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Determinants, methods, and solutions of evacuation models for passenger ships: A systematic literature review

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ABSTRACT

Passenger ships facilitate the mobility of people at sea and are a significant revenue stream for societies. Simultaneously, they should meet safety standards. One of the main safety pillars is offering passengers a reliable emergency evacuation plan. The International Maritime Organization (IMO) has disseminated guidelines for passenger ships to enhance the evacuation process understanding. Although the number of passenger ships is rising worldwide, implementing IMO's guidelines, particularly advance evacuation analysis, is still a young research area. Hence, this paper attempts to study previous research on human evacuation from the IMO perspective to uncover the current position of the issued guidelines in the literature. Accordingly, this research reviews 115 research publications published in scientific journals, peer-reviewed conferences, and doctoral and master dissertations from January 1999 to August 2022. As a result, the authors present the literature review of state-of-the-art papers to establish a firm foundation of past research. After identifying gaps, breakthrough points are clarified for future research about the benefits of handling uncertainty in input parameters, understanding human evacuation behavior, mutual interrelation among evacuation factors, and potential adoption of digital technologies in human evacuation from passenger ships.

1. Introduction

During the last decade, the tourism industry significantly contributed to economic growth (Figini and Vici, 2010). Passenger ships carrying at least 12 passengers, including cruise ships and passenger ferries, make up a significant part of society's revenue. Thirty million passengers are expected to travel on cruise ships, generating over $154 billion in revenues worldwide in 2019 (Cruise Lines International Association, 2021). Conversely, traveling by sea increases the safety risk for passengers. Allianz (2021) reported 69 passenger ship losses from 2011 to 2020. In addition, see Table 1, at least 2526 people lost their lives due to incidents from 2011 to 2018.

The facts mentioned pushing IMO to enhance safety at sea. The Maritime Safety Committee (MSC), which is primarily responsible for coping with all safety issues at sea, published principal safety regulations through different circulars (Circ.) (IMO, 2016). They aim to upgrade basic maritime safety standards for ships, first released by the International Convention for the Safety of Life at Sea (SOLAS) in 1914. Evacuation models have been integral to the issued regulations. Xie et al. (2020a) pinpoints evacuation as an effective action for lowering the casualty rate at sea. A ship evacuation process occurs in three successive distinct periods: (1) response, (2) evacuation, and (3) embarkation and launching period (IMO, 2016). Evacuation time is the central part of the evacuation process. It must not exceed the onset of circumstances threatening passengers' safety. Initially, the response period starts off noticing initial notifications (e.g., alarm) until deciding to move. Then, the evacuation period starts from the moving point to an assembly station. Afterward, the launching period commences. The mustered people in the assembly stations (or embarkation stations) must abandon the ship with a ship signal to reach a safe place. If the assembly and embarkation stations are separate, there is also a travel time between the assembly and embarkation stations.

Meanwhile, evacuation factors have a critical function during the evacuation process. Various factors influence the process, including environmental, configurational, behavioral, and human. Table 2 categorizes them according to definition (Lee et al., 2003).

Fig. 1 depicts a ship evacuation process sequence considering influencing elements.

The MSC has pushed ship designers to analyze the evacuation process by putting the evacuation factors into practice. Considering the

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Table 1
Passenger ship incidents.

Year	Ship name	Type	Fatalities	Reference
2011	• MV Spice Islander	• Passenger ferry	1,529[a]	Fundi (2018)
2012	• Costa Concordia	• Cruise ship	32	Vanem and Skjong (2006)
2013	• MV ST Thomas Aquinas	• Passenger ferry	120	Fahcruddin et al. (2019)
2014	• MV Sewol	• Passenger ferry	304	Kim et al. (2016)
2015	• Dongfang Zhi Xing	• Cruise ship	442	Baird (2018)
2016	• Aung Soe Moe Kyaw 2	• Passenger ferry	99	Christine and Bonnemains (2018)
Total			2526	

[a] 203 passengers died, and 1326 passengers are still missing but presumably dead.

Table 2
Aspects of evacuation process for passenger ships.

Aspect	Definition	Features
• Environment	• It defines the external drivers affecting the moving speed of passengers.	• Static and dynamic conditions of the ship (ship motions, transverse, and longitudinal stability) and • hazard (e.g., fire products including heat, smoke, and toxic gases)
• Configuration	• It covers the layout of a passenger ship	• The structure of evacuation routes and landing areas
• Behavior	• It encompasses the passenger's response to a situation.	• Travel speed, • family and group interactions, and • crossing flows
• Human	• It consists of passenger properties.	• Age, • gender, and • physical conditions

factors in modeling at an early stage of ship design can preclude any extra safety assessment later in calculating evacuation time. Specifically, it can reduce the possibility of rebuilding ships for only satisfying new safety evacuation standards. Simplified and advanced analysis are two categories of evacuation analysis (IMO, 2016). A simplified analysis is according to a deterministic method assuming passengers as nonautonomous agents. However, the latter considers passengers autonomous agents under the uncertain influence of input parameters, such as ship motion (Nasso et al., 2019). Ship designers should implement relevant corrective actions if the evacuation time exceeds the allowed time. Existing passenger ships could also carry out appropriate evacuation actions to reach the permitted evacuation duration (IMO, 2016). Given the above discussion, two research questions arise:

- What is the current situation of evacuation models for human evacuation from passenger ships regarding evacuation factors, modeling approaches, and solution methods?
- How do evacuation factors affect human behavior in the event of an accident?

This paper presents a review to identify the current situation and create a roadmap for future research in this area. The authors have not identified any comprehensive literature overview in this domain. This paper tries to cover this gap by reviewing, categorizing, and analyzing 105 publications released between January 1999 and August 2022. The specific review choices resulting from this sample of papers are explained in detail in Section 3.1. Before coming to that section, the authors first discuss earlier review/partial-review papers in Section 2. Research methodologies are clarified in Section 3. Detailed analyses and classifications are coming in Section 4. The current gaps analysis and future research opportunities are presented and discussed in Section 5. Finally, Section 6 contains the conclusion and directions for future research.

2. Literature review

Understanding the state of the current literature establishes a firm base for advancing knowledge and uncovering novel research areas (Pignatelli et al., 2005). Therefore, the previous review/partial review papers and IMO guidelines are listed in Table 3.

Given Table 3, the authors have been unable to identify any comprehensive review study for human evacuation analyzing state-of-

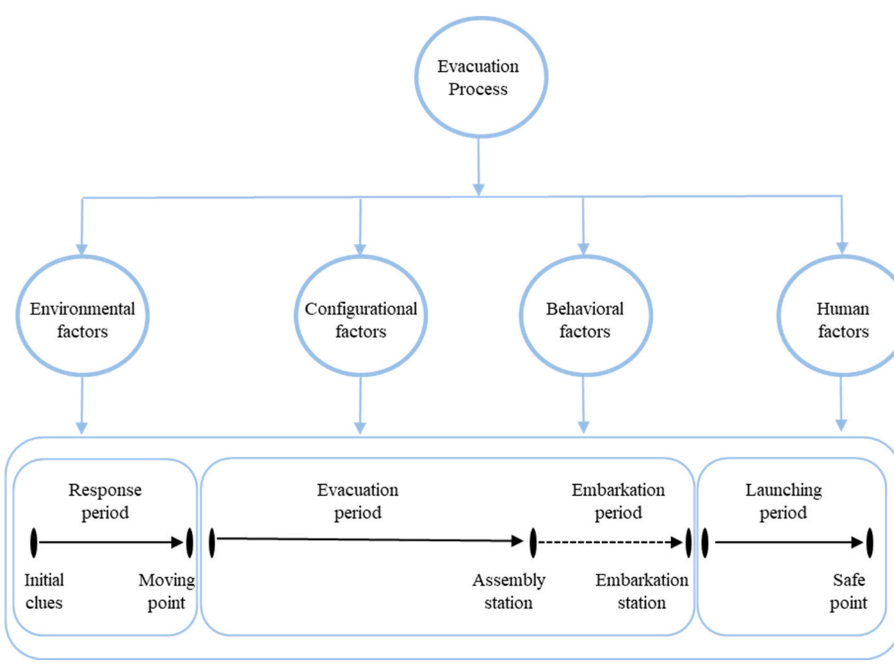

Fig. 1. Graphical representation of the evacuation process with evacuation factors.

Table 3
Characteristics of earlier review/partial review studies in the passenger-ship evacuation research area.

Scope	Regulatory reference	Range	Sample size	Paper
• IMO's requirements	• MSC/ Circ.909	1995–2001	25	Lee et al. (2003)
• Determinants of passenger injuries	• IMO, Athens Convention	2001–2008	20	Yip et al. (2015)
• IMO guidelines analysis	• IMO, MSC.1/ Circ.1238	2002–2015	10	Bucci et al. (2016)
• Modeling, analysis, and planning of evacuation models	• IMO, MSC.1/Circ. 1533	1973–2017	53	Sarvari et al. (2018)
• IMO guidelines analysis and evacuation projects description	• IMO, MSC.1/Circ. 1533	1974–2018	57	Stefanidis et al. (2019)
• IMO guidelines analysis	• IMO, MSC.1/Circ. 1533	1999–2017	23	Nasso et al. (2019)
• Evacuation factors, modeling approaches, and solution methods	• IMO, MSC.1/Circ. 1533	1999–2022	115	Our study

the-art research papers considering evacuation factors. Most review papers in Table 3 are limited based on the scope and period. In this area, review papers are divided into two groups. The first group of review studies is based on assessing past findings and the current situation. For instance, Sarvari et al. (2018) and Yip et al. (2015) investigated a range of publications for a specific period. The second group of review papers is according to the IMO guidelines for analyzing evacuation methods for passenger ships. For example, Bucci et al. (2016), Lee et al. (2003), and Stefanidis et al. (2019) primarily focus on examining the IMO guidelines for passenger ships.

