DATA-DRIVEN MODELLING AND RISK ANALYSIS OF HUMAN EVACUATION FROM PASSENGER SHIPS

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Abstract

The safety and efficiency management of Human Evacuation from Passenger Ships (HEPS) is moving towards to a new scheme of data-driven risk analysis and evidence-based safety management. This PhD study by Published Works, presented as a compilation of six peer-reviewed articles, systematically establishes a holistic, risk-based analytical framework through integrating multidimensional risk analysis, causal-structural modelling, causal inference analysis and simulation-based prediction. It aims to advance the scientific foundation for HEPS safety by developing a coherent identification-analysis-simulation-management workflow that progresses from fundamental risk understanding to operational decision-support.

This PhD study by Published Works makes five fundamental contributions to maritime evacuation safety. The first contribution is pioneering the investigation of risk heterogeneity across operational contexts through an integrated Enhanced Multilevel Association Rule Mining (EMARM), the Weighted Influence Non-linear Gauge System (WINGS), the Total Adversarial Hasse Diagram Technology (TAHDT) and the Matrices Impacts Croises-Multiplication Appliance Classement (MICMAC) analytical model. It provides the first scientific evidence that critical risk influencing factors can be dynamically reconfigured across different watchkeeping periods, establishing a new scheme for developing temporally adaptive evacuation strategies. The second contribution establishes an integrated Association Rule Mining (ARM), the WINGS and the Adversarial Interpretive Structure Model (AISM) analytical framework for assessing maritime occupational accidents, systematically identifying risk influencing factors, quantifying their causal interactions, and constructing hierarchical topologies to reveal intrinsic risk transmission pathways. The third contribution pioneers the causal inference exploration of exit choice behaviour during emergency evacuation through an optimised Double Machine Learning (DML) analytical method. By optimising the nuisance function and adopting large-scale valid questionnaire data for quantitative

causal analysis, it distinguishes causal effects from spurious correlations in evacuation decision scenarios, identifying core factors governing passenger exit choice and establishing a reliable paradigm for formulating targeted human evacuation intervention strategies onboard passenger ships. The fourth contribution proposes a comprehensive risk assessment framework for the entire HEPS process based on a Human–Ship–Environment–Organisation (HSEO) system. By integrating hybrid modelling approaches including Failure Mode and Effects Analysis (FMEA), Bayesian Belief Networks (BBNs), Evidential Reasoning (ER), Complex Network (CN) theory, Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Interpretive Structural Modelling (ISM), this framework enables systematic identification, quantification, and prioritization of risks across all evacuation phases. The fifth contribution is the development of an integrated simulation-machine learning methodology for HEPS time prediction, combining agent-based simulation with state-of-the-art machine learning algorithms to achieve rapid and accurate evacuation forecasting while balancing predictive accuracy with computational timeliness for emergency decision-support.

By synthesizing these contributions, this PhD study by Published Works establishes a multi-layered analytical framework that spans from microscopic risk factor analysis to macroscopic system-level safety assessment. It transforms conventional experience-based safety management into a quantitatively-grounded, scientifically-driven paradigm, providing maritime stakeholders with advanced methodological tools for evidence-based safety planning. The demonstrated impact through high citation rates, industry awards for equipment development, and successful grant applications underscores this research's significant academic and practical value in enhancing evacuation safety for next-generation passenger ship operations.

Declaration

This submission by Xinjian Wang to the Doctoral Academy at Liverpool John Moores University is for PhD by Published Works. This submission consists of six high-quality journal papers and a synthesis statement and is the fulfilment of its requirements and according to the guidelines and regulations set out by the Doctoral Academy at Liverpool John Moores University. The six lead author or co-author papers were published in peer-reviewed journals in 2023 to 2026 and have not been used in the submission for another research degree.

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

15/08/2026

Abbreviations

AHP	Analytic Hierarchy Process
AISM	Adversarial Interpretive Structure Model
ARM	Association Rule Mining
BBN	Bayesian Belief Networks
BN	Bayesian Networks
CN	Complex Network
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DL	Deep Learning
DML	Double Machine Learning
ELM	Extreme Learning Machine
EMARM	Enhanced Multilevel Association Rule Mining
EMCIP	European Marine Casualty Information Platform
ER	Evidential Reasoning
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HDT	Hasse Diagram Technique
HEPS	Human Evacuation from Passenger Ships
HSEO	Human-Ship-Environment-Organisation
ISM	Interpretive Structural Modelling
LightGBM	Light Gradient Boosting Machine
MICMAC	Matrices Impacts Croises-Multiplication Appliance Classement
ML	Machine Learning
RF	Random Forest
RIFs	Risk Influential Factors
SLIM	Success Likelihood Index Method
TAHDT	Total Adversarial Hasse Diagram Technology
WINGS	Weighted Influence Non-linear Gauge System

CHAPTER 1 INTRODUCTION

Maritime transportation is an important pillar of global economic development and also the main mode of international transportation (Li *et al.*, 2025; Wang *et al.*, 2025a). In recent years, it has undergone a remarkable advancement, characterized by a substantial increase in vessel traffic density, ship size, and operational complexity (Jovanović *et al.*, 2022; Kumar *et al.*, 2025). This rapid expansion, while facilitating global trade, has inevitably heightened the risks within the maritime domain. The increased frequency of ship activities and denser traffic patterns have led to a greater propensity for maritime accidents (Ma *et al.*, 2026).

Among various types of maritime accidents, passenger ship accidents are especially concerning due to their potential for catastrophic consequences. Tragedies such as the capsizing of the “Sewol” and the sinking of the “Eastern Star” have resulted in devastating loss of life, underscoring the severe impact of such disasters (Andreadakis and Dalaklis, 2024; Wang *et al.*, 2023b). In these critical situations, the process of Human Evacuation from Passenger Ships (HEPS) becomes the final and most crucial line of defence for reducing casualties (Nevalainen, 2015; Victor, 2017). The effectiveness of evacuation operations directly determines the ultimate outcome of an accident, making it a focal point in maritime safety research.

The success of HEPS is governed by a complex set of Risk Influential Factors (RIFs), many unique to the maritime environment. The ship's navigational state, particularly its motion and inclination in adverse weather, directly affects evacuees' mobility and safety (Wang *et al.*, 2021c). Experimental studies confirm that ship motion significantly reduces walking speed and increases evacuation difficulty (Guo *et al.*, 2025; Wang *et al.*, 2021b; Wang *et al.*, 2021c). Environmental conditions and disaster progression, such as fire spread or flooding, can obstruct escape routes (Ruponen, 2017; Xie *et al.*, 2022). Crucially, human factors play a decisive role: crew operational status, including

their proficiency in guiding passengers and handling life-saving appliances, and passenger behaviours, such as competitive actions or reliance on instructions are pivotal (Bartolucci *et al.*, 2021; Österman *et al.*, 2020). These elements often lead to injuries during evacuation; for instance, passengers may fall and get injured due to competitive behaviour, while crew can be harmed during lifeboat deployment due to improper operations (Liu et al., 2025; Wang et al., 2023). Understanding these variables is central to research on maritime safety, which aims to systematically examine the complex interplay of human, technical, and organizational elements in safety-critical contexts.

The numerous RIFs affecting HEPS do not exist in isolation but are deeply intertwined, forming a complex system of interactions. The performance of the crew, for example, is influenced by the captain's decisions, which are in turn affected by the evolving environmental conditions and the state of the ship (Wang *et al.*, 2023b; Xue *et al.*, 2019). This interconnectedness means that a failure in one part of the system can cascade, leading to systemic failure (Cao *et al.*, 2025). Beyond the internal systematic correlation of HEPS, it should be noted that the safety of passenger ships is positioned in the safety at sea a whole. The lessons learnt from overall maritime accidents are valuable and insightful for passenger ships, which can effectively supplement the internal risk analysis of HEPS process. Consequently, a holistic risk assessment is essential to move beyond the analysis of individual components and to identify the key RIFs and their causal relationships across the entire HEPS process, encompassing assembly, abandonment, and rescue (Bugra Sar, 2023; Wang *et al.*, 2023b). Such a comprehensive framework allows for the quantification and prioritisation of risks, providing a scientifically robust foundation for safety management of passenger ships.

Following the identification of these critical RIFs, a proactive approach to risk control becomes possible. This necessitates the use of simulation-based modelling to predict HEPS outcomes under a variety of potential emergency scenarios (Zhang *et al.*, 2025).

By numerically analysing the impacts of factors such as passenger composition, familiarity levels, and ship motion, these models can accurately forecast evacuation times and identify potential bottlenecks in a vessel's design or evacuation plan (Kim *et al.*, 2022; Wang *et al.*, 2022). The insights generated from such predictive analyses are instrumental in the development of sophisticated emergency decision support systems, which can provide ship masters with the critical, data-driven information needed to make rational decisions on when to evacuate and when to abandon a ship, thereby enabling proactive risk mitigation and enhancing the safety of life at sea (Wang *et al.*, 2023b).

1.1 Coherence and Significance

The safety and efficiency of HEPS are assured by a data-driven, evidence-based, and multidimensional methodological framework. This PhD study by Published Works builds upon six core papers, structured around five foundational pillars that form a coherent and progressive research system. These pillars encompass: 1) the heterogeneity analysis of RIFs across different operational contexts through enhanced multilevel Association Rule Mining (ARM) and adversarial hierarchical modelling; 2) the development of an integrated analytical framework for maritime occupational accident assessment combining ARM, causal analysis, and hierarchical topology mapping; 3) the advancement of causal inference modelling for passenger evacuation exit choice using optimised Double Machine Learning (DML); 4) the systematic risk assessment of the entire evacuation process by integrating hybrid modelling approaches; and 5) the time prediction of HEPS through integrated simulation and Machine Learning (ML) approaches with multi-criteria evaluation. Collectively, they provide the foundation for a new generation of safety analysis frameworks for HEPS.

The first pillar is the heterogeneity analysis of RIFs in maritime accidents across different operational contexts (Paper 1), with critical implications for HEPS safety

management. This work pioneers an integrated multidimensional analytical model which synergises an Enhanced Multilevel Association Rule Mining (EMARM) algorithm, the Weighted Influence Non-linear Gauge System (WINGS), Total Adversarial Hasse Diagram Technology (TAHDT), and Matrices Impacts Croises-Multiplication Appliance Classement (MICMAC). By analysing a substantial dataset of 1,294 maritime accident reports, this study is the first to systematically investigate how the characteristics of critical RIFs differ across the watchkeeping periods of the third, second, and chief officers. The findings reveal a significant heterogeneity in risk profiles, demonstrating that crew fatigue and performance variations during specific watch periods directly impact emergency response capabilities. This research provides a scientific basis for developing temporally adaptive evacuation strategies that account for circadian rhythms and accumulated crew fatigue, thereby enhancing HEPS preparedness during critical emergency situations.

The second pillar is the development of an integrated analytical framework for maritime occupational accident assessment (Paper 2), with direct relevance to crew safety and performance during HEPS operations. By combining ARM, the WINGS, and the Adversarial Interpretive Structure Model (AISM), this research systematically identifies RIFs, quantifies their causal interactions, and reveals their hierarchical topology. This data-driven framework elucidates complex risk transmission pathways and dynamic evolution mechanisms, thereby providing a methodological foundation for enhancing risk prevention and enabling precise, evidence-based safety management to ensure crew can perform effectively during critical evacuation scenarios, thereby reducing occupational injuries and improving overall HEPS outcomes.

The third pillar is the advancement of causal inference modelling for passenger evacuation exit choice through an optimised DML analytical framework (Paper 3), delivering novel mechanistic insights for HEPS. The framework’s principal innovation

lies in distinguishing genuine causal effects from spurious correlations, quantifying the average treatment effects of multi-dimensional behavioural factors across diverse exit decision strategies. This pillar transitions HEPS behavioural research from descriptive correlation exploration to rigorous causal mechanism interpretation, accurately identifying core response and congestion-phase behaviours that dominate passenger exit choice. By validating causal robustness through placebo tests and statistical significance evaluation, this research offers targeted behavioural intervention evidence, enabling the formulation of scenario-adaptive evacuation guidance and refined crowd management strategies for passenger ship operations.

The fourth pillar is the systematic risk assessment of the entire HEPS process (Papers 4 and 5). Drawing on causal chains extracted from passenger ship accident reports and integrating Complex Network (CN) theory with Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Interpretive Structural Modelling (ISM) methods, Paper 4 moves beyond traditional analyses focused solely on time-based metrics or linear causality, establishing instead a holistic, multi-layered hierarchical structure of risks across the assembly, abandonment, and search-and-rescue phases. Then, Paper 5 construct a comprehensive RIFs network to analyse the topological characteristics and interrelationships of 27 distinct RIFs. By adopting the Human-Ship-Environment-Organisation (HSEO) analysis system, it identifies, quantifies, and prioritises key RIFs and their interaction mechanisms, thereby providing a macro-level theoretical basis for emergency decision-makers to optimise evacuation strategies and enhance safety management.

The fifth pillar is the time prediction of HEPS based on simulation and ML (Paper 6). This research integrate key RIFs identified from maritime accidents and evacuation studies into an agent-based simulation platform. The validated models enable the parameterised analysis of complex evacuation scenarios under varying conditions, generating extensive datasets for subsequent ML training. By comparing multiple

state-of-the-art ML models, this research achieves rapid and accurate prediction of HEPS time. It further introduces a weighted multi-criteria evaluation framework combining Analytic Hierarchy Process (AHP) and weight entropy methods, advancing the research from computationally intensive simulation to intelligent, real-time decision support for proactive emergency management.

By integrating these five pillars in an identification-analysis-simulation-management logical workflow, this PhD by Published Works establishes a comprehensive, risk-based safety analysis framework for HEPS. The framework progresses from identifying heterogeneous risk patterns and quantifying causal mechanisms, through analysing exit choice behaviours and modelling systemic risk interactions, to finally enabling real-time evacuation prediction and decision support. This ensures a holistic analysis spanning from micro-level individual to macro-level systemic risks, providing a rigorous scientific foundation for next-generation evacuation analysis and safety management. This research ultimately supports the development of a data-driven, evidence-based, and resilient emergency evacuation system for passenger ships.

1.2 Context

Maritime accidents involving passenger ships often leading to evacuations and loss of life, this is demonstrated in tragedies of Estonia, Costa Concordia, Sewol and Norman Atlantic (Fang *et al.*, 2023; Wang *et al.*, 2021d; Wang *et al.*, 2023b). At such times, HEPS serves as the final measure to mitigate the casualties of the accident (Wang *et al.*, 2021a). However, HEPS presents distinctive characteristics, including its unique evacuation mode, personnel's limited familiarity, varied and complex behaviour, and the challenging effects of ship movement (Fang *et al.*, 2022; Wang *et al.*, 2021b). Due to delayed initiation of research efforts and insufficient data availability, only a limited number of existing studies have thoroughly analysed the risks inherent in HEPS processes (Fang *et al.*, 2024; Wang *et al.*, 2022).

In this context, a systematic and data-driven investigation into HEPS is conducted in this PhD by Published Works under a coherent identification-analysis-simulation-management research workflow. Notably, passenger ship safety is recognised as an integral component of maritime safety systems, whereby lessons drawn from general maritime accidents are adopted to supplement HEPS risk analysis and enhance the generalisability of developed frameworks and safety strategies. Firstly, a multidimensional integrated model is developed to explore the contextual heterogeneity of RIFs across diverse crew watchkeeping periods, with context-specific crew risk patterns uncovered to underpin temporally adaptive safety management of HEPS. Based on such heterogeneity analysis, an integrated occupational accident evaluation framework is further established to quantify the hierarchical topology and causal transmission of crew-related RIFs, enabling precise risk mitigation for on-site HEPS operations. To address human-induced evacuation uncertainties, optimised causal inference models are advanced to distinguish genuine causal mechanisms from spurious correlations underlying passenger exit choices, supporting targeted behavioural intervention strategies for refined evacuation management. Following micro-level analyses of crew and passenger risks, holistic multi-layered risk structures and RIFs networks are constructed to cover the entire HEPS process encompassing assembly, abandonment, and search and rescue phases. Incorporated with the HSEO analysis system, this methodology enables the systematic identification, quantification, and prioritisation of core systemic risks. Ultimately, accident-validated RIFs are integrated with agent-based simulation and state-of-the-art ML techniques to facilitate intelligent time prediction and multi-criteria strategy assessment of HEPS. Through this step-by-step research design, targeted safety technologies and management strategies are proposed to enhance the safety and efficacy of HEPS.

