022.

[23] X. Bao, Y. Wang, and Z. Li, "Causal chain analysis of ship fire accidents using Bayesian network and safety barrier theory," *Reliability Engineering & System Safety*, 2023.

[24] L. Chen, P. Zhang, and H. Wang, "Comprehensive evaluation of marine ship fires risk based on fuzzy broad learning system," *Journal of Marine Science and Engineering*, vol. 11, no. 7, p. 1276, 2023, doi: 10.3390/jmse11071276.

[25] A. G. Kim, S. Lee, and J. Park, "Advancing maritime safety: Early detection of ship fires through intelligent vision-based systems," *Fire*, vol. 7, no. 3, p. 84, 2024, doi: 10.3390/fire7030084.

[26] X. Bai, Z. Tao, X. Xu, C. Zhou, and Y. Wang, "A review of ship fire detection technologies in maritime transportation," *Ocean Engineering*, vol. 346, p. 123989, 2026, doi: 10.1016/j.oceaneng.2025.123989.

[27] A. Komianos, B. Navas de Maya, G. Psarros, O. C. Astrup, G. Theotokatos, E. Boulougouris, and D. Vassalos, "Fire prevention and mitigation measures onboard large passenger ships," in *Proc. 1st International Conference on the Stability and Safety of Ships and Ocean Vehicles*, Glasgow, U.K., 2021.

[28] Gard, "Fire safety onboard ships: A continuous cause for concern," *Gard Insight*, 2022.

[29] C. Sakar, M. Buber, B. Koseoglu, and A. C. Toz, "Risk analysis for confined space accidents onboard ship using fuzzy bow-tie methodology," *Ocean Engineering*, vol. 263, p. 112386, 2022, doi: 10.1016/j.oceaneng.2022.112386.

[30] Y. Li, H. Zhang, and C. Wang, "An integrated risk assessment framework for fire accidents on passenger ships," *Ocean Engineering*, 2025.

[31] R. J. Torraco, "Writing integrative literature reviews: Guidelines and examples," *Human Resource Development Review*, vol. 4, no. 3, pp. 356–367, 2005.

[32] H. Snyder, "Literature review as a research methodology: An overview and guidelines," *Journal of Business Research*, vol. 104, pp. 333–339, 2019, doi: 10.1016/j.jbusres.2019.07.039.

[33] R. Whittemore and K. Knafl, "The integrative review: Updated methodology," *Journal of Advanced Nursing*, vol. 52, no. 5, pp. 546–553, 2005.

[34] J. Reason, *Managing the Risks of Organizational Accidents*. Aldershot, U.K.: Ashgate, 1997.

[35] M. J. Page *et al.*, "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, 2021.