Among all mentioned papers in Table 3, Sarvari et al. (2018) almost reviewed all relevant academic journals and conference papers on human evacuation from passenger ships. Although they analyzed the influencing evacuation factors on the evacuation process, the number of publications in their analysis is low. Furthermore, covered papers were published before 2017. The current work coincidences with Sarvari et al. (2018). The reason is about 60 percent of publications are released between 1999 and 2017. Therefore, this paper attempts to include them in the database and examine them based on the defined objectives, for example clustering the collected publications according to research type, quantitative (modeling or data collection) or qualitative (questionnaire, case study description, or evacuation software analysis). In addition, although Gwynne et al. (2003) and Galea et al. (2014a), with 61 and 31 citations until March 2022, are disregarded in the review of Sarvari et al. (2018), they are reviewed in this paper since they offer a significant contribution to the process of data collection and validation for human evacuation from the passenger ships.

Moreover, 1999 was a watershed year when the IMO issued the first circular regulations of evacuation analysis for passenger ships, so 1999 is applied as the cut-off year. Following this synthesis, this study intends to present a systematic review of the influencing factors on the human evacuation process for passenger ships and appropriately determine the modeling approaches and solution methods. At the same time, this paper looks at how emerging technologies such as digital twin (DT) and virtual reality (VR) can shift the performance of the evacuation process. Fig. 2 depicts the trend in the number of publications over the study period. Although research has been active during the first decade (1999–2009), this area has received more attention over the second decade (2010–2022).

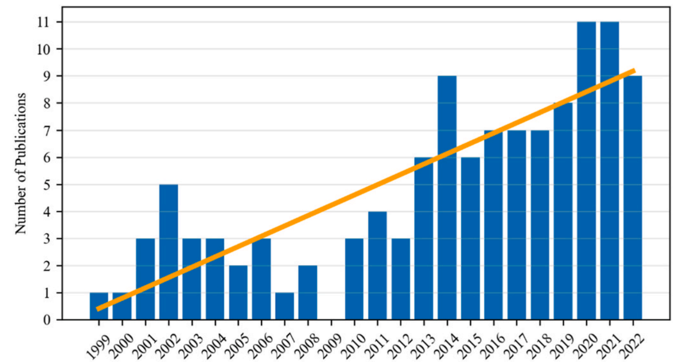

Fig. 2. Publications distribution.

3. Research methodology

This paper applies a four-step process to analyze the content in literature reviews. This process aligns with the qualitative content analysis methodology (Mayring and Brunner, 2007). It consists of (1) material collection, (2) descriptive analysis, (3) category selection, and (4) material evaluation steps portrayed in Fig. 3.

3.1. Material collection

The current research was carried out from September 2021 to June 2022. This paper covers peer-reviewed papers, conference papers, and doctoral and master dissertations in scientific English language journals from January 1999 to August 2022. The material collection is conducted in five stages. The stages are as follows.

- Identifying keywords: they are referred to our research questions to identify the keywords. Therefore, the keywords are defined as" passenger ship (cruise, ferry, ocean liners), evacuation, emergency, human/passenger behavior."
- Defining search strategy: this paper pursues a search string strategy. It combines keywords, truncation symbol (keyword root + *), and boolean operators (AND to include all search terms, OR to include alternative terms, NOT to exclude specific terms). The search is conducted in title, keywords, and abstract.
- Searching in databases: the authors selected the Web of Science (WoS) database for gathering material. Likewise, the search is carried out on the Open Access Theses and Dissertations database (OATD) to identify relevant research.
- Crosschecking in publishers: the collection is crosschecked by publishers to determine records' accuracy to include/exclude the intended keywords.
- Reporting outputs: the selection set is first transferred to Excel sheets for data cleaning and organizing collected papers. Afterward, the database is called in Python data frames for analysis and visualizations. Pandas, NumPy, and Matplotlib libraries are employed to analyze data.

Fig. 4 demonstrates the employed search strategy for retrieving relevant studies.

The authors initially searched on WoS. The search yielded papers consisting of at least one of the keywords in the first step and a word from the root of evacua (evacua*). It produced 4300 records. After that, any paper concerning evacuation from buildings, hospitals, trains, aircraft, and stadiums is excluded. The excluding strategy stood on WoS's advance search option and the authors' inspection by reading the paper's title (if necessary, the abstract is read as well). Similarly, theses and dissertations are retrieved from the OATD database. Ultimately, 115 papers are downloaded and classified. The records are distributed as 27% from Elsevier, 24% from Springer, 6% from IEEE, 4% from MDPI,

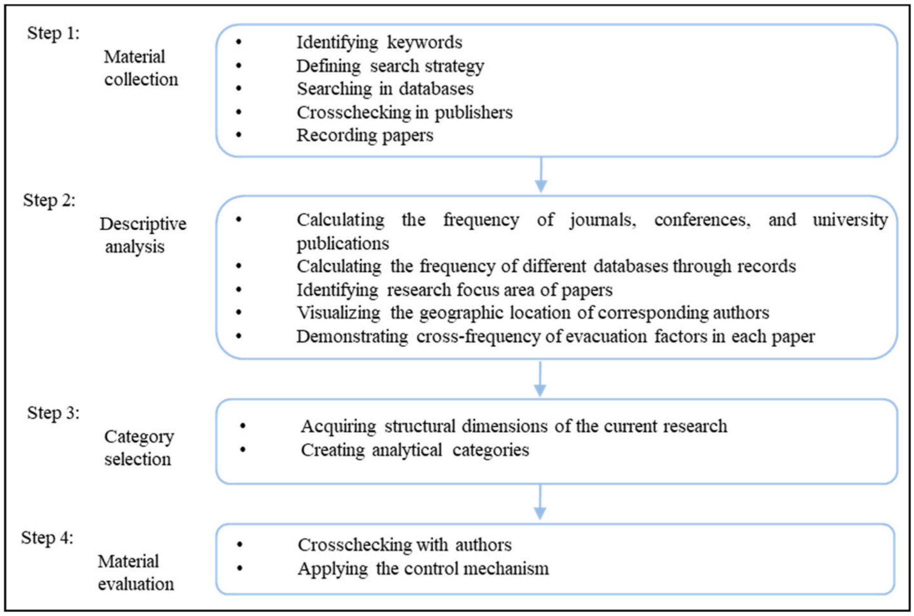

Fig. 3. Holistic workflow diagram.

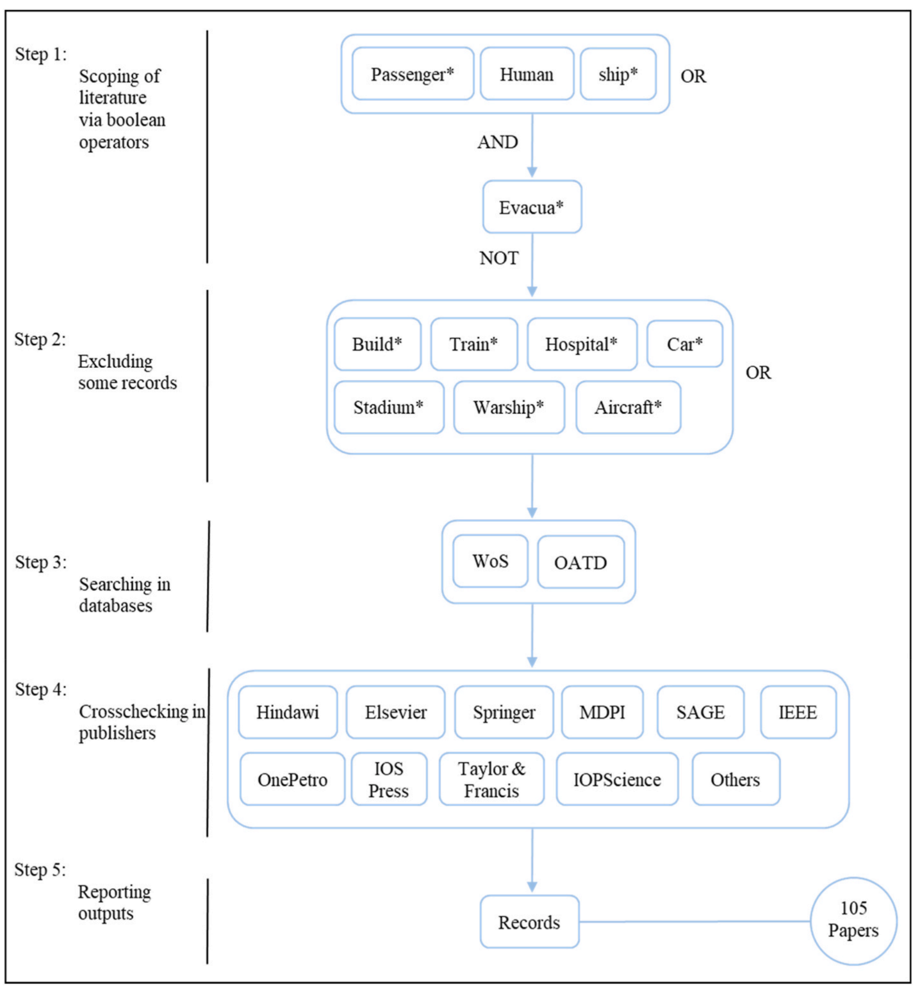

Fig. 4. Records extraction.