This PhD by Published Works represents a systematic and holistic exploration of risk issues in HEPS. The research outcomes deliver reliable data, advanced methodologies,

and practical tools crucial for simulating, dissecting, and managing the HEPS process. These deliverables serve multiple critical purposes, including identifying congestion points and bottlenecks within existing ship layouts, assessing evacuation plan effectiveness, optimising crowd management strategies, and developing sophisticated emergency decision-support systems. Ultimately, these contributions culminate in a significantly elevated safety standard for passenger ships, ensuring the well-being of all persons on board.

This PhD by Published Works has made substantial contributions to the field of passenger ship safety research, resulting in the following Deliverables (D1-D6):

D1: Pioneered an integrated multidimensional analytical framework to investigate the heterogeneity of RIFs across different operational contexts based on a large dataset of accident reports.

D2: Proposed a novel data-driven analytical framework integrating ARM, WINGS, and AISM to systematically identify, quantify, and model the hierarchical structure of RIFs in maritime occupational accidents.

D3: Developed an optimised causal inference framework, integrating DML and multi-model calibration strategies, to reveal the causal mechanisms of passenger exit choice behaviour during emergency evacuation.

D4: Developed a novel risk assessment method for HEPS, involving three stages of assembling, boarding, and abandoning ship, through risk modelling. A case study was conducted to demonstrate the method’s effectiveness and applicability.

D5: Developed a quantitative risk assessment method for HEPS, involving three stages of hazard identification, topological analysis, and structural-causal modelling, through

integrating CN, DEMATEL, and ISM.

D6: Created an innovative simulation-based predictive framework by integrating agent-based modelling with nine state-of-the-art ML algorithms and developing a weighted AHP-entropy evaluation system, providing crucial support for emergency response planning.

1.2.1 Research Questions

The following Research Questions (RQs) guide this PhD by Published Works, ensuring a structured and impactful investigation into the risk assessment of key RIFs, and time prediction of HEPS:

RQ1: How do the critical RIFs in maritime accidents differ across various operational contexts?

This research seeks to investigate the heterogeneity of accident causality by developing an integrated multidimensional analytical model. The objective is to identify and compare the distinct risk profiles associated with each watchkeeping period, providing a basis for context-specific safety management strategies.

RQ2: How can a comprehensive analytical framework be developed to systematically identify and assess the complex interactions among RIFs in maritime occupational accidents?

This research develops an integrated ARM–WINGS–AISM framework to quantitatively analyse maritime occupational accident data. It identifies key RIFs, quantifies their causal relationships and influence strengths, and constructs a hierarchical topology to reveal intrinsic risk transmission pathways, thereby providing actionable insights for

developing targeted safety management strategies in maritime transport.

RQ3: How can genuine causal relationships behind passenger exit choice behaviour be reliably identified beyond conventional correlational analysis?

This research constructs a refined DML framework that mitigates confounding bias through nuisance function optimisation. It further seeks to establish robust causal inference by adopting multi-model evaluation and placebo testing to quantify behavioural effects across diverse evacuation decision scenarios.

RQ4: What are the key RIFs affecting the safety of HEPS, and how can their complex interrelationships be systematically quantified?

This research establishes a comprehensive risk analysis framework for the entire HEPS process by integrating CN theory with structural modelling methods. It seeks to identify, prioritise, and model the causal relationships between critical RIFs based on historical accident data.

RQ5: What is the best model for accurately and quickly predicting the HEPS time, and how to select a model that is suitable for predicting HEPS time?

In this research, several state-of-the-art ML models are selected and introduced to enable the rapid prediction of HEPS time. Furthermore, a standardised weighted-model selection approach is developed that effectively balances accuracy and timeliness.

This PhD by Published Works is consolidated through six pivotal articles, which collectively scrutinise the key RIFs, risk assessment, and time prediction of HEPS. The RQs form a coherent analytical progression, commencing with the data-driven identification and heterogeneity analysis of RIFs (RQ1), extending to the complex risk

interaction analysis in maritime occupational accidents (RQ2), and further advancing to the causal inference modelling for passenger evacuation exit choice (RQ3) and the systematic assessment of evacuation scenarios (RQ4). The progression culminates in the development of integrated simulation-ML frameworks for the rapid and accurate time prediction of HEPS (RQ5). Through rigorous quantitative analysis and modelling, these papers elucidate the causal mechanisms and systemic risks within the maritime safety and HEPS domains. The collective findings offer invaluable, data-driven insights for prospective evacuation planning, vessel design, and emergency decision-support systems. Such insights hold paramount significance in augmenting the proactive risk control and emergency response capabilities of passenger ships, thereby safeguarding public safety and enhancing life safety at sea.

1.2.2 Aims and Objectives

This PhD by Published Works aims to establish a holistic, risk-based safety analysis framework for HEPS that systematically integrates data-driven methodologies, including multidimensional risk analysis, causal inference and CN modelling, and simulation-based prediction. By drawing on extensive datasets from maritime accident reports, occupational case records, and validated evacuation simulations, this research enhances the scientific understanding of risk mechanisms and evacuation dynamics. The findings support the development of evidence-based safety management strategies and sophisticated decision-support systems for emergency response in complex marine environments.

To achieve this aim, this PhD by Published Works is structured around the following Research Objectives (ROs):

RO1: Develop a multidimensional framework for the heterogeneity analysis of maritime accident risks.

(1) Establish a novel integrated analytical model by mining a dataset of maritime accident investigation reports, systematically categorised by the distinct watchkeeping periods of the third, second, and chief officers.

(2) Employ a synergistic combination of EMARM, WINGS, TAHDT, and MICMAC analyses to identify and classify the unique causal pathways and hierarchical structures of RIFs specific to each watch period.

RO2: Develop an integrated analytical framework to systematically assess RIFs in maritime occupational accidents.

(1) Develop a novel ARM-WINGS-AISM framework to systematically identify RIFs and elucidate their complex interactions in maritime occupational accidents.

(2) Construct a hierarchical topology of RIFs to reveal intrinsic risk transmission pathways and support the development of precise, data-driven prevention strategies.

RO3: Establish an optimised causal inference framework for identifying driving mechanisms of passenger exit choice behaviour during emergency evacuation.

(1) Develop a refined DML framework by implementing multi-model comparison and dynamic nuisance function optimisation to eliminate confounding bias in passenger evacuation behavioural datasets.

(2) Adopt comprehensive statistical verification including significance testing and placebo experiments to distinguish genuine causal effects from spurious correlations and quantify behavioural impacts on multi-scenario exit choice strategies.

RO4: Establish an innovative risk assessment framework for the HEPS process.

(1) Develop a HSEO analytical framework through systematic review of investigation reports, academic literature and real passenger ship accident reports to construct a comprehensive risk assessment framework based on HSEO for HEPS.

(2) Construct a hybrid risk assessment model integrating risk analysis with network and structural modelling to quantify and prioritise risks throughout HEPS, supporting emergency decision-making.

RO5: Develop an integrated simulation and ML framework for the time prediction of HEPS.

(1) Develop a validated agent-based simulation model for HEPS by integrating key HSEO factors, and generate extensive scenario-driven datasets through parameterised simulation of diverse evacuation conditions.

(2) Construct a robust prediction framework by applying and systematically comparing multiple state-of-the-art ML models, and introduce a weighted multi-criteria evaluation method to identify the optimal model balancing predictive accuracy and timeliness for emergency decision-support.

Collectively, these six peer-reviewed articles advance HEPS safety by establishing a coherent identification-analysis-simulation-management framework. This research provides a systematic approach for quantifying heterogeneous risk patterns, modelling systemic risk interactions, and enabling real-time evacuation prediction. This contributes to enhanced evacuation safety, optimised vessel design, refined crowd management strategies, and proactive risk control, thereby empowering passenger ships and their crew members to respond with greater safety and resilience in

increasingly complex emergencies.

1.3 Thesis Structure

The subsequent sections present six peer-reviewed articles that form the integrated foundation of this PhD by Published Works.

Chapter 2 reviews the relevant literature through a systematic examination of five interconnected research domains: heterogeneity analysis of maritime accident risks, analytical frameworks for occupational accidents, exit choice behaviour analysis for ship passengers, risk assessment of the HEPS process, and time prediction for evacuation operations.

Chapter 3 introduces the integrated methodological framework developed in this research, outlining the progressive analytical approaches employed, including multidimensional risk analysis using EMARM-WINGS-TAHDT-MICMAC, causal-structural modelling through ARM-WINGS-AISM, and simulation-based prediction integrating agent-based modelling with ML, etc.

Chapter 4 presents the primary research contributions, analysing the intrinsic connections between each finding and the RQs established in Section 1.2.1. It further elaborates on the theoretical advancements, practical implications, and demonstrated impact of this research through academic recognition, industrial application, and policy influence.

Finally, Chapter 5 synthesises the key conclusions of this PhD by Published Works and discusses their broader significance, while identifying promising future research directions for advancing HEPS safety through enhanced data collection, model integration, and intelligent decision-support systems.

CHAPTER 2 REVIEW OF LITERATURE: FOUNDATIONS FOR DATA-DRIVEN AND RISK-BASED ANALYTICAL FRAMEWORK

This chapter presents a literature review structured around five interconnected research streams: heterogeneity analysis of maritime accident risks, analytical frameworks for occupational accidents, casual inference of exit choice behaviour, risk assessment of the HEPS process, and time prediction for evacuation operations. These components collectively establish a coherent identification-analysis-simulation-management workflow that systematically progresses from fundamental risk understanding to operational decision-support for HEPS safety. The review thereby establishes a comprehensive research foundation for this PhD by Published Works that integrates multidimensional risk analysis, causal inference and causal-structural modelling, systematic risk assessment and simulation-based prediction to enhance the safety and resilience of HEPS. Their logical progression and interrelationships are systematically examined in the following sections.

2.1 Research Content and Review on Heterogeneous Maritime Accident Analysis

Understanding the heterogeneity of maritime accidents forms the critical foundation for targeted risk management in passenger ship operations. As illustrated in Table 1, while existing research has examined variations across ship types, regions, and weather conditions, this section reviews a pivotal yet underexplored dimension of heterogeneity: the differential risk profiles across distinct watchkeeping periods. Such analysis is essential for transcending the limitations of generic safety protocols and developing temporally adaptive evacuation strategies that account for circadian rhythms and accumulated crew fatigue, those factors critically relevant to HEPS efficiency and safety.

Table 1 The comparative results of literature on the heterogeneity of maritime accidents.

Literatures	Research Content	Methodology	Key Findings
Brandt *et al.* (2024)	Impact of various weather conditions on different types of maritime accidents	ML	Significant differences were found in the impact of weather conditions across different accident types.
Huang *et al.* (2023)	Regional disparities in the distribution of maritime accidents	Weighted association rule mining	Notable variations were observed in the number of accidents across different sea areas.
Zhang *et al.* (2022)	Comparison of key RIFs in high-accident-density sea areas	ML	Regional characteristics significantly influence fatality and injury outcomes, with key RIFs varying by area.
Cao *et al.* (2024a)	Accident characteristics across different ship types	WINGS & ARM	Notable differences were identified in the critical RIFs between different ship types.
Eliopoulou *et al.* (2016)	Impact of ship age and type on accident frequency	Descriptive & Inferential Statistics	Both ship age and type were found to have a significant impact on the frequency of accidents.
Berg *et al.* (2013)	Role of crew factors in complex navigational environments	Literature Review	Crew experience, communication skills, and background knowledge were identified as critical for safety.
Chang and Park (2019)	Relationship between ship speed and accident type	Regression Analysis	Higher speeds typically increase collision risk, while lower speeds raise the risk of grounding.

Literatures	Research Content	Methodology	Key Findings
Marine Accident Investigation Branch (2004)	Impact of the 6-on/6-off watch system on accident rates	Comparative Study	The 6-6 watch system was associated with higher accident rates due to insufficient continuous sleep for crew members.
Størkersen *et al.* (2012)	Influence of different duty regimes on navigational safety	Experimental Study/Survey	While different watch systems influenced crew fatigue levels, their impact on navigational safety was minimal.
van Leeuwen *et al.* (2021)	Variability in how watch systems affect officers' alertness	three-process model	Different watchkeeping systems were found to variably affect the alertness of duty officers.
Heikkila (2016) and Shi *et al.* (2021)	Relationship between watch system design and navigational risk	Structured Literature Review	A well-designed watch system can improve duty alertness and reduce ship navigational risks.
Devereux (2022)	Relationship between seafarers' injury risk and time into watchkeeping duration	Statistical Modeling	The risk of injury was higher at the beginning and middle of the watch period but declined toward the end.
Ugurlu *et al.* (2018)	Risk characteristics of early morning vs. night watch	Human factor analysis and classification system for passenger vessel accidents	Early morning watch leads to crew fatigue and poor psychological conditions, while improper operations are common during night watch.
Vinagre-Ríos *et al.* (2021)	Comparison of accident severity between night and day	Statistical Analysis	Accidents occurring during the night watch tend to be more severe than those during the day.

Early investigations into maritime accident heterogeneity primarily adopted comparative and statistical approaches. Studies by Brandt *et al.* (2024) and Huang *et al.* (2023) exemplified this trend, analysing how accident characteristics diverge under different weather conditions and across various sea areas, respectively. Research was further expanded to incorporate factors such as ship type, age, and operational speed, establishing that critical RIFs vary significantly with these contextual parameters (Cao *et al.*, 2024b; Eliopoulou *et al.*, 2016). The impact of crew-related factors, including experience and communication skills, was also identified as a key determinant of navigational safety in complex environments (Berg *et al.*, 2013). However, these early studies, while valuable, often provided a static and fragmented view, lacking a unified framework to decipher the complex, system-level interactions of RIFs specific to dynamic operational contexts like watch schedules, a limitation that equally constrains the development of evidence-based HEPS protocols.

A significant advancement in this domain has been the development and application of integrated analytical models that combine correlation mining with causal and hierarchical analysis. The integration of ARM with the WINGS marked a critical step forward, enabling researchers not only to identify frequently co-occurring RIFs but also to quantify the strength and direction of their causal influences (Cao *et al.*, 2024a; Wang and Zhang, 2022). To further delineate the underlying structure of these interacting risks, hierarchical analysis techniques such as the Hasse Diagram Technique (HDT) were introduced. These methods help visualize the priority and relationships among RIFs, as demonstrated in applications ranging from food safety to energy-intensive industries (Sun *et al.*, 2024; Zhu and Liu, 2020). Nevertheless, traditional HDT can struggle with the uncertainty and dynamic adversarial scenarios typical of maritime operations.

To address these limitations and achieve a holistic understanding, recent research has emphasized methodological integration. Techniques like the MICMAC have been coupled with causal models like DEMATEL and structural models like ISM to classify

RIFs based on their driving and dependence power, thereby validating and complementing findings from other approaches (Janssen *et al.*, 2019; Xing *et al.*, 2023). This synergy allows for a more robust identification of key systemic factors and their interrelationships.

Despite these methodological strides, a conspicuous gap remains in the systematic, evidence-based analysis of how the entire profile of critical RIFs shifts across the distinct watchkeeping periods of chief, second, and third officers. While the general impact of fatigue on performance is acknowledged, the temporal heterogeneity of systemic risk configurations is poorly understood, hindering the development of precisely tailored safety interventions for maritime evacuation scenarios where crew alertness and performance are of paramount importance.