3% from Taylor & Francis, 3% from National Taiwan Ocean University, 3% from Royal Institution of Naval Architects, 2% from OnePetro, and 2% from Hindawi. Other publishers with one publication had an overall 26% contribution. Appendix A contains the list of publishers. The records' credibility in data collection, analysis, and reporting is fulfilled by the author checking (Creswell, J.W., & Miller, 2000).

3.2. Descriptive analysis

The authors found 111 journal and conference papers, two doctoral dissertations, and two master theses- 115 research publications in total. The distribution of journals, conferences, and university publications is represented in Fig. 5. Those with more than two publications are described under the same name of journal/conference; however, others with one publication are allocated to the other categories named Others (Journal Papers/Conference Papers). They are listed in Appendix B. Appendix C is also constructed for the journal names' abbreviations. Fig. 5 reveals a growing tendency in evacuation studies for passenger ships. Among journals, Ocean Engineering (Ocean Eng.) and Safety Science (Saf. Sci.) have the largest number of publications, with 10 and 6, respectively. They have been more active in this area. They mainly researched passenger behavior/awareness, walking speed, safety perception, and risk analysis during a human evacuation from passenger ships. Meanwhile, the Pedestrian and Evacuation Dynamics conference published more papers than others, with seven amid conferences. The released papers not only focus on data collection concerning movement and evacuation dynamics of passengers considering ship motions, but they also have worked on the simulation and modeling of human evacuation.

Besides, Journal of Marine Science and Technology (JMST), Journal of Marine Science and Technology (J Mar Sci Technol), Physica A: Statistical Mechanics and its Applications (Phys. A: Stat. Mech. Appl.), Procedia Computer Science (Procedia Comput. Sci.), Mathematical Problems in Engineering (Math. Probl. Eng.), Reliability Engineering & System Safety (Reliab. Eng. Syst), Journal of Marine Science and Engineering (J. Mar. Sci. Eng.), and Computers in Industry (Comput Ind) with 14.8% contribution attempted to reflect new insights in this research area. They tried to develop system simulation models considering passengers' characteristics. While International Conference on Human Factors in Ship Design and Operation, Traffic and Granular Flow (TGF), and International Conference on Virtual, Augmented, and Mixed Reality (VAMR), with a 5% impact, push the research in this area forward. They are more inclined to manifest human factors into ship design. Moreover, the University of Greenwich, University of Huddersfield, Norwegian School of Economics (NHH), and Aalto University (with a 3.5% impact) generate new knowledge in this area. They devoted considerable effort to advancing the understanding of passenger behavior during a ship evacuation. Furthermore, Springer with 40%, Elsevier with 16%, and the Royal Institution of Naval Architects with 8% have a remarkable impact on emerging the research area of human evacuation from passenger ships. They built the foundation of knowledge by conducting questionnaires, conducting onboard experiments, and simulating/modeling the human evacuation process from passenger ships. Afterward, IEEE (6%), National Taiwan Ocean University (6%), Hindawi (4%), and Taylor & Francis (2%), along with Springer (28%) and Elsevier (26%), shifted the state of research in this area and yielded fresh insights into the research by analyzing advanced evacuation methodologies and taking human behavior properties into account. Since 2019, evacuation studies have received more attention from MDPI and IOS Press databases. They accelerated development in this area by applying multidisciplinary approaches, particularly computer science, mathematics, engineering, and environmental science.

Further, it is essential to identify the subject areas of publications. The research area of each publication is placed using the WoS subject area feature. This identification can enable researchers to recognize the research area's focus and open new research topics for future research. According to Fig. 6, engineering with 38.3% is more interested among researchers, followed by 36.5% for multidisciplinary approaches. Afterward, computer science and mathematics accounted for 12.2% and 3.5%, respectively.

Moreover, those research areas with two or fewer publications are listed in the others' category (physics, environmental science, psychology, construction building technology, neuroscience, and medicine). Interdisciplinary research pays increasing attention among scholars in this research area. The reason is the presence of different evacuation factors involved in the human evacuation process. There is a need to consider all together to fulfill IMO's requirements. Integrating techniques from other disciplines, such as engineering, environmental science, oceanography, operations research, management science, etc., augment the understanding and describing human evacuation problems from passenger ships.

Next, from Fig. 7, Asia (52.2%) and Europe (44.3%) have the most significant academic contribution among others (Africa and South America have zero publications). Most publications in Asia are researched in Chinese and South Korean maritime institutions, with 39 and 12 papers, respectively. One of the solid reasons for the importance of this area for Chinese and South Korean scholars can be the sinking of Dongfang Zhi Xing and MV Sewol passenger ships with the loss of 442 and 304 passengers and crew, respectively (Baird, 2018; Kim et al., 2016). Hence, the Chinese and South Korean maritime sectors have inspired researchers and ship designers to reach safer evacuation solutions at sea. The UK (17 papers) and Norway (7 papers) have been more active and interested in Europe. Not only a disaster such as Costa Concordia and MS Scandinavian Star but also IMO's guidelines have pushed

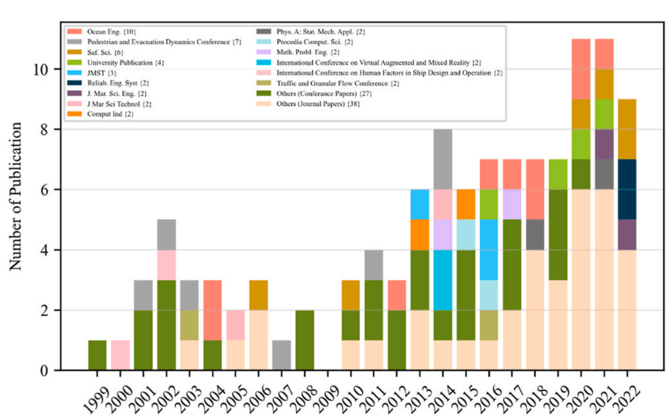

Fig. 5. Distribution of different journals, conferences, and university publications.

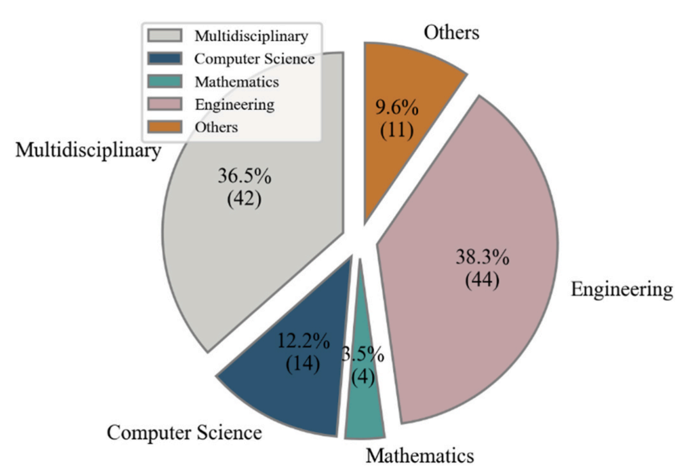

Fig. 6. Distribution of publications' research subject areas.

Fig. 7. Geographic locations of the corresponding author.

the maritime industry to rise in research and development activities in terms of human evacuation modeling. Other countries on the list have a 34.8% contribution (Japan, Greece, Germany, Poland, Taiwan, Finland, Italy, Spain, Netherlands, Sweden, Canada, USA, Australia, Croatia, and Turkey). It shows that the popularity of human evacuation problems is growing among scholars in different geographic regions. Eventually, according to the first author's affiliations, Edwin Richard Galea from the University of Greenwich with seven publications, and Xinjian Wang from Dalian Maritime University with six publications, have the most considerable contribution in this research area.

Table 4
The principal analytical categories of the study.

Analytical category	Features	Appendix
Modeling approach	• Mathematical, • simulation, • experimental, • • conceptual- and analytical-based, and hybrid	D
Traffic assignment formulation	• System-optimal and • user equilibrium	E
Model parameters	• Environmental factors o Fire products (smoke, heat, and toxic gas), o ship stability condition, o ship motions, and o other external forces (wave, sea state, and time of day) • Configurational factors o Ship layout, such as the layout of corridors, staircases, and doorways, and o initial distribution of passengers and crew across the ship. • Human factors o Passenger behavior, including walking speed and social relationship o passenger age, o passenger gender, o passenger physical condition (agility and mobility impairment), o passenger height, o passenger weight, and o passenger onboard evacuation experience • Behavioral factors o Crow behavior (family group behavior, counter and crossing flows, and crow assistance)	F
Hazard type	• Fire, • flooding, • sinking, • storm, and • capsizing	G
Solution method	• They are presented based on methods applied in the paper, e.g., the Cellular Automata (CA) method.	H

3.3. Category selection

The structural dimensions of the current research and chief topics of analysis, including detailed analytical categories, are represented in Table 4. Each category consists of different features discussed in greater detail in Section 4. The MSC scope has various study subjects, such as updating the SOLAS convention, piracy and armed robbery against ships, and cyber security. However, the current work focuses on emergency evacuation from passenger ships. The present study targets the evacuation factors listed in Table 2 to determine underlying features. Then, the collected papers are analyzed and categorized concerning the identified features. A detailed presentation of all publications in different analytical categories is described in Appendix D to H.

Fig. 8 demonstrates the popularity of different modeling approaches for representing the behavior of the problem. The most significant portion of researchers prefers to apply simulation approaches for defining their model (with 52.2%). It is followed by hybrid (simulation/mathematical, simulation/experimental, simulation/questionnaire) and experimental approaches with 19.1% and 17.4%, respectively. 7% of the used methods account for the mathematical approaches. Only a minority of researchers, 4.3%, prefer to employ analytical modeling approaches. It shows the popularity of simulation techniques and increasing attention to hybrid and experimental methods.

The other analytical category is traffic assignment formulation. Karabuk and Manzour (2019) classified land-based evacuation models into an optimal system formulation and a user equilibrium formulation. Their definition is considered for ship-based models—the former attempts to offer an evacuation plan to improve the main objective (macroscopic perspective). In contrast, a user equilibrium formulation generates an evacuation plan based on the characteristics of each passenger and addresses the problem at a more granular level (microscopic perspective). For example, an evacuation model can minimize the overall evacuation time with and without considering passengers' physical condition. The former can be in the first category; however, the latter focuses on every passenger's mobility. Moreover, 64.3% of researchers address their problem from a user equilibrium perspective. It shows there is increasing attention to understanding passenger behavior in this area.

Model parameters are the third analytical category. Parameters are concerned with the model's configuration. For example, the model's settings can vary according to the ship's motion mode. Fig. 9 demonstrates how many times two parameters are assessed together in the collected papers. Thirteen factors interacted more with each other

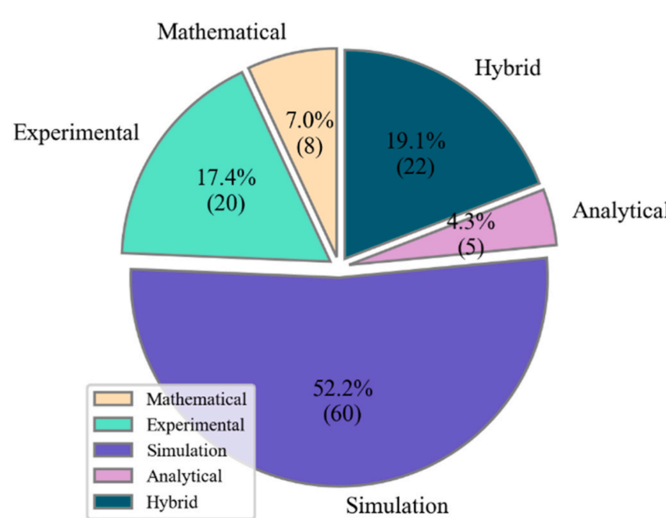

Fig. 8. Distribution of publications according to the modeling approach.

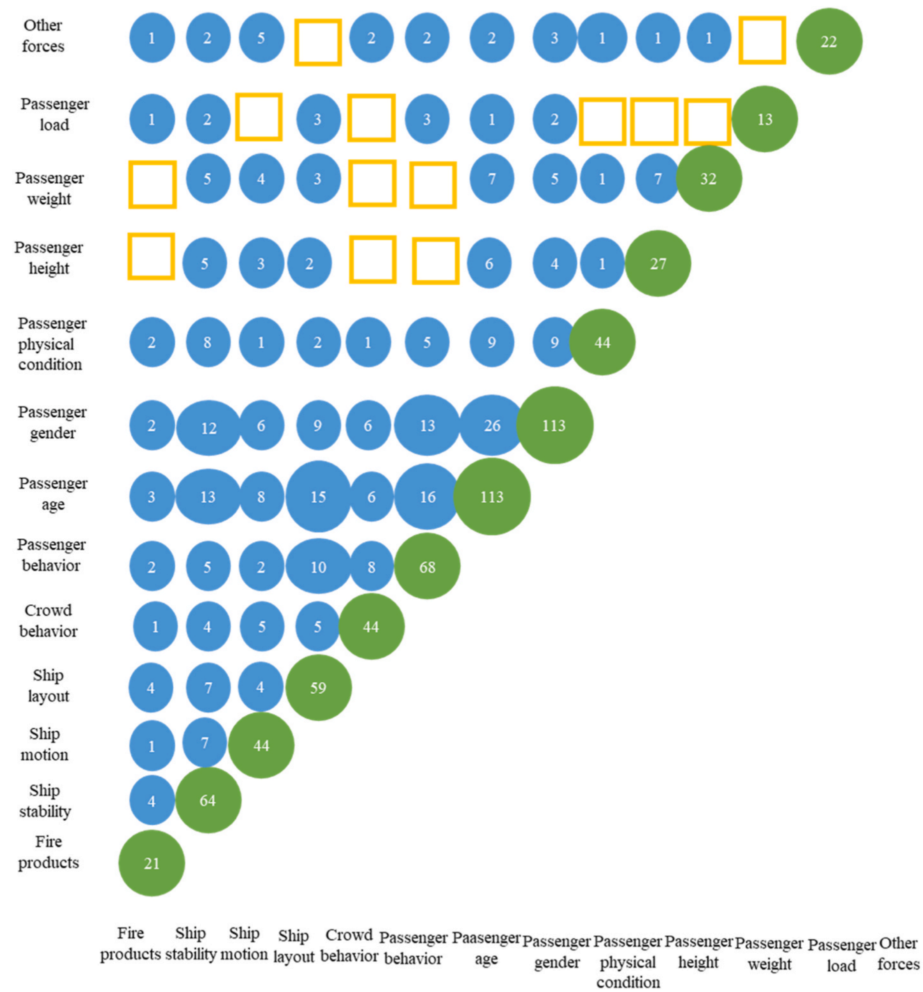

Fig. 9. Cross-frequency analysis of evacuation parameters among the collected papers.

among other evacuation factors. The blue circles indicate how many times two parameters are viewed in modeling simultaneously, while the green ones indicate a parameter is solely applied. For example, ship stability is repeated ten times with passenger age. Conversely, yellow squares ascertain the gaps for future research.

The next category is the hazard type. Hazard refers to a potential source of damage to a passenger ship or people onboard. However, when the hazard happens, it can become a disaster (Shi, 2019). The most significant proportion of papers disregards considering the kind of hazard that threatens passengers' lives. In contrast, 21 publications consider fire as a hazard. Six research papers examine flooding and storm, with three for each. Although foundered (sunk and submerged) accidents with 54.4% of the total losses in the world ocean are the most frequent hazards that ships encountered from 2010 to 2020 (Allianz, 2021), only six papers addressed it in the literature. Three papers also take two hazards into account simultaneously. Also, Allianz reported wrecked (grounded): 19.6%, fire and explosion: 11.3%, machinery failure and damage: 5.8%, collision (involving vessels): 3.4%, hull damage (holed, cracks): 3%, and other causes (piracy and miscellaneous): 2.5% are other hazards. They can be other directions for future research to consider in formulating and analyzing human evacuation models.

Finally, the solution method category is analyzed. Applied solution methods are categorized based on the paper's objective. 31.3% of researchers used an evacuation tool to simulate the process. Some are based on discrete models allowing agents to occupy a discrete set of points in terms of space representation (such as MaritimeEXODUS and IMEX). In contrast, others are continuous models considering a constant sequence without interruption between different points in a defined space (such as VELOS and Pathfinder). Moreover, hybrid tools benefit from both models' properties (e.g., EVI and EvacSim). Appendix I lists available evacuation simulation tools in the literature.

The collected papers are thus evaluated and analyzed according to the features described in Table 4. The details of the analytical dimensions of the review study are thoroughly discussed in the following sections.

3.4. Material evaluation

The sample papers are cross-checked with another database, including Scopus whereby the authors verify the paper's properties, such as the research area. The aim is to improve the validity of the analysis. The author checking technique is consequently applied to control the credibility of the sample papers. After reading the abstract, they would be kept if they are consistent with the study objectives. Finally, the collection with 115 publications is established for further analysis.

4. Detailed analyses of the literature

This section gives the results of the analysis. The collection is studied according to analytical categories to determine the status in this research area. The gaps are identified, and the future research agenda is accordingly established. Although there can be an overlap in classification, this paper tries to categorize them according to the objective of each paper appropriately.

4.1. Problem classifications

There are various subjects in this area of study. Although the authors pursued particular aims, the papers can be classified into the following categories. Appendix J classifies papers according to their objectives.

4.1.1. Traffic assignment category

This subsection tries to classify the collected papers based on the traffic assignment analytical category. Papers with the aim of optimizing the overall performance of the egress system are placed in the evacuation time and route optimization subcategory. In comparison, the passenger behavior modeling subcategory pays attention to papers with user equilibrium formulation features.