To address this knowledge gap, this PhD by Published Works (Paper 1) pioneers an integrated multidimensional analytical model, the EMARM-WINGS-TAHDT-MICMAC framework. It first employs an EMARM algorithm to identify multi-level coupling relationships among RIFs at both state and factor levels. Subsequently, the WINGS method is applied to elucidate the non-linear causal interactions among these factors. An innovative TAHDT, grounded in game theory, is then utilized to establish a robust hierarchical structure of RIFs. Finally, MICMAC analysis classifies the RIFs based on their driving and dependence power. This comprehensive framework provides the first systematic evidence of significant heterogeneity in critical RIFs across different watchkeeping periods, establishing a foundational perspective for the context-specific risk analyses that are followed in this thesis and offering crucial insights for designing watchkeeping-specific HEPS procedures and crew training protocols.

2.2 Research Content and Review on Analytical Frameworks for Maritime Occupational Accidents

The preceding sections established methodologies for decoding risk heterogeneity and achieving proactive, transparent prediction. This section extends this analytical progression to a specific, high-stake domain directly relevant to HEPS: maritime occupational accidents. As illustrated in Table 2, it reviews the evolution of research from qualitative, descriptive inquiries towards quantitative, systemic frameworks capable of elucidating the complex causal structures and hierarchical risk pathways that underpin personnel casualties during emergency evacuation operations, a critical concern for passenger ship safety.

Initial research into maritime occupational accidents was predominantly qualitative, relying on systematic literature reviews, legal analyses, and interview-based studies to explore contributing factors such as regulatory frameworks, crew health, and organizational practices (Akamangwa, 2016; Carballo Piñeiro and Kitada, 2020; Li *et al.*, 2022). While providing valuable contextual insights, these approaches often lacked the empirical robustness for generalizable safety interventions, particularly in the high-stakes context of maritime evacuation where crew performance directly determines evacuation outcomes. A limited number of quantitative studies emerged, primarily utilizing survey data and statistical models to examine occupational health patterns and injury outcomes (Österman *et al.*, 2020; Song *et al.*, 2021; Zhang *et al.*, 2020). However, these were constrained by reliance on self-reported data and an insufficient capacity to model the dynamic interactions among RIFs, a significant limitation for understanding the complex causality of personal injuries during HEPS processes.

Table 2 The comparative results of literature on the maritime occupational accident analysis.

Literature	Research Topic	Methodology	Key Findings
Li *et al.* (2022)	Key characteristics of seafarer occupational health research (2000-2020)	Systematic Literature Review	Identified a growing scholarly focus, particularly on mental health, with a substantial increase in related publications.
Carballo Piñeiro and Kitada (2020)	Legal policies protecting seafarer occupational safety and health	Legal Analysis	Underscored the need for targeted interventions to address workplace gender discrimination.
Akamangwa (2016)	Impact of environmental compliance on seafarer health and well-being	Qualitative Interviews (Semi-structured)	Environmental compliance requirements adversely impact seafarer health primarily through increased workloads and extended working hours.
Zhang and Zhao (2017)	Seafarer occupational health practices in China vs. international standards	Interdisciplinary Approach (Sociological, legal perspectives & empirical data)	Identified significant gaps between occupational health practices in China and relevant international standards.
Österman *et al.* (2020)	Occupational safety and health among passenger ship seafarers	Exploratory Survey	Musculoskeletal disorders and psychological disorders were the predominant health concerns.
Song *et al.* (2021)	Relationship between working conditions, welfare, and	Survey	Seafarers with job satisfaction from sailing or strong family support exhibited enhanced occupational health outcomes.

Literature	Research Topic	Methodology	Key Findings
	occupational health of Chinese seafarers		
Zhang *et al.* (2020)	Risk analysis model for maritime occupational accidents	Bayesian Networks (BN) Modelling	Identified the most influential RIFs and developed a risk analysis model.
Rinne *et al.* (2020)	Mortality risk comparison between Finnish seafarers and the general workforce	Statistical Analysis	Found a significantly elevated mortality risk among seafarers overall, particularly for deck officers, engine officers, and chef staff.

In parallel, the broader maritime safety field witnessed significant methodological advances. Traditional probabilistic risk assessment methods like Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) were applied but often proved computationally intractable for the high-dimensional, interconnected RIFs characteristic of occupational accidents (Pei *et al.*, 2024; Sakar *et al.*, 2021; Zhang *et al.*, 2019). ARM offered a powerful alternative for uncovering frequent, non-obvious patterns in large accident datasets without prior assumptions (Caesar and Tamakloe, 2024; Çakır *et al.*, 2021). Nevertheless, ARM is inherently limited to revealing correlations, not causality, a critical shortcoming for developing effective interventions for HEPS where understanding causal pathways is essential.

To infer causal directions, methods like the DEMATEL were introduced, enabling the discernment of cause-effect relationships within complex systems (Ma *et al.*, 2022a). A significant enhancement came with the WINGS, which separately quantifies the inherent importance of individual factors and their interactive influences, providing a more nuanced understanding of system dynamics than DEMATEL (Wang *et al.*, 2025a). While WINGS excels in causal modelling, it does not efficiently delineate the hierarchical structure of RIFs. Interpretive ISM addresses this by constructing multi-level hierarchical networks. Its extension, the AISM, further mitigates the subjective bias of traditional ISM by introducing confrontation mechanisms, enabling multi-perspective hierarchical decomposition and offering enhanced capabilities for mapping risk transmission pathways (Huang *et al.*, 2024c; Li *et al.*, 2024).

Despite these sophisticated tools, significant gaps persist in the specific domain of maritime occupational accidents as they relate to HEPS. Research remains scarce on the deep causal structures and hierarchical risk transmission pathways leading to personnel casualties during evacuation operations. Existing studies often focus on isolated methodological applications, failing to comprehensively integrate correlation mining, causal quantification, and hierarchical structuring to construct an end-to-end

analytical pipeline for understanding injury mechanisms in HEPS scenarios.

To address this gap, this PhD by Published Works (Paper 2) introduces a novel integrated ARM–WINGS–AISM framework. This comprehensive approach first employs ARM to identify significant association rules among RIFs from a structured occupational accident database. It then leverages WINGS to quantitatively analyse the causal relationships and influence intensities from a dynamic information transfer perspective. Finally, it applies AISM to construct an antagonistic hierarchical topology, visually elucidating the intrinsic risk transmission pathways from root causes to surface-level events. By integrating these three methodologies, the ARM–WINGS–AISM framework establishes a complete analytical chain that systematically uncovers the mechanistic underpinnings of maritime occupational accidents during evacuation scenarios, providing a robust, data-driven paradigm for developing dynamic, evidence-based safety management systems and precise prevention strategies for evacuation operations onboard passenger ships, thereby laying the methodological groundwork for the comprehensive HEPS risk assessment frameworks explored in the subsequent section.

2.3 Research Content and Review on Evacuation Exit Choice Behaviour Analysis

The preceding sections established multi-layered risk analytical frameworks for maritime accident assessment. This section extends this analytical progression to a core, human-centric domain directly relevant to HEPS: passenger exit choice behaviour during emergency evacuation. As illustrated in Table 3, it reviews the evolution of research from descriptive statistical inquiries towards data-driven predictive modelling and emerging causal inference frameworks capable of distinguishing spurious correlations and genuine behavioural causality, a critical concern for crowd management onboard passenger ships.

Table 3 The comparative results of literature on the evacuation exit choice behaviour analysis.

Literature	Research Focus	Methodology	Key Findings
Lovreglio *et al.* (2016)	Exit choice behaviour modelling	Mixed Logit Model	Demonstrated that exit choice is a multi-attribute decision influenced by distance, visibility, and crowd dynamics, capturing heterogeneity in individual decision-making.
Shiwakoti *et al.* (2017)	Passenger behaviour in emergency evacuation	Empirical survey and experimental analysis	Revealed strong social influence and herding behaviour affecting passenger decision-making under emergency conditions.
Wang *et al.* (2023c)	Exit choice and evacuation time prediction	ML with interpretability techniques	Showed that ML improves predictive accuracy but lacks causal interpretability, limiting the understanding of behavioural mechanisms.
Shi *et al.* (2024a)	Route and exit choice behaviour	Behavioural experiments	Identified avoidance behaviour and phototropism as key drivers influencing route and exit selection during evacuation.
Yang *et al.* (2020a)	Evacuation strategy and exit choice	Simulation-based behavioural modelling	Demonstrated that staged evacuation strategies can significantly improve evacuation efficiency by guiding exit choice behaviour.
Huang *et al.* (2024a)	Behavioural analysis with causal perspective	ML combined with causal inference	Showed that integrating predictive and causal approaches improves identification of true driving factors beyond correlational relationships.

Literature	Research Focus	Methodology	Key Findings
Chernozhukov *et al.* (2018)	Causal effect estimation in high-dimensional data	DML	Proposed a robust framework that removes confounding bias and enables reliable causal effect estimation in complex, high-dimensional settings.
Xu *et al.* (2026)	Post-disaster behavioural choice modelling	ML combined with causal inference	Demonstrated that integrating causal inference with ML reveals underlying behavioural mechanisms in evacuation decision-making.

Initial research into maritime evacuation exit choice was predominantly descriptive, relying on questionnaire surveys, evacuation simulation experiments, and basic statistical analyses to explore contributing factors such as individual passenger attributes, environmental layout conditions, and basic behavioural responses (Arshad *et al.*, 2022; Lovreglio *et al.*, 2016; Shiwakoti *et al.*, 2017). While providing valuable contextual insights into passenger decision preferences, these traditional approaches often lacked the empirical robustness for generalizable evacuation optimisation, particularly in the high-stakes context of maritime emergency evacuation where dynamic passenger decisions directly determine overall evacuation efficiency. A growing number of data-driven studies emerged, primarily utilizing ML models and feature analysis techniques to examine the correlation between multi-dimensional variables and passenger exit selection outcomes (Wang *et al.*, 2023c). However, these were constrained by inherent correlation-oriented modelling logic and an insufficient capacity to eliminate confounding biases, a significant limitation for understanding the genuine causal mechanisms of passenger exit choice behaviours during HEPS processes.

In parallel, the broader evacuation safety field witnessed significant methodological advances. Traditional statistical analysis and simulation methods were widely applied but often proved limited for the high-dimensional, heterogeneous behavioural data characteristic of ship passenger evacuation (Yang *et al.*, 2020b). Advanced ML models offered a powerful alternative for capturing complex nonlinear relationships and heterogeneous behavioural patterns in large-scale evacuation datasets (Shi *et al.*, 2024b). A significant enhancement came with emerging causal inference methods, which separate confounding interference through counterfactual modelling and orthogonal estimation, providing a more rigorous understanding of behavioural decision mechanisms than conventional correlational analysis (Chernozhukov *et al.*, 2018). While causal inference excels in identifying genuine variable causality, traditional causal tools struggle with high-dimensional behavioural data and complex

situational interactions in maritime evacuation scenarios. The DML method addresses this limitation by integrating ML fitting advantages and causal identification logic, effectively adapting to complex human behavioural datasets (Huang *et al.*, 2024b).

Despite these sophisticated tools, significant gaps persist in the specific domain of exit choice behaviour as they relate to HEPS. Research remains scarce on systematically distinguishing correlation and causality within passenger evacuation decision systems. Existing studies often focus on isolated methodological applications or predictive optimisation, failing to integrate intelligent feature screening, nuisance function optimisation, and robust causal verification to construct an end-to-end analytical pipeline for exploring exit choice mechanisms in HEPS scenarios.

To address this gap, this PhD by Published Works (Paper 3) introduces a novel optimised DML causal inference framework. This comprehensive approach first conducts systematic literature mining and questionnaire data collection to summarise multi-dimensional factors affecting passenger exit choice. It then leverages multi-model comparison and dynamic selection to optimise nuisance function estimation, eliminating confounding biases within complex behavioural datasets. Finally, it adopts statistical significance testing and multi-group placebo experiments to verify the robustness of causal identification and quantify heterogeneous behavioural effects across diverse exit choice strategies. By integrating data screening, model optimisation, and causal verification, the optimised DML framework establishes a complete analytical chain that systematically uncovers the mechanistic underpinnings of passenger evacuation exit choice behaviour, providing a robust, data-driven paradigm for developing scenario-adaptive evacuation guidance and precise passenger safety intervention strategies onboard passenger ships, thereby supplementing the behavioural causal analytical foundation for the comprehensive HEPS risk assessment frameworks explored in subsequent sections.

2.4 Research Content and Review on Risk Assessment of HEPS from Multiple Perspectives

Traditional evacuation analyses primarily rely on “time” as a single metric, whereas systematic risk assessment seeks to identify, quantify, and prioritise all critical RIFs affecting the entire HEPS process (assembly, abandonment, and search and rescue). After identifying heterogeneous risk patterns and quantifying causal mechanisms, this section reviews risk assessment methodologies for HEPS as a complete system from multiple perspectives, i.e. probabilistic and causal modelling approaches, network-based and structural analysis methods. This represents a paradigm shift from efficiency evaluation to systematic safety management.

Risk assessment in maritime safety has evolved from qualitative expert judgment to quantitative probabilistic risk assessment. Classical tools such as Failure Mode and Effects Analysis (FMEA), FTA, and ETA have been widely applied (Marino *et al.*, 2023; Uflaz *et al.*, 2023; Ugurlu and Cicek, 2022). During abandon-ship procedures, crew behaviour is critical in minimising human error. Consequently, some studies have adopted methods such as fuzzy decision-making and the Success Likelihood Index Method (SLIM) to identify and quantify factors influencing preparedness for emergency drills, thereby reducing the likelihood of human error (Akyuz, 2016; Tac *et al.*, 2020). However, these classical approaches often prove inadequate for capturing human and organisational factors within complex systems, particularly when data are sparse and uncertainty is high.

To address these limitations, as shown in Table 4, BN have gained increasing application in maritime risk assessment due to their strong capacity for uncertainty reasoning and intuitive modelling of causal relationships (Fan *et al.*, 2020). BN integrate data from diverse sources, including accident reports, expert judgments, and simulation results, while allowing probabilistic updates and diagnostic reasoning (Cao

et al., 2023b; Wan *et al.*, 2019). Nevertheless, conventional BN struggle to process ambiguous, subjective linguistic terms provided by experts (e.g., “high risk”) and face challenges in fusing potentially conflicting expert opinions (Fan *et al.*, 2020).

Although risk assessment methodologies have advanced in other maritime domains, systematic HEPS risk assessment covering the entire process remains at an early stage. Existing studies often concentrate on specific phases of evacuation (e.g., assembly process) or individual risks (e.g., human error). The Sewol ferry case provides an illustrative case, where studies assessed upper-deck evacuation risks during ship listing and developed improved protocols (Kim *et al.*, 2019). However, such studies lack a comprehensive framework that spans the entire process from assembly to search and rescue and integrates HSEO factors (Wang *et al.*, 2023a).

In addition to probabilistic and causal modelling approaches, network-based and structural analysis methods have recently been employed to deepen understanding of risk interdependencies in complex transportation safety systems. Among these, CN theory offers a structural perspective by analysing the topological features of RIF interactions. It facilitates the identification of highly connected or influential risk nodes, thereby supporting system-level risk diagnosis. For example, Ren *et al.* (2023) constructed a cause-and-effect network of 792 dangerous goods transport accidents using high-order network modelling and identified 16 key causal factors through weighted k-core decomposition. In the railway domain, Zhou *et al.* (2015) extracted causal event chains from UK railway accident reports to build a directed-weighted network and analysed its topology to identify critical accident causes. Similarly, Ma *et al.* (2022b) applied CN theory to ship grounding accidents, revealing coupling relations among hazardous factors via directed network modelling. However, while CN excels at mapping interaction intensity and structural influence, it is inherently limited in uncovering explicit causal relationships among RIFs.

Table 4 The comparative results of literature on the risk assessment in maritime safety fields.