4.1.1.1. Evacuation time and route optimization. Evacuation time optimization gains a significant portion of research objectives in the collected papers. All research subjects with the same subject matter are included in this classification (response time, assembly time, and embarkation time). The aim is to minimize the evacuation time considering evacuation factors. Furthermore, the route optimization module intends to provide safe evacuation routes in which the characteristics of passengers/crew distribution and the ship's layout are considered. The authors aim to determine the emergency evacuation routes available for evacuees or analyze the operational level considering congestion and counter-flow movements.

This kind of research has several advantages. For instance, total evacuation time calculation can be employed for updating the whole evacuation time in a real-time emergency response. Specifically, it can assist crew and passengers in handling the remaining time based on the available evacuation routes (Lin and Wu, 2018). Conversely, it has some shortcomings. For example, it lacks to consider passengers as conscious agents in a real-life case. Explicitly, how different aspects of passengers, such as the level of compliance, can affect the total evacuation time. Critically, this paper attempts to categorize them to represent a clear view of estimating the whole evacuation time in the presence of evacuation factors. This category consists of 48.7% of studies.

4.1.1.2. Passenger behavior understanding. 31.3% of publications attempted to focus mainly on understanding passenger behavior. It is critical during evacuation as it minimizes total evacuation time and casualties in emergency maritime situations (Finiti, 2021). Many authors attempted to advance understanding of passenger behavior by finding the most significant drivers, such as ship stability (mostly considered trim and heel angle) and disaster development (most researchers considered fire), in their reaction to the emergency. Some carried out a series of evacuation trials at sea to calculate passenger gait speed under predefined emergency scenarios. In contrast, some conducted questionnaires to explore new insights with an interactive study with passengers (Deere et al., 2012; Wang et al., 2020c; Yip et al., 2015).

The main advantage of considering passenger behavior is to design an effective emergency evacuation system to ensure safety standards (Wang et al., 2020c). Likewise, passenger behavioral responses to an emergency can enhance understanding of control efforts and crowd behavior (Li et al., 2019). While understanding the various source of uncertainty in passenger behavior calls for more investigations and quantifications in this research area. Specifically, how internal and external drivers, such as stress level and ship motions, can impact the behavior. Hence, the relevant samples are categorized to reveal the importance of evacuation factors in behaving passengers during an evacuation process.

4.1.2. Solution methods

The solution method category is the next analysis classification. It consists of three subcategories: (1) description of evacuation models, (2) data collection and validation, and (3) optimization solvers.

4.1.2.1. Description of evacuation models. Another category represents the description of evacuation models (11% of studies). Parts of the collected papers described maritime evacuation models to understand the evacuation process better. Some analyzed the current evacuation models considering simplified and advanced approaches, while others tried to evaluate evacuation simulation tools (Miyazaki et al., 2004; Sun et al., 2018a). The offered category can deliver a clear view for selecting a simulation-based evacuation tool according to the models' configuration. K V Kostas et al. (2014a) reflected the applicability of VELOS for assessing passenger and crew activities in normal and hectic conditions of evacuation operations. Also, Guarin et al. (2014) described the concept of escape and evacuation from passenger ships using the pedestrian dynamics simulation tool EVI.

Although the available simulation-based evacuation models can provide solutions, there is a need to design a real-time decision support system to track the evacuation process. It is suggested that the system can be based on a data-driven multistage optimization framework. Various real-time operation data is obtained from different agents involved in the evacuation process. They can be modeled with machine learning (ML) techniques under the uncertain development of a disaster (Roy et al., 2021).

4.1.2.2. Data collection and validation. Researchers tried to collect data through either paper-based methods, including surveys or questionnaires, interviews, or computer-based techniques such as video cameras (7% of the collected papers). Regarding questionnaire surveys, some researchers tried to analyze different points of the passengers' views during the evacuation process. They determined the impact of various factors on the evacuation process and passenger behavior. For example, Liu and Luo (2012) and Lozowicka (2021) analyzed the influence of demographic differences, including age, gender, educational level, mobility level, experience onboard, and traveling companion, on passengers' behavior and safety awareness and perception during an emergency evacuation Ro-Ro passenger ship.

Moreover, Finiti (2021) applied two different methodologies (case study and interview) as complementary tools. They attempted to understand likely passenger behavior by analyzing the collected data from some survivors of the Costa Concordia disaster in terms of gender, age, companions, and experience. Furthermore, data related to passenger behavior under different circumstances, such as ship stability angles, play an essential role in understanding the evacuation process. Actual onboard experiments can further shift our understanding of the evacuation process. A notable example is five full-scale semi-unannounced assembly trials performed at sea under the EU Seventh Framework Programme project SAFEGUARD (IMO Fire Protection Sub-Committee, 2012). The aim was to generate passenger response time data, validation, and calibration data sets for ship-based evacuation models and establish a set of fire and trim/heel scenarios. Studies with the same subject matter fall in this category. Video-based observation is another popular method for gathering data in evacuation studies (Galea et al., 2014a; Na et al., 2019; Wang et al., 2021a).

This category can deal with relations between different data collection methods and evacuation factor data. It can help researchers find a suitable database based on their problem requirements. For instance, Deere et al. (2012) is a source of human factors data for the passenger assembly process on large passenger ships. They utilized hybrid methods, including video cameras and infrared beacons. Still, there is room for measuring biological and psychological passengers' cognitive states, such as stress levels, and how they affect the evacuation process. Moreover, sociological-based data, such as cultural diversity, can give ship managers more insight into passenger behavior (Galea et al., 2015; Zhang et al., 2017). Therefore, they are another challenge in collecting and analyzing data in this research area.

4.1.2.3. Optimization solvers. In the simplified version of evacuation analysis, the overall performance of the evacuation system is critical, whereas, in the advanced version, the egress of each human while various factors, such as hazards and ship motions, affect the behavior is the primary objective. In doing so, two types of methodologies are provided.

On the one hand, researchers use various approaches to solve the formulated evacuation problems for passenger ships. The authors have split the applied methodologies into three main categories according to the paper's objective. Firstly, many authors use simulation and mathematical tools such as MaritimeEXODUS, VELOS, CPLEX, and MATLAB to reach a solution. Secondly, some employed optimization models to harness uncertainty of the different elements of the evacuation process, such as human evacuation behavior. They include Polynomial chaos-(PC) and Monte Carlo-based (MC). For instance, Xie et al. (2020a) applied PC expansion with Gauss quadrature to quantify the uncertainty of evacuation time for passenger ships. Furthermore, Wang et al. (2013) employed an MC-based sampling method to analyze available safety egress time under ship fire (SFAT). Thirdly, researchers applied meta-heuristic algorithms for solving real-life evacuation problems (Lozowicka, 2021). For example, Łozowicka (2010, 2005) utilized the Genetic Algorithm (GA) to find the shortest evacuation time and route. Although GA can propose a feasible structure fitted to problem parameters, there is a possibility of falling to the local optimum for this algorithm. Also, the degree of complexity is raised by considering more evacuation factors. Therefore, it is suggested to employ hybrid techniques to escape it. For example, Kaveh and Ghobadi (2020) presented a hybrid evacuation model using the graph theory and metaheuristic algorithms to find the best evacuation route under a fire situation considering human factors.

On the other hand, passengers and crew are characterized as unique individuals with distinctive personality traits and cognitive abilities. Fifty publications applied microscopic models, including social force-based, velocity-based, acceleration-based, and CA, to work out the dynamic behavior of passengers. The most considerable contribution was seen for velocity-based models with 52%—cell-based and social force-based models comprised 26% and 14%, respectively. The minor portion stands for accelerated-based models with 8%. However, there can be a potential extension to study the influence of evacuation factors, particularly dynamic conditions of the ship, on passenger behavior within microscopic-based models (IMO, 2016). In land-based evacuation path planning, Yang et al. (2022) integrated three forces, i.e., pedestrians' self-driving force, the pedestrian's interaction force, and the interaction force between pedestrians and obstacles, in the format of a social force model. Furthermore, Fang et al. (2022a, 2022b) improved social-force models to simulate the influence of inclination on passenger walking speed. These methodologies are documented in Appendix H.

4.2. Modeling approaches

Researchers apply various modeling approaches in this research area to formulate the behavior of the problem. The collected papers can be divided into five categories according to the modeling approaches. This paper specifies which methods are more widely employed and offer more significant research advancement opportunities among these categories.

4.2.1. Simulation-based approaches

One of the popular techniques in human evacuation modeling is simulation. The reason can be financial, ethical, and safety issues posed by full-scale evacuation trials for passenger ships (Deere et al., 2012; Galea et al., 2014b). Full-scale human evacuation experiments are time-consuming (Xie et al., 2020b). Therefore, researchers attempt to understand the dynamics of passenger behavior during human evacuation through simulation techniques. Balakhontceva et al. (2015), Chen and Lo (2019), and Kim et al. (2019, 2020) addressed passenger behavior under particular environmental factors such as ship motions, heeling, trimming, and listing the ship. Moreover, Azzi et al. (2011) and Salem (2016) described passenger behavior under ship fires. They tried to understand how fire outbreaks onboard can affect the life safety of passengers and crew. They simulate the development of fire and the spread of combustion products under different fire scenarios. Furthermore, Balakhontceva et al. (2016), Ruponen et al. (2015), and Spanos and Papanikolaou (2014) simulated evacuation processes under storms and flooding. They draw an emergency response to abandon the ship. Łozowicka (2010) and Ni et al. (2018) reflect evacuees' movements and behavior in the presence of the contraflow and obstacles. Also, Brumley and Koss (2000) and Zhang et al. (2017) observed different patterns of passenger behavior according to their characteristics, such as age, gender, height, and weight, during the evacuation process.

Simulation approaches are commonly applied to modeling evacuation problems at a microscopic level. For instance, CA simulation techniques are employed to capture passenger behavior during movement (Hu and Cai, 2017; Wang et al., 2020c). However, tracking passenger behavior in the presence of other evacuation factors, such as disaster development, can generate more scenarios and accordingly produce a more complicated problem. The generated problem cannot be easily tackled with only a simulation-based approach. Therefore, it is recommended to integrate this technique with other techniques. For example, Xie et al. (2020c) recently constructed a surrogate model of passenger assembly time with response time parameters to improve the simulation time of a large-scale crowd for passenger ship fire evacuation.

4.2.2. Experimental-based approaches

Another approach to analyzing ship evacuation is based on an experiment. Researchers conduct experiments either in a simulator or onboard. They collect data regarding passenger walking speed under moving characteristics of the ship, such as heeling and trim. In this stream, Bles et al. (2001), Sun et al. (2018a), and Zhang et al. (2017) designed their experiments in a ship corridor simulator or ship operating simulator. Katuhara et al. (2003) and Liou and Chu (2016) conducted a series of onboard walking experiments to gather data in various sea conditions on training ships. Furthermore, several evacuation trials were conducted on passenger ships to validate marine-based computer models (Gwynne et al., 2003; Murayama et al., 2000; Walter et al., 2017).

The advantage is that researchers can have greater control of the basic experimental setup. For example, Wang et al. (2021b) considered the test area of the experiment to be larger than the calculation area to improve the accuracy of the experimental consequences. Also, Wang et al. (2021a) calculated the walking speed of about 90 cadets in diverse sea areas and conditions on different days due to the ship's uncontrollable motion states. Nevertheless, there is a deficiency in carrying out onboard experiments by taking evacuation factors, such as disaster development (e.g., fire), ship motions (e.g., pitching), and crossing flows, into account simultaneously. Moreover, the authors found that research participants are well-trained people in onboard experiments. They understand how to act in abnormal and emergency occurrences; the results may lead to overfitting issues. Therefore, new technologies, such as VR, can raise the possibility of involving untrained passengers considering evacuation factors. VR technology is discussed later in Section 5.7.2.

4.2.3. Mathematical-based approaches

Another category of modeling is mathematical. Modelers utilize quantitative techniques to describe the relations between parameters or variables. Chu et al. (2013), Lozowicka (2021), and Xie et al. (2020c) represented the behavior of the evacuation problem using mathematical properties and arguments, such as Legendre polynomials and Leung–Ng algorithms. They dealt with evacuation times and routes. Mathematical approaches, such as the minimum cost model and the quickest path/-flow, are generally employed to find an optimal lower bound for evacuation time, considering the distance to the destination and queue length (Hamacher and Tjandra, 2002). They disregard passenger behavior during the emergency. Therefore, it is suggested to integrate the mathematical model into a simulation model, such as the social force model. This integration propagates the movement law and path selection behavior of pedestrians.

4.2.4. Conceptual- and analytical-based approaches

These studies analyze practical factors to find a framework for different aspects of human evacuation studies. For example, Guarin et al. (2014) presented the concept of escape and evacuation from the point of ship design and risk management. Nevalainen et al. (2015) broke an evacuation problem into the elements and tried to work out human evacuation from the passengers' perspective. They investigated four accident reports to map environmental factors influencing passenger behavior during ship evacuation.

This type of research can give a clear view of the interaction between passengers and evacuation factors. Specifically, it can unlock passengers' perception and interpretation of the evacuation process and ship-based disasters. For instance, Finiti (2021) tried to find indications of passengers' behavior from the survivors of the Costa Concordia disaster using the Talk-Through method. Nevertheless, it is typically a challenging task to have survivors view a real-life disaster or talk with every passenger. Instead, it is recommended to analyze the passenger behavior under emergency with crew and safety engineers onboard.

4.2.5. Hybrid approaches

Some researchers combined two modeling methodologies, which are indicated as hybrid approaches. They can reinforce the precision of evacuation models and simultaneously control different aspects of the evacuation process. For instance, Chen et al. (2016), Jasionowski et al. (2011), Qiao et al. (2014), Dracos Vassalos et al. (2002), and Xie et al. (2020a) integrated simulation and mathematical modeling approaches to track the evacuation process in light of at least two evacuation factors (e.g., fire and passenger properties). They attempted to reduce the complexity of the evacuation model for a large-scale passenger ship. Meanwhile, Kang et al. (2010), Miyazaki et al. (2004), Murayama et al. (2000), and Sarvari et al. (2019) simultaneously employed simulation and experimental approaches. In addition, Brown et al. (2008) and Casareale et al. (2017) applied questionnaire approaches with simulation and experimental techniques to improve modeling efficiency.

Nevertheless, the majority of the proposed hybrid models lack generalization features. For instance, Sarvari et al. (2019) presented a user equilibrium formulation-based model for a Ro-Ro ferry boat sinking regarding evacuation time, death toll minimization, and evacuation plans. However, how effective the proposed model is while being fed with real-time data obtained from a passenger ship under the same emergency can improve the model's validity. Consequently, the potential extension includes the development of a robust hybrid modeling approach that can be operated across a variety of ship-based evacuation models is suggested.

4.3. Case study

37.4% of the collected papers evaluated the performance of the proposed methodology within a case study. Remarkably, researchers analyzed various subjects, including understanding passenger behavior, emergency evacuation route, travel time, the influence of obstacles in cabins, social impact on evacuation behavior, passengers' walking speed and safety awareness, the concept of dynamic affordances, and the application of wireless sensor networks in the ship evacuation process. They attempted to provide managerial insights regarding passenger behavior or ship interior design to ship designers. However, researchers considered specific passenger ships, demographic, and transverse/longitudinal stability angles. Therefore, testing the proposed evacuation models by other real-life cases is suggested to increase the generalizability of results to different settings. The case studies are listed in Appendix K.

4.4. Model parameters

Parameters are quantities driving the evacuation process. Understanding these parameters can hence facilitate modeling of the evacuation process more reliably. Parameters are represented through four evacuation factors. Most publications (38.7%) considered human factors in their modeling, while 29% of authors tried to reflect the impact of environmental factors on the evacuation process. The other significant factors were configurational (20%) and behavioral, 12.3%. Hindrances and obstacles are highlighted in calculating passengers' travel speed on flat terrain and stair up/down in the advanced version of guidelines for passenger ships. Therefore, such considerations about behavioral factors are necessary and a gap in the literature. Appendix F can indicate a clear view of engaging the evacuation factors in the literature.

5. Discussion and future opportunities

This section outlines the deficiencies of the current studies and accordingly provides future research directions on human evacuation studies. Based on the classifications presented in Section 4, the authors categorize the findings into five sub-sections.

5.1. Handling uncertainty

Future research based on the identified gaps in uncertainty issues can be conducted in three category levels: (1) parametric, (2) modeling methods, and (3) solution methods. In the remainder of the paper, the term uncertainty is utilized, but it must be defined first. Wallace (2003) defined uncertainty as a lack of predictability for outcomes. It is due to the gap between the needed and available information for fulfilling a task. Emblemsvåg and Endre Kjølstad (2002) also specified that uncertainty is intertwined with the complexity of factors influencing a system.

5.1.1. Modeling uncertainties on parametric level

Availability of perfect or imperfect/partial information drives the decision-making process into certain or uncertain situations, respectively. Uncertainty is presented as randomness, hazard, and deep uncertainty. Firstly, the randomness stems from the random nature of low-impact events. To presume that input data varies randomly, the existence of sufficient and reliable historical observations for estimating the probability distribution and validity of the data are requisites (Marchau et al., 2019). Secondly, low-probability peculiar events with high impact characterize hazard. Thirdly, the deep uncertainty comes from insufficient information to estimate the objective or subjective probability of plausible future events (Marchau et al., 2019). Besides, Obaidurrahman et al. (2021) classified uncertainty into fuzziness and epistemic uncertainty. The former is related to flexibility in constraints and goals. The latter concerns a lack of knowledge of the input data and is often presented as linguistic attributes.