Literature	Research Topic	Methodology	Key Findings
Fan *et al.* (2020)	The effect of human factors on maritime safety	Tree Augmented Network-Bayesian Belief Networks	The critical RIFs for all accident types are ship age, ship operation, voyage segment, information, and vessel condition.
Cao *et al.* (2023a)	Analysis of factors affecting the severity of marine accidents	Tree Augmented Network-Bayesian Belief Networks	The “accident type”, “engine power”, “gross tonnage”, “ship type” and “location” are the five most important AIFs of three accident severity grades.
Ren *et al.* (2023)	Key causal factors in dangerous goods transport accidents	CN Theory	Identified 16 key causal factors from numerous accidents using high-order network modeling and weighted k-core decomposition, revealing the interconnections among RIFs and key system nodes.
Ma *et al.* (2022b)	Risk propagation of hazardous events for ship grounding accidents	CN Theory	Used directed network modeling to reveal the coupling relationships among various RIFs in ship grounding accidents, structurally analyzing risk propagation paths.
Xing *et al.* (2023)	RIFs in offshore structure lifting operations	GRA and DEMATEL	Successfully quantified the strength and direction of causal influences among 21 RIFs, identifying the fundamental and resulting factors affecting lifting quality.
Liu *et al.* (2023)	Unsafe acts analysis	DEMATEL-ISM Method	Effectively distinguished between surface-level manifestations and root causes of unsafe acts, constructing a multi-level hierarchical structure of RIFs and clarifying causal and dependency relationships.

Literature	Research Topic	Methodology	Key Findings
Akyuz (2016); Tac *et al.* (2020)	Human error factors in abandon-ship drill preparedness	Fuzzy Decision-Making/SLIM	Capable of identifying and quantifying factors influencing emergency drill preparedness, helping to reduce the likelihood of human error.

To address this gap, DEMATEL has been increasingly applied to infer causal influence paths among RIFs. By constructing an influence matrix, DEMATEL enables researchers to quantify not only the existence but also the strength and direction of causal relationships. For instance, Xing *et al.* (2023) integrated grey relational analysis with DEMATEL to evaluate 21 RIFs affecting offshore structure lifting quality. Nevertheless, in highly interdependent systems such as HEPS, analysing causality alone may overlook the hierarchical structure embedded within risk interactions.

In this context, ISM complements DEMATEL by decomposing the system into a multilayered hierarchy, thereby capturing both vertical and horizontal dependencies among RIFs. Liu *et al.* (2023) employed a combined DEMATEL–ISM approach to identify unsafe acts, effectively distinguishing root causes from surface-level manifestations. Together, these methods support a more structured and transparent risk diagnosis process.

To address those gap mentioned above, this PhD by Published Works (Papers 4 and 5) proposes a holistic risk assessment framework for the entire HEPS process. It first develops an HSEO risk indicator system through systematic literature reviews and analysis of maritime investigation reports. Its main innovation is a hybrid risk assessment model that integrates FMEA, AHP, BBNs, and Evidential Reasoning (ER), thereby combining structural diagnosis, expert weighting, and probabilistic inference under uncertainty. To enhance causal reasoning and multi-level interaction analysis, the framework also incorporates network-based and hierarchical methods, including CN theory, DEMATEL, and ISM. This allows not only for the identification and prioritisation of RIFs, but also for mapping their interaction intensity, causal pathways, and hierarchical structure. This PhD by Published Works provides HEPS with a scientific tool for transitioning from passive accident analysis to proactive risk management, offering robust decision support for ship operators and regulatory authorities.

2.5 Research Content and Review on the Time Prediction-Based Decision Support of Human Evacuation

The systematic risk assessment of the entire HEPS process, as reviewed in the previous section, logically culminates in the imperative for proactive emergency management. This section, therefore, transitions from understanding systemic risks to enabling operational decision-making, focusing on the pivotal role of evacuation time prediction. Accurate and rapid prediction of HEPS time serves as the critical computational foundation for effective decision-support systems, directly informing life-saving commands such as when to evacuate and when to abandon ship. Through a systematic cross-domain literature review, this section identifies transferable modelling principles that can inform the development of a robust evacuation decision support for passenger ships.

To explicitly review the methods that have been utilised, a literature search was conducted using the Web of Science database, focusing on studies published between 2014 and 2024. The literature search combined keywords from two core themes: (1) evacuation-related terms (human evacuation, emergency evacuation) and (2) prediction-related terms (prediction, forecast). The filtering process involved title and abstract screening, excluding non-English/non-empirical studies, and unrelated studies (e.g., studies where the terms only appeared in the background). As a result, 277 studies on human evacuation prediction across various fields were retained. Based on the visualisation of key trends from the search, as shown in Figure 1, it is evident that ML and Deep Learning (DL) methods have been increasingly applied in evacuation prediction, especially the past five year, with most applications focusing on the evacuation of buildings (Li *et al.*, 2023; Sahebi *et al.*, 2023; Wang *et al.*, 2023c), metros (Guo *et al.*, 2023; Yang *et al.*, 2023), and natural disasters (Sun *et al.*, 2024).

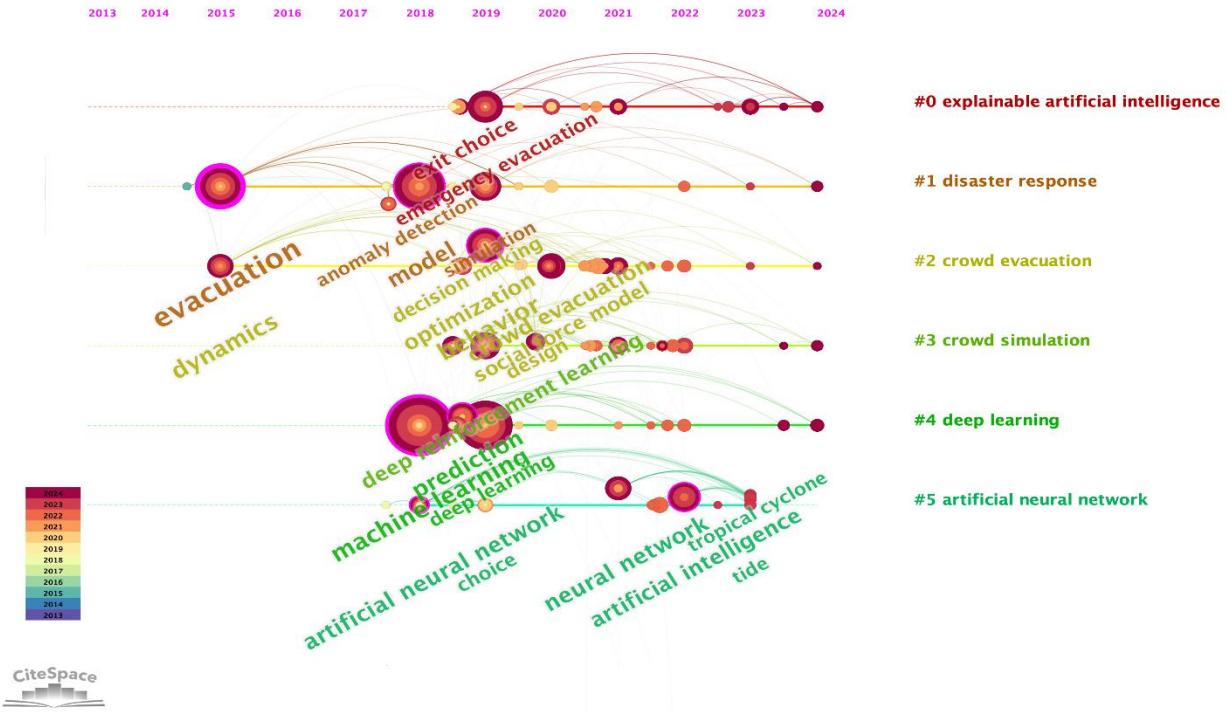


Fig. 1 The development trend of keywords in evacuation prediction research over time.

Currently, the application of ML and DL for building evacuation prediction is growing established. For instance, Li *et al.* (2023) applied the Extreme Learning Machine (ELM) with an improved seagull optimization algorithm for emergency risk assessment in a university library. The results showed that the improved ELM model enables efficient and rapid assessment of the emergency evacuation risk. Wang *et al.* (2023c) used simulated data to model HEPS time and exit selection, demonstrating the reliability of ML for planning evacuation strategies. Sahebi *et al.* (2023) assessed multiple ML models in a hospital fire scenario, showing that the Random Forest (RF) model yielded the best predictive performance. These studies confirm that ML models can effectively model complex human behaviours and spatial constraints in static indoor environments.

In recent years, ML and DL have gradually been introduced into evacuation research in transportation, primarily in metro rail systems. Guo and Zhang (2022) proposed a simulation-ML hybrid framework integrating nine input variables and three objectives,

validated with real-world data from a metro station in Singapore. Guo *et al.* (2023) further combined simulation and ML to predict human evacuation time and crowd density in congested metro areas, proposing an active guidance strategy to mitigate congestion. Yang *et al.* (2023) developed a multi-objective optimisation model for metro evacuation routes. By enhancing the backpropagation neural network model with the atomic orbit search algorithm, prediction accuracy was improved. These approaches demonstrate the growing potential of ML in modelling evacuation in large-scale and high-density transport systems.

Natural disasters are sudden events with often severe consequences. In the aftermath of such events, fast and accurate prediction of human evacuation time is critical, where ML and DL approaches can effectively achieve this goal and address key challenges in such natural disaster evacuations. Sun *et al.* (2024) introduced an interpretable ML model to predict household evacuation decisions during hurricanes, outperforming traditional models in accuracy and explanatory power. Similarly, Sreejith and Sinimole (2022) developed a ML model to predict the household evacuation preparation time during a flood event. These studies are instructive for HEPS, as they show that data-driven methods can manage the unpredictability of human response in crisis situations and the dynamic progression of an emergency, factors equally critical in a maritime disaster where the ship's state and environmental conditions are continually evolving.

Despite these advancements in land-based domains, the direct application of these ML models to the HEPS context remains limited and faces distinct challenges. Maritime evacuations introduce unique complexities not prevalent in other fields, including the dynamic motion of the ship (e.g., rolling and pitching), the effect of listing on passenger walking speed and balance, lower environmental familiarity among passengers, and the critical impact of crew guidance operations. Existing land-based models do not inherently account for these HSEO-factor-driven constraints, rendering their predictions potentially unreliable for maritime emergency decision-making.

Consequently, there is a pressing need to develop and validate HEPS-specific prediction frameworks that integrate these pivotal RIFs.

To address this gap, this PhD by Published Works (Paper 6) develops an integrated simulation-ML framework specifically tailored for HEPS time prediction. This research first identifies key HSEO factors, such as guiding behaviour, passenger demographics, stair availability, and ship inclination, and integrates them into a validated agent-based simulation model to generate extensive, scenario-driven evacuation data. This approach ensures that the unique maritime evacuation environment is fundamentally encoded in the training dataset. Subsequently, the framework applies and systematically compares a suite of state-of-the-art ML models, including RF, Support Vector Regression, and a novel Attention-enhanced Light Gradient Boosting Machine (LightGBM). A key innovation is the introduction of a weighted multi-criteria evaluation method, combining AHP and entropy weight, to select the optimal model by balancing prediction accuracy with computational timeliness. This holistic framework advances HEPS research from computationally intensive, post-hoc simulation towards intelligent, real-time prediction, thereby providing the core computational engine for proactive emergency decision-support systems on passenger ships.

2.6 The Relationship across the Whole Research Content

The preceding five sections collectively establish a comprehensive, risk-based safety analysis framework for HEPS, structured around a coherent identification-analysis-simulation-management workflow. This integrated approach systematically progresses from decoding the fundamental nature of maritime risks to enabling proactive, intelligent decision-support for emergency response.

Section 2.1 laid the foundational pillar by pioneering a multidimensional analytical framework (EMARM-WINGS-TAHDT-MICMAC) to investigate the heterogeneity of

RIFs across different operational contexts, specifically maritime watchkeeping periods. Section 2.2 further deepened the causal analysis by introducing a novel integrated analytical framework (ARM-WINGS-AISM) to systematically assess RIFs in maritime occupational accidents, with direct implications for crew and passenger safety during evacuations. Building on this foundational understanding of risk causality, Section 2.3 further advances the research approach into the realm of behavioural mechanism exploration. It develops an optimised causal inference framework for identifying inherent driving factors behind passenger evacuation exit choice behaviour. The paradigm then shifts from causal understanding to systemic assessment. Section 2.4 established a comprehensive risk assessment framework for the entire HEPS process by integrating CN theory with causal-structural modelling methods (DEMATEL-ISM). Finally, Section 2.5 culminates the research workflow by focusing on operational decision-support, developing an integrated simulation and ML framework for the rapid time prediction of HEPS.

The synergy among these research components creates a powerful, end-to-end analytical chain for HEPS safety. The framework begins with the identification and heterogeneous analysis of risk patterns (Section 2.1), the systematic assessment of occupational accident causality (Section 2.2) and causal inference of exit choice behaviours (Section 2.3), then progresses to a holistic risk assessment of the entire evacuation system (Section 2.4), and finally achieves real-time predictive capability for evacuation management (Section 2.5). This ensures a holistic analysis spanning from macro-level systemic risks to micro-level individual behaviours, all encapsulated within the overarching HSEO paradigm.

Ultimately, this cohesive and progressive research framework contributes to the broader vision of safer and more resilient passenger shipping. The findings and methodologies developed in this PhD by Published Works provide a scientific foundation for enhancing HEPS safety across vessel design, crew training, operational

planning, and emergency management, paving the way for more evidence-based and risk-informed safety practices in the global maritime industry.

CHAPTER 3 METHODOLOGY

This chapter delineates the integrated methodological framework developed in this PhD by Published Works, combining multidimensional risk analysis, causal-structural and causal inference modelling, systematic risk assessment and simulation-based prediction to address maritime safety and evacuation challenges. It introduces an EMARM-WINGS-TAHDT-MICMAC framework for investigating risk heterogeneity across watchkeeping periods, an ARM-WINGS-AISM methodology for occupational accident analysis, and a causal inference framework for exit choice behaviour during emergency evacuation. The chapter further presents a comprehensive risk assessment system for the entire HEPS process based on the HSEO framework, along with an integrated simulation-ML approach for evacuation time prediction and decision-support. Collectively, these methodologies establish a rigorous scientific foundation for the analyses and contributions detailed in the subsequent chapters.

3.1 The Holistic Framework

The integrated methodological framework of this PhD by Published Works comprises five interconnected analytical pillars underpinned by six core published papers, as illustrated in Fig. 2. Each pillar addresses specific RQs through the development and application of innovative methodologies, establishing a coherent identification-analysis-simulation-management workflow for HEPS safety enhancement. The framework systematically integrates multidimensional risk analysis using the EMARM-WINGS-TAHDT-MICMAC model to investigate risk heterogeneity across operational contexts; causal-structural modelling through the ARM-WINGS-AISM framework for occupational accident analysis; causal inference modelling for passenger exit choice behaviour; hybrid risk assessment integrating HSEO analysis with FMEA, BBN, ER, CN theory and DEMATEL-ISM methods for the entire evacuation process; and simulation-based prediction employing agent-based modelling with ML algorithms for

evacuation time forecasting and decision-support.

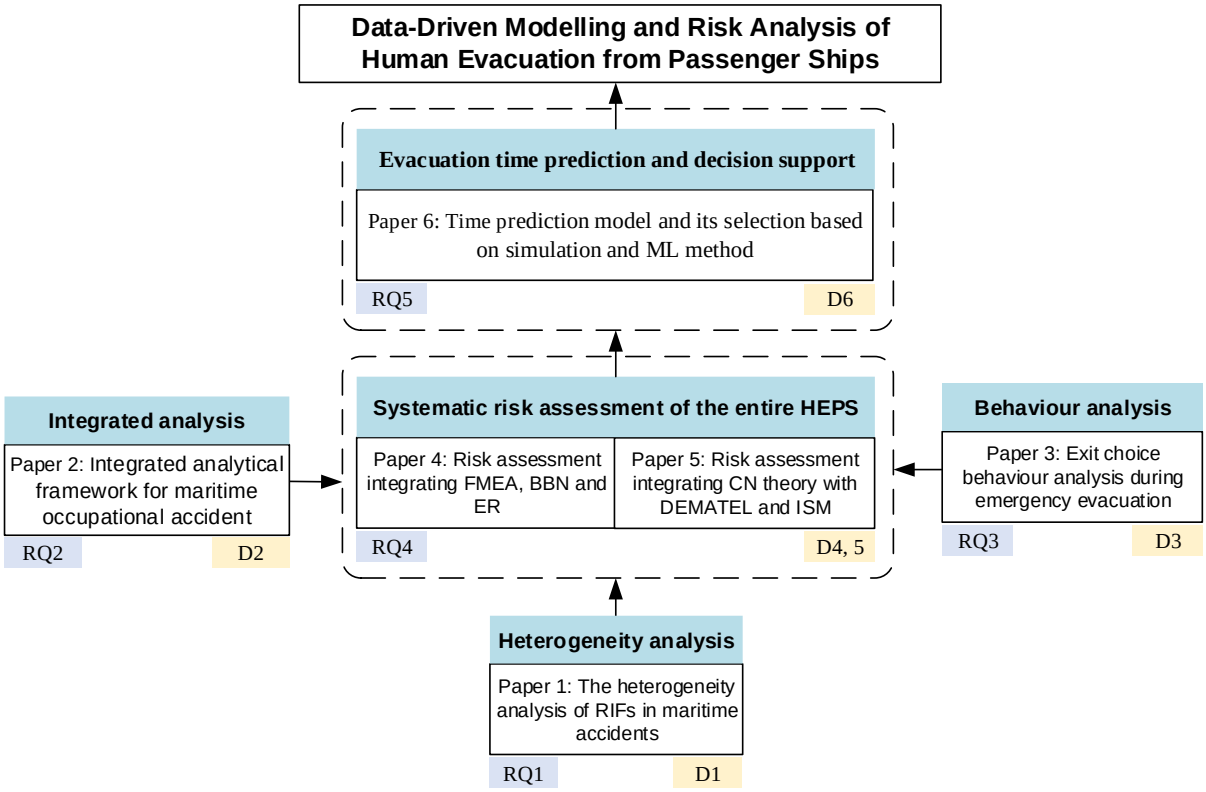


Fig.2. The whole framework in this PhD by Published Works.

In **Paper 1** (Wang *et al.*, 2025a), RQ1 was addressed through the development of an integrated multidimensional analytical model. This approach, synergising EMARM, the WINGS, the TAHDT, and the MICMAC, was employed to investigate the heterogeneity of critical RIFs across different watchkeeping periods. This approach enabled a systematic investigation into how critical RIFs differ across distinct watchkeeping periods, facilitates the development of temporally adaptive evacuation strategies that account for circadian rhythms and accumulated crew fatigue.

Paper 2 (Wang *et al.*, 2025b) addresses RQ2 by proposing a novel analytical framework integrating ARM, the WINGS, and the AISM. This integrated ARM-WINGS-AISM methodology systematically identifies RIFs from accident data, quantifies their causal interactions and impact strengths, and constructs an antagonistic topological hierarchy.

The framework thereby elucidates the complex multidimensional interactions and intrinsic risk transmission pathways among RIFs in maritime occupational accidents, providing a comprehensive tool for systematic risk assessment and prevention strategy development.

Expanding the research from correlational feature analysis to causal mechanism identification, Paper 3 (Wang *et al.*, 2026) tackled RQ3 by developing an optimised DML causal inference framework. This research systematically integrates multi-model comparison and dynamic nuisance function optimisation to mitigate pervasive confounding bias inherent in evacuation behavioural data. Crucially, it adopts a comprehensive validation strategy using statistical significance testing for causal effect evaluation and placebo experiments for robustness verification, ensuring rigorous and reliable causal identification of passenger exit choice behaviour.

Building on the preceding papers, **Papers 4 and 5** (Liu *et al.*, 2025; Wang *et al.*, 2023a) tackled RQ4 by conducting a comprehensive safety analysis of the entire HEPS process, treating the HEPS system as an integrated whole. Through a methodologically innovative approach, this research developed a systematic hazard identification framework tailored to the specific hazards encountered during HEPS process. Subsequently, a hybrid risk assessment model was introduced to quantify and prioritise these risks, integrating both structural analysis and causal reasoning, demonstrating the model's capacity to support real-world risk management in maritime evacuation scenarios.

Expanding upon the insights garnered from previous papers, **Paper 6** (Zhang *et al.*, 2025) further explored RQ5. This research developed an agent-based simulation model that comprehensively incorporates the effects of various RIFs for passenger ships. By employing different combinations of these variables, the model generated a wide range of evacuation scenarios. To address the challenge of rapid prediction, this research then

systematically assessed several state-of-the-art ML models for forecasting HEPS time. The performance of these models was rigorously benchmarked, and a standardized weighted model selection approach was developed to effectively balance the critical criteria of prediction accuracy and computational timeliness.

These six research papers collectively establish a comprehensive, risk-based safety analysis framework for HEPS, progressing through a coherent identification-analysis-simulation-management workflow. Their methodological interconnectivity enables a holistic investigation that spans from decoding heterogeneous risk patterns and quantifying causal mechanisms to analysing exit choice behaviours and modelling systemic risk interactions, culminating in real-time evacuation prediction and decision support. By systematically integrating multidimensional risk analysis, causal inference, CN modelling, and simulation-based prediction, this research establishes a scientific foundation for next-generation evacuation analysis and safety management, supporting the development of a data-driven, evidence-based, and resilient emergency evacuation system for passenger ships.

3.2 A Multidimensional Analytical Framework for the Heterogeneity Analysis of Maritime Accident Risks towards HEPS Safety Enhancement

As the foundational step in establishing a risk-based safety analysis framework for HEPS, this research pioneers an integrated multidimensional analytical framework. Recognizing that effective HEPS management requires a deep understanding of context-specific risks, particularly those arising from crew fatigue and performance variations during watch cycles, this research synergises four distinct techniques: EMARM, the WINGS, TAHDT, and MICMAC, as shown in Fig. 3. The aim is to systematically analyse the heterogeneity of RIFs across the watchkeeping periods of the third, second, and chief officers, thereby establishing a critical evidence base for temporally adaptive evacuation strategies.

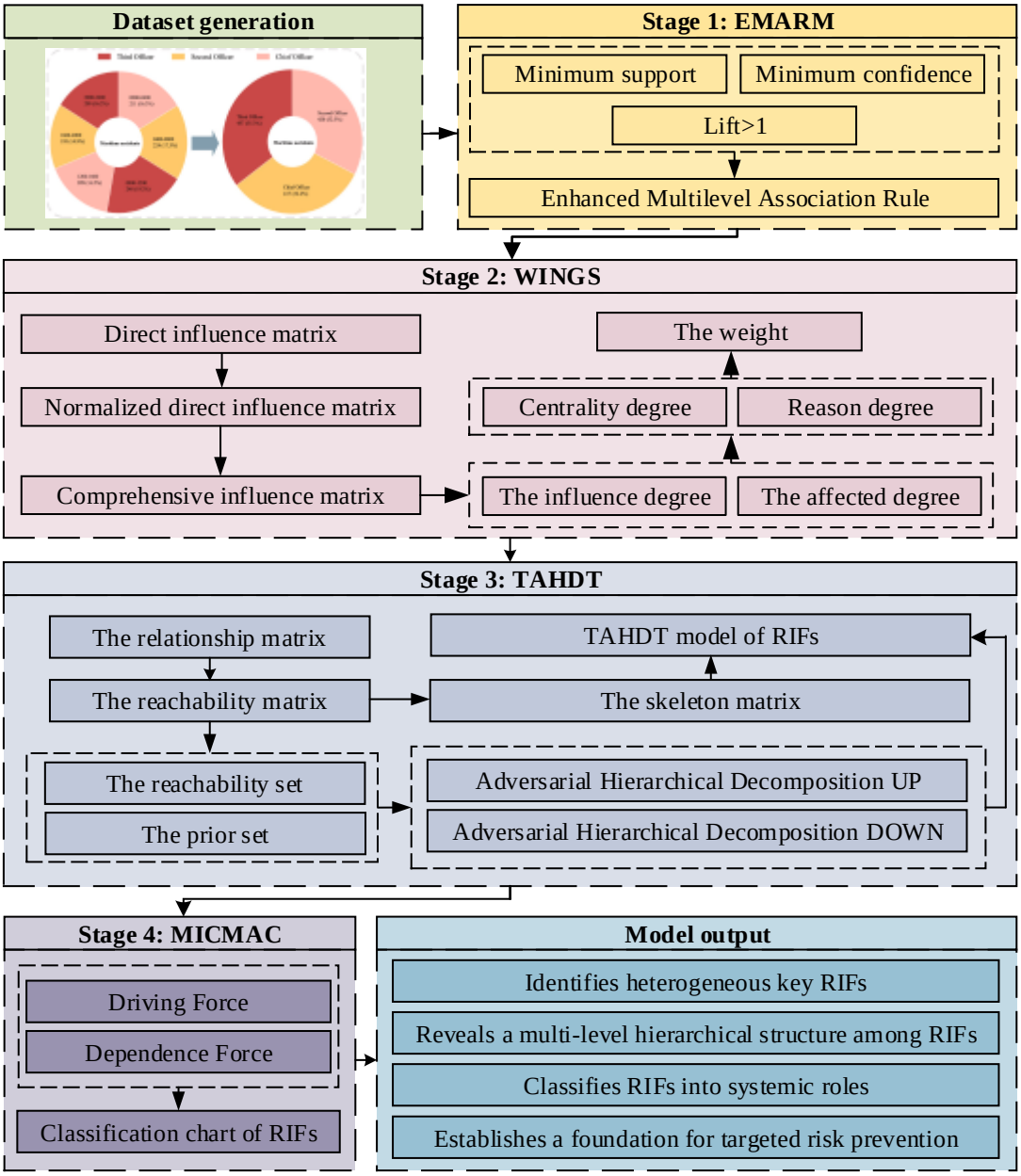


Fig. 3. The methodological framework for Paper 1.

The foundation of this methodology is a large-scale, categorized accident dataset. Data were collected from 1,294 maritime accident investigation reports from seven global maritime authorities spanning the years 2000 to 2019. A key innovation was the classification of each accident according to the watchkeeping period in which it occurred, creating three distinct sub-datasets that enable a rigorous comparative analysis of the underlying risk structures specific to maritime operational contexts that directly impact HEPS preparedness. A comprehensive RIF indicator system

comprising 34 factors was developed within the HSEO framework to ensure standardised analysis across all datasets, thereby maintaining direct relevance to maritime evacuation scenarios.

To analyse the data with specific implications for HEPS safety management, a sequential, multi-perspective analytical process was executed. First, the EMARM algorithm was employed to mine frequent itemsets and enhanced multilevel association rules between RIFs within each watch-specific dataset. Second, the WINGS model was established in a data-driven manner to elucidate causality and determine the reason and centrality degrees of each RIF. Third, the improved TAHDT approach was utilised to establish logical hierarchical structures of RIFs, prioritizing intervention points for HEPS safety measures. Finally, the MICMAC method was applied to classify the RIFs based on their driving and dependence forces, validating the hierarchical findings and identifying fundamental drivers that require attention in HEPS safety protocols.

This framework successfully reveals the significant heterogeneity in critical RIFs across different watchkeeping periods, providing a nuanced, context-specific understanding of accident causation highly relevant to HEPS planning. The findings demonstrate that risk profiles are dynamic rather than static, directly impacting crew alertness and performance during potential evacuation events. This methodology not only provides a new perspective for improving bridge resource management but also enables the development of HEPS strategies specifically tailored to address the unique challenges inherent in each watch period, ultimately contributing to more reliable passenger ship evacuation outcomes through evidence-based, temporally-aware safety interventions.

3.3 An Integrated Analytical Framework for Assessing Occupational Accidents towards Enhanced Human Safety during HEPS

To systematically investigate the complex causal mechanisms and hierarchical interactions among RIFs in maritime occupational accidents, this PhD by Published Works proposed a novel integrated analytical framework that synergistically combined ARM, the WINGS, and the AISM, as shown in Fig. 4. This ARM-WINGS-AISM framework established a complete analytical chain, progressing from initial data feature extraction through to an in-depth analysis of system element interrelationships. The framework was designed to systematically identify RIFs, quantify their causal strengths and interaction intensities, and ultimately construct a hierarchical topology that elucidates the intrinsic risk transmission pathways relevant to maritime evacuation scenarios.

The analytical procedure begins with data preparation and ARM. A structured and reliable dataset was constructed using maritime occupational accident reports (2013-2021) from the European Marine Casualty Information Platform (EMCIP), following a rigorous three-stage screening process that yielded 505 valid cases. Subsequently, 17 analytically valuable RIFs were identified and classified into four categories. A key procedural step involved discretizing continuous variables and systematically coding all RIF states according to the standardized EMCIP Taxonomy to ensure computational consistency. The FP-Growth algorithm was then employed to mine association rules, with optimal minimum support and confidence thresholds (0.3 and 0.5 respectively) determined through sensitivity analysis. This phase autonomously identified significant association patterns among RIFs that could potentially compromise evacuation safety, providing the foundational data for subsequent causal analysis of HEPS-related risks.

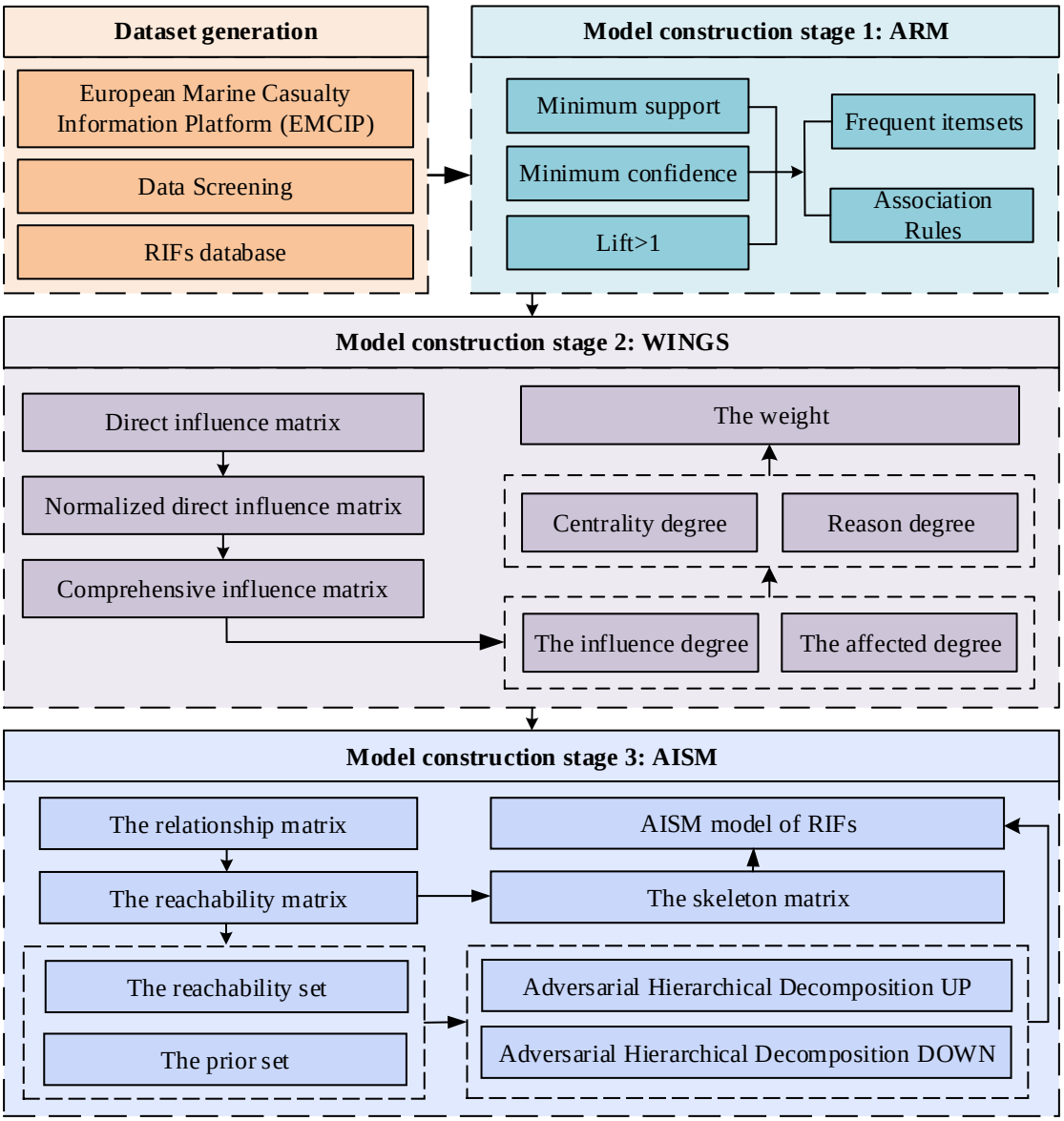


Fig. 4. The methodological framework for Paper 2.