Passenger behavior, ship motion, and disaster development can be possible sources of uncertainty in a ship evacuation process. They can be classified according to the uncertainty type. Under the second research question, this paper discusses the uncertain influence of evacuation factors on human behavior. Passenger behavior is the main element in managing an evacuation process (Wang and Wu, 2020a). One's behavior is simultaneously influenced by environmental factors, such as disaster products, and physiological, psychological-, and sociological-based factors, for instance, physical condition and cultural differences

(Nevalainen et al., 2015). Finding the correct type of uncertainty considering passengers' behavior can approach ship managers to have a more reliable evacuation plan. Disaster development is another source of uncertainty that affects the evacuation process, particularly passenger behavior. Disaster develops over time, and exposure to a threat makes the cognitive function of decision-making more challenging, and one's choices become limited. Depending on the disaster type, the uncertainty assessment process can vary. For example, a fire progresses and may need a different realization than flooding. Ship motions are another uncertain driver affecting evacuees. They are movements that a ship can witness in different directions by forces, such as waves and storms. Each move can affect passengers' behavior in other ways (Wang et al., 2021a).

There is room for further progress in uncertainty assessment for human evacuation studies at a parametric level. Moreover, taking these uncertainties into modeling paves the way to represent reality, minimize risk, bring remarkable competitive merit for ship designers, and enhance usability (Van Reedt Dortland et al., 2014).

5.1.2. *Uncertainty modeling methods*

After identifying the uncertainties, the next step is to model them. As the problem variables mentioned above constantly change and it is questioning to find their clear values, uncertainty modeling can harness their fluctuations. Uncertainty modeling approaches can deal with this type of problem. They include robust optimization, stochastic programming, Bayesian-based network (BN), MC-based simulation, ML-based, and hybrid techniques. This section presents more explanations regarding these approaches and how they can handle an evacuation problem.

5.1.2.1. Robust optimization. Robust optimization (RO) is a methodology for handling optimization problems under uncertainty. RO calls data from an uncertainty set instead of running a specific probability distribution. As objective function and constraints are assumed to belong to a given uncertainty set, the decision-maker establishes a feasible solution for any realization of the uncertainty (Bertsimas and Sim, 2003). RO-based methodologies have a significant drawback. The proposed solution can be highly conservative as this methodology aims to harness all possible worst-case realizations of the uncertainty (Bertsimas et al., 2012). Another challenge is that while mathematically finding an optimum is relatively straightforward once all the parameters are defined, proving that this optimum is a global optimum for real-life satiation is an entirely different and far more challenging aspect. However, this is where the robustness comes into play and lessens this challenge, albeit not eliminating it completely.

In contrast, they offer two main merits that can be appropriate for evacuation problems. First, the robust counterpart, a deterministic equivalent of the original model, is still computationally tractable regardless of the number of uncertain parameters. Second, experts' opinions can be involved in constructing uncertainty sets (Bertsimas et al., 2012). Ship motions and disaster development intertwine and affect passenger behavior. They can be established in an uncertainty set. At the same time, maritime experts and ship designers can provide their views to specify the boundaries of uncertainty set. Although researchers apply this technique in a land-based situation (Rabbani et al., 2018), investigating the influence of RO-based approaches on human evacuation models is recommended in ship evacuation.

5.1.2.2. Stochastic programming. Another approach is stochastic programming. This modeling paradigm can provide decision-makers with the expected objective value subject to various constraints over uncertainty realizations in a sequential decision-making process (Birge and Louveaux, 2011). Although this tool fulfills the objective functions, it needs an accurate estimation of the probability distribution of the random variables (Bertsimas et al., 2012). Insufficient verified data in this area of research can hinder estimating an accurate probabilistic description of the random variables.

The ship evacuation process can also be formulated as a multi-stage stochastic programming model. For example, based on a two-stage stochastic programming model, the first-stage decisions can be related to the availability of evacuation routes at the beginning of the disaster event. Passengers' behavior is realized after knowing which routes are available under disaster developments or ship motions scenarios. Each scenario can correspond to how a hazard or ship motion can affect the ship's availability or passenger behavior. Afterward, recourse decisions are made to determine which evacuation routes are still available and what corresponding travel time is. Therefore, further studies focusing on stochastic-based approaches are suggested to assess the simultaneous influence of disaster development and ship motion on the ship evacuation process.

5.1.2.3. BN-based approaches. BN is a robust potential method to address decision-making in uncertain situations where variables are highly interlinked (Marcot and Penman, 2019). However, this approach increases the computational cost when variables rise. Another drawback of this methodology is that translating variables' dependencies into the mathematical formulation can be tricky and produce misleading results (Robert, 2007). A BN can formulate an evacuation guidance model with conditional dependencies among input parameters. For instance, when different ship motions meet other hazards, an evacuation plan can be distinct based on how the combination will affect human evacuation behavior. Specifically, the roll motion of a ship in the presence of a fire accident can result in different passengers' walking speeds compared to pitch motion combined with flooding. Accordingly, passengers demand different evacuation routes depending on how fast they move. Therefore, a BN technique can model the dependency among influencing drivers on human evacuation behavior.

Moreover, there is a feature within BN techniques that facilitates representing maritime specialists' knowledge in modeling. This feature can cover the lack of sufficient verified data in this area of research. Although Sarshar et al. (2013a, 2014) applied BN-based methods through evacuation modeling under uncertainty, additional studies will be needed to develop a complete picture of this technique.

5.1.2.4. MC-based simulation approaches. MC simulation technique has been commonly used to explore uncertainty analysis of the random inputs in ship-based evacuation models. It is a reliable and cost-effective technique (Wang et al., 2013). Nevertheless, MC-based methods require many scenarios due to the slow convergent rate. The more scenario you design, the higher complexity the problems face (Matala, 2008). To overcome the first issue, researchers tried to fuse evacuation models with Latin hypercube sampling in the ship-based evacuation problems. Xie et al. (2020a) proposed PC expansion based on the corresponding distribution of random variables to reduce the number of evaluation samples.

Surrogate-based models, such as the Gaussian process, can also be integrated into MC techniques and reduce the run time. Furthermore, variance reduction techniques can improve the computational efficiency of MC simulations (Turner and Davis, 2013). Another main drawback of MC-based techniques is the necessity of knowing an accurate probability distribution of the random variables. One of the main requirements to estimate an exact distribution is access to a large amount of historical data, which, undoubtedly, many projects face data scarcity. In this regard, examining methods, such as the bootstrapping technique, can lessen the amount of data. Another solution to escape data scarcity is applying the fuzzy analysis method. Fuzzy numbers are employed to track the effect of uncertainty. Kong et al. (2014) presented a framework of fuzzy assessment for a building under fire. They determined fire development rate and pre-evacuation time using fuzzy numbers to describe the uncertainty associated with fire development. Future works could study the influence of these extensions on MC-based approaches.

5.1.2.5. ML-based approaches. ML-based techniques can also model uncertainty in decision-making processes. Bayesian deep learning, ensemble learning, and neural network-based techniques are three widely-used types of uncertainty quantification methods that can significantly increase the reliability of results (Abdar et al., 2021). In a land-based evacuation, Zhao et al. (2020) leveraged the random forest technique to estimate people's emergency behavior based on social and environmental factors during the pre-evacuation stage. Also, Katzilieris et al. (2022) developed logistic regression models and ML-based techniques to analyze the evacuees' response behavior in communities under the emergence of wildfires. Moreover, researchers tried to apply deep learning-based techniques to deal with evacuation problems. Zhang et al. (2021) proposed a deep reinforcement learning algorithm with a social force model to train agents to find the fastest evacuation route in an evacuation of a room with obstacles. Future research can consider the potential effects of ML-based algorithms more carefully.

5.1.2.6. Hybrid approaches. Some researchers consider simultaneously macroscopic and microscopic models in describing evacuation problems to formulate an emergency evacuation problem closer to a real-life situation. They apply hybrid approaches. Hassanpour et al. (2022) modeled human evacuation behavior and the building's interior design using a hierarchical hybrid agent-based framework combining CA and graph-based models in a land-based problem. Zhang and Jia (2021) proposed a hybrid multiscale approach to work out the movement of followers, the guidance behavior of leaders, and the follower-leader interaction. IMO (2016) pays attention to environmental aspects of the evacuation plan together with geometrical, population, and procedural elements. Future research can be devoted to developing hybrid approaches to bring these aspects into play. A hybrid robust-stochastic programming approach can be a potential solution. Disaster development can be described through various stochastic scenarios, and uncertainty sets can be established for defining different ship motions.

5.1.3. Uncertainty solution approaches

Researchers deployed different solution methods to tackle a modeled evacuation problem under uncertainty. Many benefits from simulation tools. While a few scholars have used general solvers such as CPLEX and MATLAB to test evacuation problems. Furthermore, some employed metaheuristic algorithms, such as GA to improve the performance and quality of solutions. However, the above-mentioned methods focus mainly on human behavior under fire situations. Future research can focus on applying simulation technology, such as DT, or metaheuristic algorithms, such as a tabu search, to model sources of uncertainty affecting passenger and crew behavior, evacuation time, and escape routes. New guidelines for an advanced evacuation analysis document that a congestion region is not precisely known in advance. Applying uncertainty analysis techniques, such as the Benders decomposition algorithm and ML-based techniques, can close us to more quality solutions beforehand in a reasonable time based on various scenarios affecting the congestion points density (Romanski and Van Hentenryck, 2016).