The core analytical phase integrates WINGS and AISM methods to quantify causal relationships and establish hierarchical structures. The direct influence matrix was constructed based on significant associations identified by ARM, followed by normalization and derivation of the comprehensive influence matrix through influence transmissibility theory. WINGS implementation calculated key indicators including influencing degree, influenced degree, centrality degree, reason degree, and comprehensive weight for each RIF, quantifying their causal roles within the accident system. Building upon these results, the AISM method was applied to transform the

complex factor relationships into a multi-level hierarchical structure. The procedural sequence involved: eliminating weak influence relationships using an intercept threshold criterion, solving the reachability matrix through Boolean operations, identifying strongly connected components via Tarjan's algorithm, and performing hierarchical extraction to form both UP-type and DOWN-type topological hierarchies.

In summary, the integrated ARM-WINGS-AISM framework provides a systematic, data-driven paradigm for analysing maritime occupational accidents with direct application to HEPS safety enhancement. The methodology progresses sequentially from identifying associative patterns, to quantifying causal intensities, and finally to mapping hierarchical risk structures that directly inform evacuation protocol optimization. This comprehensive approach not only reveals the complex causal mechanisms and dynamic risk evolution pathways inherent in maritime occupational safety but also establishes a robust analytical foundation for developing targeted, evidence-based risk prevention and control strategies specifically designed to improve maritime evacuation outcomes through enhanced crew safety and operational reliability.

3.4 An Optimised DML Causal Inference Framework for Evacuation Behaviour Mechanism Analysis

Building upon the correlational predictive capability of existing evacuation behavioural models, this PhD by Published Works developed an optimised DML causal inference framework to address the critical limitation of correlation-dominated behavioural analysis in HEPS scenarios. Recognizing that reliable identification of causal mechanisms underlying passenger exit choice directly supports targeted evacuation guidance and refined crowd management, as illustrated in Fig. 5, this methodology systematically integrates multi-model optimisation, nuisance function calibration, and comprehensive causal validation procedures. The framework aims to distinguish

genuine behavioural causality from spurious data correlations while ensuring robust and stable causal estimation, specifically tailored for exploring human decision-making mechanisms during emergency evacuation onboard passenger ships.

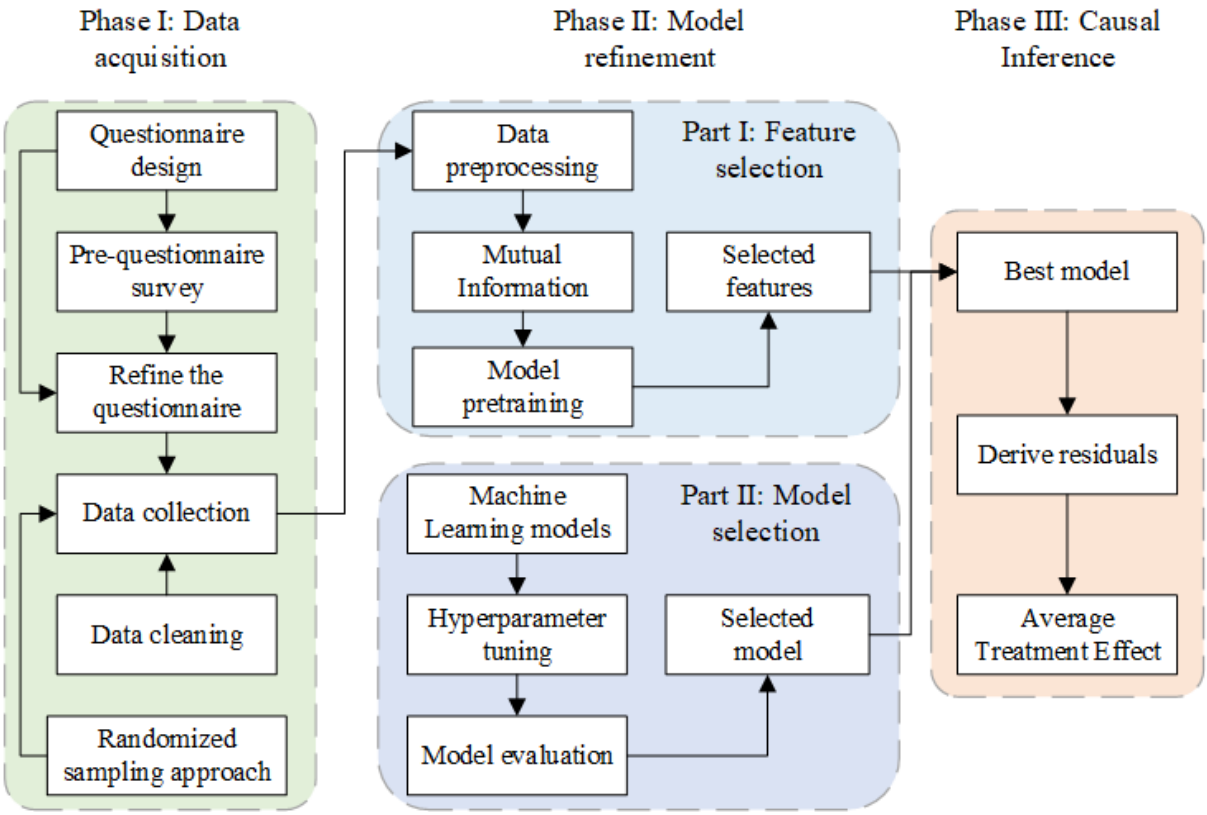


Fig. 5. The methodological framework for Paper 3.

The foundation of the framework is a structured and systematic approach to causal model construction. The process began with a validated dataset of 1,380 passenger evacuation questionnaires, covering multi-dimensional individual, behavioural, and situational features inherent in maritime evacuation scenarios. To address pervasive confounding bias and high-dimensional feature interference in human behavioural data, multiple classical ML algorithms were systematically compared for nuisance function estimation. Subsequently, optimal model architectures were selected and fine-tuned via rigorous hyper-parameter calibration and cross-fitting strategies, ensuring outstanding out-of-sample prediction performance for residual estimation.

To ensure the validity and stability of causal identification, a multi-layer verification procedure was implemented on the optimised DML framework. At the statistical level, significance testing was employed to quantify the statistical credibility of average treatment effects, screening core behavioural factors that exert stable causal impacts on diverse exit choice strategies. At the robustness level, dual placebo experiments covering treatment and outcome permutation were conducted with 1,000 iterative resampling, eliminating random noise and verifying that estimated causal effects are not derived from accidental data correlation.

This framework provides a robust and validated solution that bridges the research gap between correlational behavioural description and rigorous causal mechanism interpretation specifically for HEPS applications. It successfully establishes a complete analytical pipeline including feature screening, nuisance function optimisation, causal effect estimation, and multi-dimensional robustness verification. The causal inference results confirm that response-phase proactive behaviours and congestion-phase orderly behaviours serve as the dominant drivers shaping passengers' exit selection preferences. By delivering both quantitative causal estimation and transparent mechanism interpretation, this research equips maritime safety stakeholders with a rigorous analytical tool for decoding complex human evacuation decision logic, enabling precise behavioural intervention and scenario-adaptive evacuation optimisation, ultimately improving the scientificity and effectiveness of crowd management for HEPS systems.

3.5 A Comprehensive Risk Assessment and Decision Support Framework for Enhancing HEPS Safety

Building upon the systematic identification and analysis of RIFs, this research develops two complementary methodological frameworks to advance HEPS safety assessment. The first framework (Section 3.5.1) establishes a comprehensive risk

modelling approach that integrates multiple analytical techniques to address the multidimensional nature of evacuation risks. The second framework (Section 3.5.2) further enhances this understanding through a network-based structural analysis, revealing the complex causal relationships and hierarchical organization of RIFs. Together, these frameworks provide both quantitative assessment capabilities and deep structural insights for evidence-based safety decision-making.

3.5.1 A Novel Risk Assessment and Decision Support Framework for the HEPS Process

To conduct a systematic safety assessment of the entire HEPS process, this research developed an innovative risk modelling and decision support framework. This approach moved beyond traditional evacuation analyses based solely on time metrics, aiming instead to identify, quantify, and prioritise RIFs across the full HEPS process. At its core, the framework established a comprehensive analysis system based on HSEO dimensions, as illustrated in Fig. 6. It integrated FMEA, BBNs, and ER algorithms to address subjectivity and uncertainty in expert assessments, while further incorporating structural and network-based methods to capture the interdependencies, causality, and hierarchical relationships among RIFs.

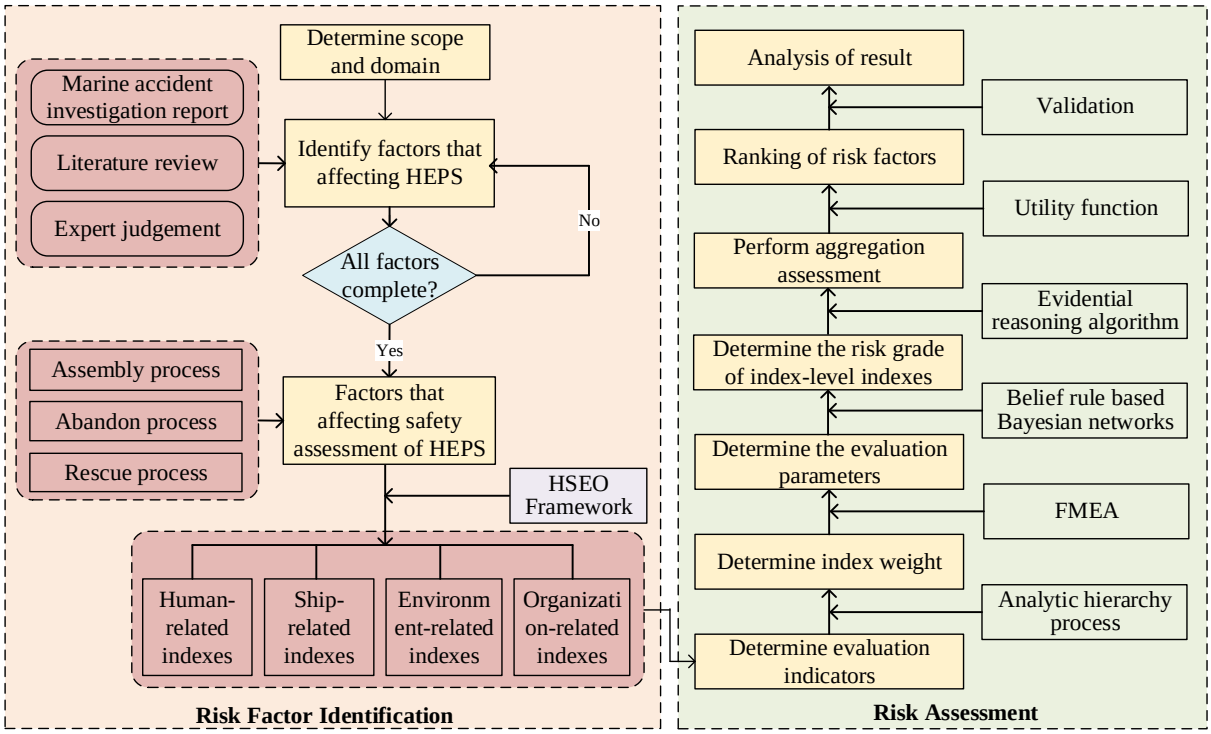


Fig. 6. The methodological framework for Paper 4.

The first stage of the framework involved hazard identification and structured analysis. Through systematic review of marine accident investigation reports and relevant literature, this research identified potential RIFs across the three phases of HEPS. These RIFs were then categorised under the HSEO framework, producing a multi-level risk indicator system encompassing four dimensions: human, ship, environment, and organisation. The HSEO structure ensured comprehensive hazard identification, covering aspects such as captain decision-making, crew proficiency, passenger behaviour, availability of lifesaving equipment, impacts of adverse sea conditions, and adequacy of emergency planning.

The second stage focuses on quantitative risk assessment. To overcome the limitations of conventional FMEA, a hybrid model was developed that integrates FMEA, the AHP, BBNs, and ER. AHP was used to weight risk indicators according to their relative importance. The framework's innovation lies in the use of a belief rule-based Bayesian network, which allows experts to express assessments using linguistic terms

(e.g., “high risk” and “moderate probability”) while fusing incomplete or conflicting judgements through ER algorithms. This approach provides a more robust and credible risk evaluation.

To validate the framework, a case study was conducted using a large-scale emergency evacuation drill onboard cruise ships. Drill processes and expert evaluation data were input into the model, generating quantitative risk evaluations and rankings for each HEPS phase. The model output, a risk priority index for each factor, identified the weakest links in the evacuation chain. Comparison with drill observations and historical accident data confirmed the model’s accuracy and robustness.

In summary, this risk modelling framework not only provides a systematic hazard identification tool for HEPS but also establishes a data-driven, quantitative model capable of addressing uncertainty, causality, and structural interdependence. Its application enables ship operators, shipping companies, and maritime regulators to identify and prioritise risks more precisely, supporting the design of targeted risk-control measures and emergency plans. Ultimately, the framework contributes to improving the safety and resilience of passenger ships.

3.5.2 A Quantitative Framework for the Systematic Analysis of RIFs influencing HEPS Safety

To systematically analyse the complex causality of maritime evacuation accidents, this research further developed a quantitative risk analysis framework. The methodology integrated CN theory with the DEMATEL and ISM, as shown in Fig. 7. The aim was to move beyond linear cause-and-effect analyses to establish a holistic, multi-layered structural model of risk, thereby providing a robust theoretical basis for optimising emergency management and enhancing passenger safety.

The cornerstone of this methodology is the construction of a comprehensive risk network derived from empirical accident data. The design was informed by a systematic analysis of 36 international passenger ship casualty investigation reports from 1990 to 2023. From these reports, accident causal chains were extracted to identify 27 distinct RIFs spanning human, ship, environmental, and management domains. The frequency of causal connections between these RIFs was used to establish a weighted, directed network, forming the foundational data structure for the subsequent analyses.

To deconstruct the risk network, a rigorous multi-stage analytical process was implemented. Initially, CN theory was applied to conduct a topological analysis of the RIFs from a global perspective, with robustness analysis under different attack modes used to validate the factor rankings. Subsequently, the DEMATEL and ISM methods were integrated to analyse the network from causal and structural perspectives. This process quantified the causal relationships between factors and decomposed the complex system into a well-defined, multi-layered hierarchical structure, clarifying the propagation pathways of risk.

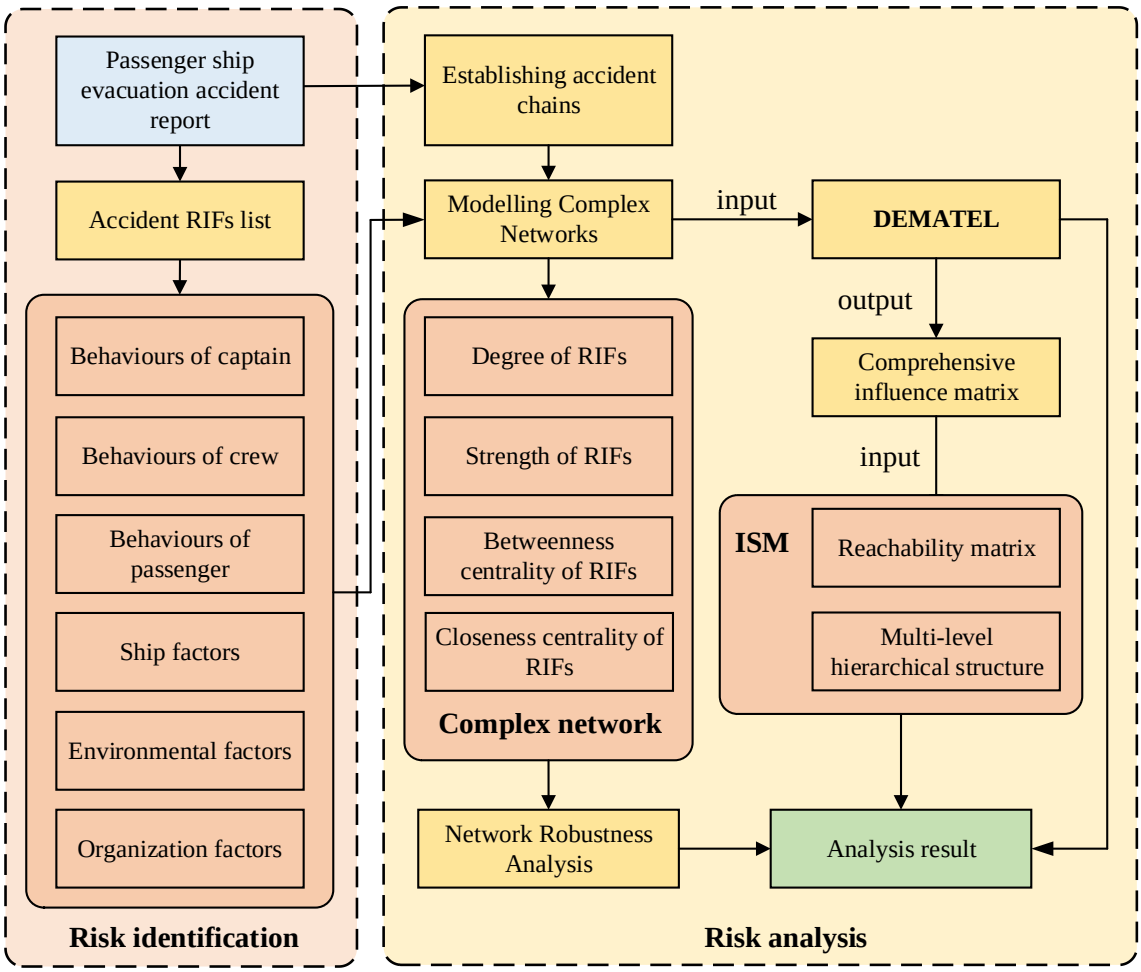


Fig. 7. The methodological framework for Paper 5.

In summary, this framework systematically reveals the complex interdependencies and hierarchical structure of RIFs in maritime evacuations. The findings provide a quantitative, evidence-based understanding of how accidents evolve, enabling emergency decision-makers to identify critical RIFs and formulate targeted countermeasures. Ultimately, this PhD by Published Works advances evacuation risk assessment from a descriptive to a structural and systemic level, enhancing the scientific basis for preventing casualties.

3.6 A Simulation-Based ML Framework for Predictive HEPS Time Estimation and Emergency Decision-Support

Based on the established risk assessment framework, this research developed an integrated simulation and ML methodology to advance the predictive modelling of HEPS processes. The studies systematically address the critical challenge of accurately forecasting HEPS time while accounting for the complex interplay of human, technical, and environmental factors.

As illustrated in Fig. 8, the first stage of this methodology involved the construction of a comprehensive agent-based simulation model. This model explicitly incorporated the effects of personnel attributes, group behaviour, ship layout characteristics, and external environmental factors specific to maritime evacuations. Through systematic variation of input parameters, the model generated a diverse portfolio of evacuation scenarios, establishing robust relationships between RIFs and evacuation outcomes. Model validity was rigorously ensured through verification against three independent performance indicators, creating a reliable foundation for subsequent ML applications.

The second stage developed a sophisticated predictive framework using state-of-the-art ML techniques. This research implemented and evaluated multiple advanced ML models, augmented by a novel attention-based LightGBM architecture specifically designed to capture complex feature dependencies in maritime evacuation data. The framework's innovation lies in its integration of simulation-generated scenarios with ensemble learning approaches, bridging advanced computational intelligence with maritime safety engineering. Model performance was rigorously validated through comparative analysis with simulation benchmarks and assessed against four operational indicators spanning accuracy and computational efficiency dimensions.

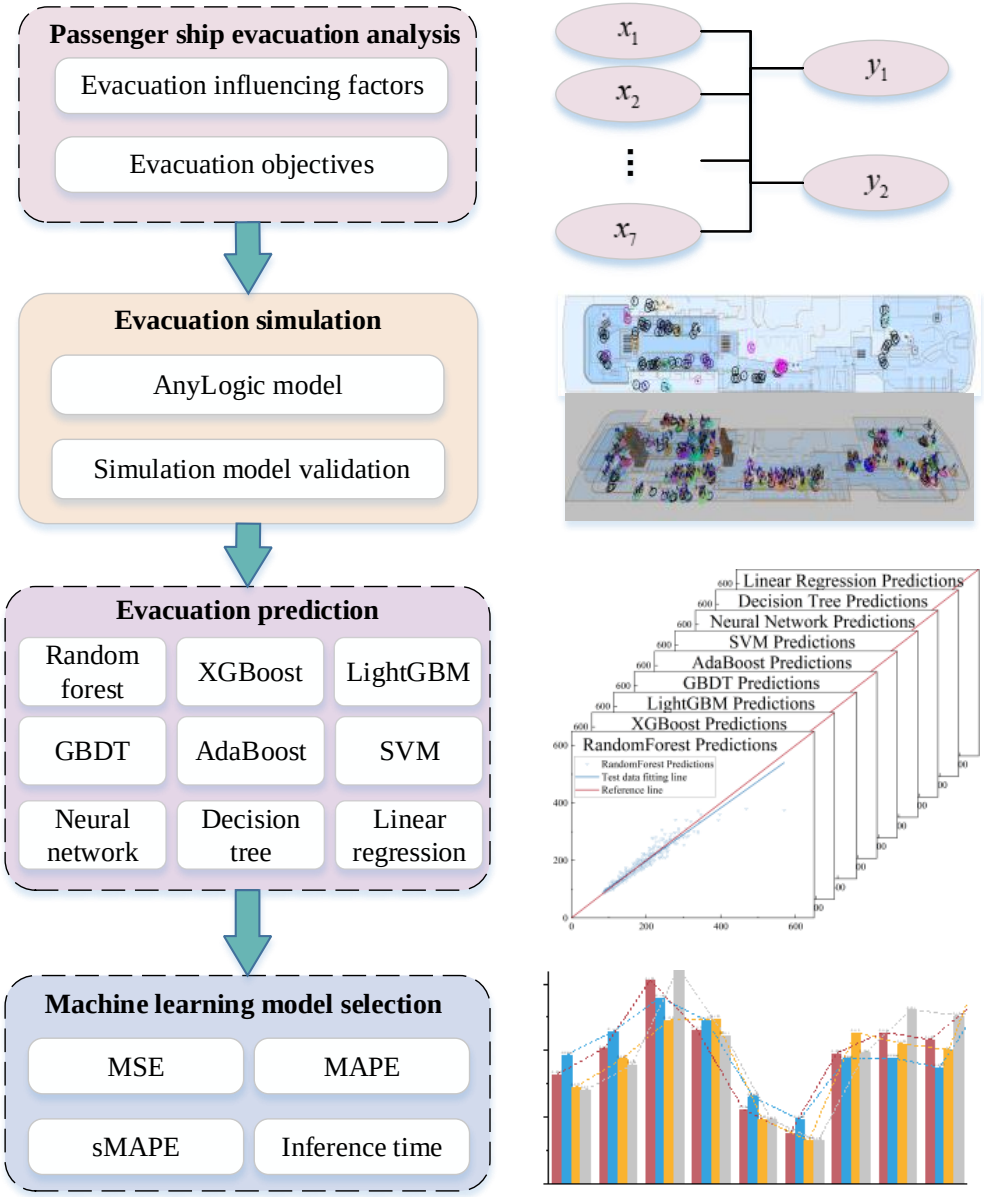


Fig. 8. The methodological framework for Papers 6.

To operationalize these advancements, this research introduced two standardised weighted model selection methods that systematically balance predictive accuracy with computational timeliness across different emergency scenarios. Through systematic categorization of evacuation phases and operational requirements, the methodology identifies optimal model configurations for specific situational needs. Furthermore, this research provides critical insights into how various RIFs influence predictive performance, enabling optimised model deployment in real-world

applications.

In summary, this integrated simulation-ML framework not only establishes a new methodology for rapid HEPS time prediction but also creates a decision-oriented modelling approach that supports emergency response planning for passenger ships. By transforming complex evacuation processes into computationally tractable and interpretable predictions, this research provides maritime safety practitioners with actionable intelligence for enhancing evacuation preparedness and operational response capabilities.

CHAPTER 4 FINDINGS and IMPLICATIONS

This chapter synthesises the principal contributions and broader impact of this PhD by Published Works. It first delineates how the developed analytical frameworks and methodologies advance the field of maritime evacuation safety, particularly in risk heterogeneity analysis, occupational accident assessment, exit choice behaviour analysis, evacuation risk assessment and evacuation time forecasting (Section 4.1). It then examines the implications of these findings for maritime safety policy, operational management, and technological innovation, with direct relevance for both strategic planning and emergency response in passenger ship operations (Section 4.2). Finally, the chapter evaluates the scope and academic-practical impact of the research, highlighting its significance through high citation rates, industry awards, and successful grant applications, while establishing a foundation for subsequent research advancements (Section 4.3).

4.1 Contributions to the Maritime Safety Field

This PhD by Published Works has made significant and multifaceted contributions to the field of maritime safety, advancing the scientific understanding and practical management of HEPS. It moves beyond traditional assumptions by establishing an evidence-based, data-driven paradigm that enhances the accuracy of safety assessments and supports proactive risk mitigation. The specific contributions are articulated as follows:

1) An Integrated Multidimensional Analytical Framework for Decoding Contextual Risk Heterogeneity

A foundational contribution of this research is the development of a novel multidimensional framework that systematically deciphers risk heterogeneity across

operational contexts. Paper 1 delivered a pioneering multidimensional analytical framework for decoding the heterogeneity of maritime accident causality. By synergising four advanced analytical methods (EMARM, WINGS, TAHDT, and MICMAC), this research provides the first systematic evidence that the profile of critical RIFs is not static, but varies significantly across different operational watchkeeping periods. This contribution equips the maritime industry with a sophisticated tool to diagnose context-specific safety challenges, enabling a move away from generic safety protocols towards targeted management strategies tailored to the unique operational risks of each watch period.

2) An Integrated Causal-Hierarchical Analysis Framework for Uncovering Systemic Risk Pathways

Addressing the complexity of risk interactions, Paper 2 devised and demonstrated an innovative ARM-WINGS-AISM framework that systematically unravels the causal structure of maritime occupational accidents. This methodology enables the simultaneous quantification of causal relationships and the construction of antagonistic hierarchical topologies, revealing intrinsic risk transmission pathways from underlying causes to surface-level events. This provides the maritime safety community with a sophisticated analytical tool for identifying systemic intervention points and developing targeted prevention strategies that address the root causes of evacuation-related injuries.

3) An Optimised DML Causal Inference Framework for Evacuation Behaviour Mechanism Identification

Complementing correlational evacuation behaviour analysis, Paper 3 delivered a refined causal inference framework that addresses the dual challenges of confounding bias and ambiguous behavioural mechanisms in maritime evacuation research. By

systematically integrating multi-model nuisance function optimisation, statistical significance verification, and dual placebo robustness testing, this research enables reliable causal effect estimation of multi-dimensional behavioural factors while distinguishing genuine causality from spurious correlation. This contribution empowers maritime safety stakeholders with a rigorous tool for decoding passenger decision-making logic, bridging the critical gap between descriptive behavioural correlation analysis and mechanistic causal interpretation in ship emergency evacuation management.

4) An Integrated System-Oriented Risk Assessment Framework for the Entire HEPS Process

Directly addressing the fragmentation in existing evacuation analyses, Papers 4 and 5 established a holistic risk assessment framework that spans the complete HEPS process spectrum from assembly to search-and-rescue. By integrating HSEO analysis with hybrid modelling approaches combining FMEA, BBNs, ER, CN theory, DEMATEL, and ISM, this research provides the first comprehensive methodology for quantifying and prioritizing risks across all evacuation phases. This contribution enables maritime regulators and shipping companies to systematically identify critical RIFs, optimize resource allocation, and develop evidence-based emergency plans tailored to the entire evacuation continuum.

5) An Integrated Simulation-ML Framework for Real-Time Evacuation Prediction and Decision-Support

Finally, Paper 6 introduced a groundbreaking simulation-ML framework that bridges high-fidelity evacuation modelling with operational decision-support. By integrating agent-based simulation capturing HSEO factors with state-of-the-art ML models including a novel Attention-LightGBM architecture, this research enables rapid and

accurate prediction of HEPS time under diverse emergency scenarios. This contribution provides ship operators with a powerful computational foundation for real-time emergency decision-making, fundamentally transforming evacuation management from reactive response to proactive prediction and preparedness.

In summary, the collective contributions of this PhD by Published Works have fundamentally enriched the maritime safety field. They provide a cohesive suite of analytical frameworks, predictive models, and assessment methodologies that collectively form a robust scientific foundation for enhancing HEPS safety across vessel design, operational planning, crew training, and emergency management, ultimately supporting the development of more resilient and responsive maritime evacuation systems worldwide.

4.2 Implications

The findings of this PhD by Published Works have substantial practical implications for maritime safety policy, operational management, technological innovation, and regulatory frameworks. These contributions extend to multiple stakeholders, including maritime regulators, shipping companies, ship operators, and safety practitioners. Collectively, the outcomes provide a scientific foundation for advancing evidence-based safety management and shaping next-generation emergency evacuation systems for passenger ships.

1) Supporting Evidence-Based Policy and Context-Specific Safety Management

This PhD by Published Works provides a robust evidence base for developing tailored safety management policies by demonstrating that accident causality exhibits significant heterogeneity across operational contexts. Paper 1 reveals that critical RIFs differ substantially between watchkeeping periods through its integrated EMARM-

WINGS-TAHDT-MICMAC framework. For instance, the second officer's watch is primarily influenced by "fatigue and physiological factors," necessitating strategies focused on fatigue mitigation, while the third officer's watch is more affected by "management and human factors" linked to operational inexperience. These findings enable maritime regulators and operators to transition from generic safety protocols towards refined, evidence-based approaches that align safety management with the distinct risk profiles of each watch period, thereby enhancing the precision of HEPS preparedness strategies.

2) Enhancing Occupational Safety Management through Systemic Risk Analysis

This PhD by Published Works establishes a robust analytical framework for identifying and prioritizing RIFs in maritime occupational safety, offering actionable insights for evidence-based safety management. Paper 2's integrated ARM-WINGS-AISM methodology systematically uncovers key risk drivers and delineates their causal and hierarchical relationships, particularly those affecting crew performance during emergency operations. The framework facilitates a deeper understanding of risk propagation mechanisms across human, operational, and environmental dimensions. These findings enable maritime enterprises to develop targeted prevention strategies, optimize safety resource allocation, and enhance real-time risk monitoring systems, thereby promoting a shift from prescriptive safety standards to context-sensitive management practices that strengthen overall safety resilience.

3) Supporting Mechanism-Driven Evacuation Guidance and Crowd Management

This PhD by Published Works provides a robust causal evidence base for developing targeted passenger evacuation strategies by demonstrating that passenger exit choice decisions are driven by definitive behavioural causal factors rather than superficial data correlations. Paper 3 reveals that core determinants of evacuation exit choice

differ distinctly across diverse decision scenarios through its optimised DML causal inference framework. For instance, passenger exit selection toward the nearest escape route is primarily driven by proactive confirmation and immediate escape behaviours, requiring emergency training focused on rapid alarm response, while exit decisions following evacuation guides rely heavily on orderly queuing and crew compliance behaviours, highlighting the significance of on-site order maintenance and professional guidance. These findings enable maritime regulators and ship operators to transition from empirical, one-size-fits-all evacuation protocols towards refined, mechanism-based intervention approaches that align safety training and emergency guidance with the causal characteristics of passenger decision-making, thereby enhancing the accuracy and practicality of emergency evacuation strategies.

4) Strengthening HEPS Risk Control through Structural Intervention Strategies

This PhD by Published Works advances operational safety management by providing a systematic framework to shift from reactive response to proactive risk control in maritime evacuations. Papers 4 and 5, through their integrated risk assessment methodologies, identify the most critical RIFs and propose targeted intervention strategies. The research presents a dual approach for risk mitigation: addressing fundamental causal factors at the underlying level while implementing strategic interventions at key intermediary nodes to block risk propagation pathways. This provides maritime authorities and shipping companies with an evidence-based tool to prioritize resources, design effective emergency procedures, and strengthen internal safety assessments, thereby enhancing the scientific foundation for casualty prevention during critical evacuation scenarios.

5) Developing Intelligent Decision-Support Systems and Training Protocols

The predictive modelling framework established in this PhD by Published Works offers

significant implications for advancing HEPS decision-support systems and crew training protocols. Paper 6 enable data-driven refinements to onboard emergency preparedness through their integrated simulation-ML approach. The findings support the development of stratified training programs that prioritize high-risk zones identified through model predictions, such as areas with historically prolonged evacuation times. Furthermore, this research facilitates the creation of modular, scenario-based training curricula that simulate complex emergencies, moving beyond conventional drill formats toward competency-based emergency response training. For decision-support systems, the predictive framework provides a basis for incorporating model-based scenario planning into routine safety audits and operational procedures, fostering a transition from reactive compliance to anticipatory, evidence-based risk governance throughout the maritime industry.

6) Informing Regulatory Frameworks and Performance-Based Standards

This PhD by Published Works provides a scientific foundation for enhancing international maritime safety regulations and certification frameworks. The developed multi-criteria evaluation framework for evacuation prediction models directly addresses limitations in current prescriptive standards. By establishing a standardized methodology for comparing and validating computational models based on both predictive accuracy and operational suitability, this research enables a transition toward performance-based regulatory approaches. These findings support regulatory bodies in developing formal guidelines for certifying evacuation analysis tools under varying vessel configurations and operational scenarios. Furthermore, the framework provides the technical basis for mandating intelligent prediction capabilities within vessel safety systems, particularly for high-capacity passenger ships, thereby systematically enhancing regulatory robustness while maintaining alignment with evolving computational methodologies.

In summary, this compilation-based PhD by Published Works establishes a solid theoretical and methodological foundation through its integrated risk analysis framework. It delivers significant practical value across maritime safety policy, operational management, technological innovation, and regulatory development. This research provides actionable insights and advanced tools for maritime stakeholders, supporting the transformation of evacuation safety from experience-based management to a quantitative, scientifically-grounded paradigm. This represents an essential advancement toward ensuring safe, efficient, and resilient passenger evacuation in increasingly complex marine environments.

4.3 Scope and Impact of This Work

The six core research papers in this PhD by Published Works collectively establish a comprehensive research paradigm for advancing emergency evacuation safety of passenger ships, shaping the future of data-driven maritime safety analysis and management. Each paper has not only made fundamental contributions to methodological innovation but has also demonstrated substantial impact through academic recognition, practical applications, and policy influence, thereby consolidating its significance in the global maritime safety landscape.

Paper 1 represents a pioneering effort in maritime risk heterogeneity analysis, developing an integrated EMARM-WINGS-TAHDT-MICMAC framework to systematically investigate how critical RIFs vary across different watchkeeping periods. This research provides unprecedented insights into the temporal dynamics of maritime safety by quantifying the distinct risk profiles associated with each officer's watch, establishing a scientific basis for context-specific safety management. Since its publication, the paper has gained significant academic recognition, with its methodology being adopted by maritime safety researchers for analysing context-dependent risk patterns and contributing to the development of temporally adaptive

safety protocols.

Paper 2 establishes an innovative analytical framework for maritime occupational safety through its innovative ARM-WINGS-AISM methodology. This research has been recognized for its capacity to simultaneously quantify causal relationships and construct antagonistic hierarchical topologies, establishing it as a reference methodology in maritime risk analysis. The framework's practical applications have extended to supporting safety management systems in shipping companies, providing actionable insights for developing targeted prevention strategies in passenger ship operations.

Paper 3 establishes a pioneering causal analytical framework for maritime evacuation behavioural research through its optimised DML methodology. This research has been acknowledged for its capacity to effectively eliminate confounding biases and distinguish genuine behavioural causality from spurious correlations, establishing it as a reliable analytical paradigm in passenger evacuation behaviour analysis. The framework’s practical applications have extended to supporting emergency evacuation design and passenger safety training systems onboard passenger ships, providing actionable insights for developing targeted behavioural intervention and efficient evacuation strategies in maritime HEPS management.

Papers 4 and 5 are instrumental in advancing holistic risk assessment for the entire HEPS process, representing a paradigm shift from fragmented analyses to comprehensive safety evaluation. Paper 4, in particular, has attracted substantial academic attention, becoming a highly cited paper in the maritime safety community. Its integrated HSEO framework and hybrid modelling approach have informed developments in maritime safety regulations and provided shipping companies with evidence-based tools for emergency planning and resource allocation.

Paper 6 completed the research framework by developing an integrated simulation-ML approach for HEPS time prediction. This research's introduction of a weighted multi-criteria evaluation method, balancing prediction accuracy with computational timeliness, has set new standards for predictive model deployment in maritime safety applications. This research has been particularly impactful in providing datasets that were utilized in the research and development of emergency evacuation equipment for passenger ships, and provided the critical computational foundation for the next generation of intelligent decision-support systems in maritime evacuation management.

The collective impact of these six papers extends beyond theoretical advancements, demonstrating substantial practical influence through high citation rates, industry award, and research funding success. These efforts contributed directly to the development of "Key Technologies and Complete Equipment for Large-Scale Waterborne Personnel Evacuation," which was awarded the second prize of the Science and Technology Progress Award by the China Institute of Navigation. The methodologies and findings have played a pivotal role in successful grant applications to prestigious funding bodies including the Royal Society (UK) and the Natural Science Foundation of China, securing significant research investment and underscoring their international recognition and importance in advancing maritime safety research.

By systematically bridging gaps between risk heterogeneity analysis, causal modelling, holistic assessment, and computational intelligence, this PhD by Published Works has established a comprehensive scientific foundation for enhancing maritime evacuation safety worldwide. This research has set the stage for the transformation of maritime evacuation safety management, ensuring that passenger ships can respond with greater intelligence, resilience, and effectiveness to complex emergency scenarios in dynamic marine environments.

CHAPTER 5 CONCLUSIONS and FUTURE DIRECTIONS

This chapter concludes the thesis by synthesising the key findings and emphasising their contributions to establishing a comprehensive, risk-based safety analysis framework for HEPS (Section 5.1). It highlights how the integrated research methodology, progressing systematically from foundational hazard identification through causal modelling to decision-support, significantly advances the scientific foundation for maritime evacuation safety. The chapter also identifies promising directions for future work (Section 5.2), including the expansion of real-world data collection across diverse vessel types and passenger demographics, the deeper integration of dynamic disaster scenarios into evacuation modelling, and the development of intelligent decision-support systems through multi-source data fusion.

5.1 Conclusions

This PhD by Published Works makes substantial contributions to the advancement of HEPS safety by systematically establishing a comprehensive, risk-based analytical framework that integrates multidimensional risk analysis, causal inference and causal-structural modelling, systematic risk assessment and simulation-based prediction. It develops a coherent identification-analysis-simulation-management workflow designed to enhance the scientific rigor, predictive accuracy, and decision-support capabilities of maritime evacuation research, combining advanced methodologies from data mining, computational intelligence, complex systems theory, and risk science.

At its core, this PhD by Published Works demonstrates the transformative potential of data-driven and model-based approaches to advancing maritime evacuation safety, particularly in decoding risk heterogeneity (Paper 1), analysing occupational accident mechanism (Paper 2) and exit choice behaviour (Paper 3), assessing systemic risks

(Papers 4 & 5), and supporting emergency decision-making (Paper 6). By employing a suite of innovative analytical frameworks and computational tools, it ensures that HEPS safety management can more effectively address the complexity, uncertainty, and dynamic interactions inherent in maritime evacuation scenarios.

Through multidimensional risk heterogeneity analysis (Paper 1), it systematically investigates how critical RIFs differ across watchkeeping periods for the first time, providing empirical evidence for developing temporally adaptive evacuation strategies that account for circadian rhythms and crew fatigue. Building on this foundation, Paper 2 introduces an integrated ARM-WINGS-AISM analytical framework that systematically identifies, quantifies, and models the hierarchical structure of RIFs in maritime occupational accidents, elucidating complex causal mechanisms with direct implications for evacuation safety. Through optimised causal inference modelling, Paper 3 establishes a rigorous analytical framework for passenger evacuation exit choice that integrates multi-model nuisance optimisation with systematic robustness verification, significantly enhancing both causal estimation accuracy and behavioural mechanism interpretability for maritime safety stakeholders.

Expanding the analytical scope, Papers 4 and 5 collectively develop a comprehensive risk assessment framework for the entire HEPS process, integrating HSEO analysis with hybrid modelling approaches to identify, quantify, and prioritise risks across assembly, abandonment, and search-and-rescue phases. Finally, Paper 6 establishes an integrated simulation and ML framework for HEPS time prediction, creating a decision-oriented modelling approach that bridges agent-based simulation with state-of-the-art ML algorithms to support rapid emergency decision-making.

This PhD by Published Works also underscores the importance of knowledge translation in advancing maritime safety practice. Its methodological frameworks and findings have been adopted by maritime safety authorities and shipping companies to

refine emergency response protocols and evacuation planning procedures. The developed datasets, analytical models, and computational tools have provided the scientific foundation for developing next-generation decision-support systems for maritime evacuation. Beyond theoretical contributions, this research delivers practical value in supporting regulatory decision-making, driving safety technological innovation, and shaping future research priorities in maritime evacuation safety. These outcomes have underpinned project applications to funding bodies such as the Royal Society and the National Natural Science Foundation of China, consolidating this PhD by Published Works' academic influence within the international maritime safety field.

5.2 Future Directions

Building upon the holistic risk-based safety analysis framework established in this PhD by Published Works, several promising research directions emerge that could further advance the scientific understanding and practical implementation of HEPS safety management. While the integrated methodologies developed across the six papers provide substantial advancements, future research could add extra value by engaging more real-world data collection, enhancing multi-model integration, and developing intelligent decision-support systems with greater adaptive capabilities.

First, research efforts should be directed towards broadening the scope and diversity of empirical data specifically for HEPS applications. The present research, while pioneering in its multidimensional analytical approaches, remains constrained by limitations in vessel types, sea states, and passenger demographics covered in existing datasets. Future studies should substantially encompass a wider spectrum of passenger ships, particularly large cruise ships with complex layouts and high-speed ferries with unique operational profiles, while incorporating more extreme sea conditions that reflect actual emergency scenarios. Additionally, comprehensive data collection focusing on vulnerable populations, including elderly passengers,

individuals with reduced mobility, and children, is essential for developing inclusive evacuation models that address the full range of human factors in HEPS scenarios.

Second, deepening the integration between dynamic simulation, risk modelling, and real-time monitoring represents a crucial evolutionary step. Future research should incorporate progressive disaster scenarios, such as escalating fires, progressive flooding, or combination emergencies, into evacuation simulations to examine the critical interactions between human behaviour and hazard evolution. Simultaneously, the risk assessment frameworks established in Papers 4 and 5 should be extended into adaptive, real-time monitoring and early-warning systems that integrate sensor data and provide immediate decision support for shipmasters during evolving emergencies. This integration should further develop to incorporate the temporal risk heterogeneity patterns identified in Paper 1, creating watchkeeping-aware evacuation systems that automatically adjust to crew performance variations.

Third, strategic advances in multi-source data fusion and intelligent system architecture will be pivotal for achieving next-generation HEPS management. Future research should focus on integrating real-time ship sensor networks, including attitude measurements, structural monitoring systems, and computer vision technologies, with weather forecasting data, passenger information systems, and the predictive ML frameworks developed in Papers 3 and 6. This integration would enable the construction of dynamic "digital twin" platforms for evacuation management that can simulate and predict evacuation outcomes under actual emergency conditions. Furthermore, developing autonomous decision-making models capable of processing these multi-modal data streams will be central to creating intelligent evacuation systems that can support complex, large-scale passenger ship operations with minimal human intervention.

This PhD by Published Works provides compelling evidence of the ongoing paradigm

shift in maritime evacuation safety from experience-based approaches to data-driven, scientifically grounded methodologies. By systematically integrating empirical research, numerical simulation, risk science, and ML, it not only advances maritime safety theory but also lays the foundation for developing intelligent evacuation systems that enable passenger ships and their crew members to respond with greater precision, resilience, and adaptability to complex marine emergencies. The future directions outlined here represent natural progressions along this transformative trajectory, pointing toward increasingly sophisticated, responsive, and ultimately life-preserving HEPS safety solutions.

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APPENDIX: PORTFOLIO OF PUBLICATIONS

There is a total of 6 papers for consideration for PhD by Published Work. All these papers are lead-authored or co-authored publications.

List of Published Works

No. Articles

1. **Wang, X.,** Cao, W., Li, T., Feng, Y., ***** Uğurlu, Ö., Wang, J., ***** 2025. An integrated multidimensional model for heterogeneity analysis of maritime accidents during different watchkeeping periods. ***Ocean & Coastal Management*** 264, 107625. https://doi.org/10.1016/j.ocecoaman.2025.107625 (**SCI Q1, Highly cited paper, Impact Factor: 5.9**)
2. **Wang, X.**, Zhao, G., Cao, L., ***** Yu, J., Li, Y., Wang, H., Cao, W., ***** 2025. Structural causality hierarchy analysis: A novel data-driven integrated method for assessing occupational accidents in maritime transportation. ***Safety Science*** 196, 107086. https://doi.org/10.1016/j.ssci.2025.107086 (**SCI Q1, Impact Factor: 6.2**)
3. **Wang, X.**, Yuan, Y., Fang, S. *****, Zhang, Z., Wang, J., ***** 2026. A novel causal inference method of exit choice behaviour analysis for passenger ships during emergency evacuation. ***Reliability Engineering & System Safety*** 272, 112489. https://doi.org/10.1016/j.ress.2026.112489 (**SCI Q1, Impact Factor: 13.7**)
4. **Wang, X.,** Xia, G., Zhao, J., Wang, J., Yang, Z. *****, Loughney, S., Fang, S., Zhang, S., Xing, Y., Liu, Z., 2023. A novel method for the risk assessment of human evacuation from cruise ships in maritime transportation, ***Reliability Engineering & System Safety*** 230, 108887. https://doi.org/10.1016/j.ress.2022.108887 (**SCI Q1, Highly cited paper, Impact Factor: 13.7**)
5. Liu, Z., **Wang, X.**, ***** Cao, W., Wang, J., Fang, S., Loughney, S., 2025. Quantitative Analysis of Risk Influential Factors of Evacuation Accidents for Passenger Ships. ***ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*** 11 (1), 04024088. https://doi.org/10.1061/AJRUA6.RUENG-1454 (**SCI Q1, Impact Factor: 2.9**)
6. Zhang, Z., Liu, Z., Zhou, Z., **Wang, X.**, ***** Majumdar, A., Cao, Y., Yang, Z., ***** 2025. Time prediction of human evacuation from passenger ships based on machine learning methods. ***Transportation Research Part A: Policy and Practice*** 200, 104664. https://doi.org/10.1016/j.tra.2025.104664 (**SCI Q1, Impact Factor: 7.2**)

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