5.2. Multi-objective optimization modeling

Future studies can also consider multi-objective optimization modeling direction in this research area. Multi-objective models can provide solutions for different objectives in one single run. Also, they can reduce the number of assumptions about the problem and near modeling to a real-life situation (Pilát, 2010). For instance, minimizing evacuation time, maximizing crew assistance, and passengers' satisfaction levels subject to the ship layout configuration can be formulated as a multi-objective evacuation model. Meanwhile, multi-criteria decision-making techniques, such as the Analytic Hierarchy Process (AHP) or the analytic network process, can be applied to analyze the weights of the multiple factors affecting objectives. Afterward, weights are employed in formulating a multi-objective evacuation model. Ping et al. (2018) proposed a quantitative analysis model in an offshore incident by integrating BN and fuzzy AHP to calculate the probability of successful escape, evacuation, and rescue in light of experts' opinions.

5.3. Human evacuation behavior understanding

Human behavior is a central ingredient for analyzing and designing an egress system. Modeling human behavior and two psychological properties regarding human behavior named passenger compliance behavior and risk perception are considered the potential research directions. In doing so, they are analyzed in this subsection, and suggestions for a better understanding of these topics are provided.

5.3.1. Modeling human evacuation behavior

Passenger behavior is a complex phenomenon affected by various environmental, human, and behavioral factors. Taking these elements into modeling subject to different constraints such as configurational factors has been a challenging research question in this area. Researchers primarily attempt to harness passenger behavior with the help of social force-, velocity-, acceleration-based, and CA models. The social-force models are based on complex rules; they do not provide satisfactory calculation efficiency (Ni et al., 2018). CA-based models are discrete in space, time, and state variables; they do not track the dynamic behavior of passengers varying instantly (Ha et al., 2012). Velocity- and acceleration-based models cannot take the behavior pressure from the crowd into consideration (Cho et al., 2016). Surrogate-based models can be, therefore, a solution for covering challenges. They can estimate outputs of simulations across the whole design space, substituting the original (more expensive and time-consuming) model and improving the computational efficiency (Dias et al., 2019). Xie et al. (2020c) developed a surrogate-based model of passenger assembly time using the Legendre PC expansion. They predicted the optimal time for the issuance of evacuation orders. Future studies can pay more attention to this technique for approximating the projections of the original model.

In addition, researchers can employ ML-based algorithms to predict human evacuation behavior. Ning and You (2019) elucidated the integration of a data-driven with a mathematical-based optimization model. An ML model interacts with a mathematical model. Concretely, information is circulated between the two models in an iterative process, improving the output's performance and reliability. These two models can be integrated using the loss function in the ML model and the objective function in the mathematical model. On the ML side, evacuation factors can be represented as features per passenger, while the mathematical side can minimize the total evacuation time.

5.3.2. Passenger compliance behavior

Understanding the compliance psychology of passengers can be a critical part of more effectively tracking the evacuation process. Also, it aligns with the advanced evacuation analysis guidelines that consider passengers as sentiment agents. Compliance behavior is the coincidence of human behavior with what they should do based on rules, instructions, and others' advice (Chu et al., 2017). Human factors (e.g., cultural differences), and environmental factors (e.g., crowd behavior), can influence the compliancy level (Hamad et al., 2003). Furthermore, Karabuk and Manzour (2019) categorized compliance behavior in a land-based evacuation situation into three classes: (1) hard, (2) soft, and (3) non-compliance behavior. Ditlev Jorgensen and May (2002) empirically studied the attitudes and behavior of passengers regarding non-compliance with instructions and how it can affect assembly time in case of an emergency on ferries. In a land-based evacuation, Chu et al. (2017) proposed a bi-level optimization methodology for modeling the compliance behavior of evacuees under environmental factors.

Therefore, understanding this human attribute according to evacuees' compliance class can be another future direction in this research area.

5.3.3. Passenger risk perception

During the response period, the critical point is the decision of passengers whether to move after they have noticed initial cues. This decision mainly depends on passengers' risk perception (RP) (Kinateder et al., 2015). RP originates from ambiguity in the evacuation process and passengers' subjective judgments about the probability of negative occurrences such as death. Taking RP into account aids in understanding the human cognitive process and may minimize the total evacuation time (Kinateder et al., 2015). In land-based fire evacuation, researchers attempted to theoretically frame the RP and discover its role during the evacuation process (Kinateder et al., 2014), while there is still a significant gap in the ship-based evacuation process to modulate RP. This lack can be owing to the absence of insufficient actual evacuation at sea.

Viking Sky cruise ship is a successful rescue operation in Norway. She faced an engine failure, which led the system to shut down the engines. She next started listing in the stormy weather. Meanwhile, 1373 passengers and crew passengers perceived uncertainty about what was going on and judged subjectively about the likelihood of unfavorable events, such as incidents (Ibrion et al., 2021). This interpretation might foster the pilot to issue the evacuation order at the best possible time. Analysis of disasters such as the Viking Sky passenger ship can smooth the path to understanding the evacuation process at sea. There is no single study in this stream to analyze the impact of passengers' RP on the evacuation process. This topic can be, therefore, another research direction.

5.4. Mutual interrelations

A significant research opportunity is investigating the relationships among evacuation parameters and how their concurrent existence can affect the human evacuation process from passenger ships. Some opportunities are listed in Fig. 9 as cross-frequency analyses of two parameters.

However, additional opportunities can be when there are more than two parameters in analyzing the evacuation plan. Table 5 indicates the simultaneous influence of three parameters on the evacuation process. For example, three papers (Brown, 2016; Sarshar et al., 2013c, 2014) performed the evacuation analysis by considering the coexistence of three parameters during the evacuation process, including fire, ship layout, and physical condition. In contrast, there is no study to analyze the interplay of fire, counterflow movements, and passenger walking speed. These future directions are listed in Table 5. Furthermore, considering four elements or even more is also applicable; however, it could be more complicated (such as counter and crossing flows, passenger physical conditions, fire, and flooding).

As a result, this study reveals that such mutual interrelations are necessary and a gap in the literature.

Table 5
Mutual interrelation among evacuation factors.

	Fire		Passenger physical condition
(Ship layout, passenger physical condition)	3	(Ship motion, crowd behavior)	0
(Ship layout, crowd behavior)	0	(Ship motion, hazard)	0
(Passenger physical condition, other forces)	0	(Walking speed, counter and crossing flows)	0
(Ship motion, passenger physical condition)	0	(Walking speed, family group behavior)	0
(Passenger walking speed, counter and crossing flows)	0		

5.5. Digital transformation

This section tries to introduce two enabling technologies that may enhance safety and emergency response in human evacuation from passenger ships.

5.5.1. DT technology

DT is a virtual model for a physical object. It mirrors the behavior of a physical counterpart using a simulation/optimization model (Kaur et al., 2020). A bi-directional data flow is crucial in communicating between the object and the model. Data is collected from Internet of Things-based (IoT) devices such as sensors installed in the physical asset and transmitted to the model in real-time. Afterward, the model is run, tested, and validated on a DT. Then, faults are diagnosed, and possible improvements will accordingly be produced. Finally, the solutions are transmitted back to the physical object. Although the application of a DT is witnessed in other industries, such as the manufacturing industry (Tao et al., 2019), there is no passenger ship-based DT. This absence can be due to many reasons. Firstly, it can be owning to the lack of a cost-effectiveness evaluation for creating a DT of a passenger ship. Specifically, this technology targets academia and industry for teaching purposes and as a source of income. Academics and ship managers need to meet their financial requirements regarding this technology for applying it through their activities. Secondly, the absence of a data-driven simulation/optimization model can be another reason. Data-driven decision-making for the evacuation process demands exponentially many data points. At the same time, human evacuation behavior is a central ingredient for analyzing and designing an evacuation model. In this regard, the simulation/optimization model should be fed with data concerning human properties such as age, gender, and stress. Therefore, data privacy issues are the third sign restricting the creation of a DT in this area. Fourthly, even though a DT can be built by tackling the challenges mentioned above, how to generalize and transfer findings from a specific demographic on a passenger ship to others can cause additional concerns.

On the other hand, a DT can benefit the maritime industry, especially when maritime transport is approaching the era of autonomous shipping. It can highlight real-time collaboration between a ship and its digital counterpart. This connection can remove human errors and improve safety at sea by establishing a correct relationship among parties, such as passengers and crew, during evacuation.

5.5.2. VR technology

VR is a three-dimensional simulated environment where the agents can feel a spatial sense (Huang et al., 2022). The applicability of VR is presented in many fields, for instance, tourism (Beck et al., 2019). In this stream, Vukelic et al. (2021) evaluated the possibility of adopting new technologies to the human evacuation process, including VR. There is an opportunity to expand the VR application in passenger ship-based emergency circumstances. Precisely, it can be employed for data collection purposes, such as passenger walking speed. Not only conducting an actual full-scale onboard experiment is time-consuming and costly, but it also can be dangerous for passengers while sailing. In this regard, a set of onboard experiments can be designed in the presence of virtual reality devices like headsets. Headsets can be programmed based on the influence of a disaster on human behavior. Similarly, this technology can transport participants to an interactive digital world considering ship motions. Then, how participants react to a virtual hazard or ship motions can affect their evacuation behavior and speed. Therefore, further research can be undertaken to investigate the application of VR in a passenger ship-based data collection process, especially in a spatial environment while a ship berths.

6. Conclusion

This paper comprehensively summarizes recent and state-of-the-art publications on human evacuation. 115 studies in scientific journals, peer-reviewed conference papers, and doctoral and master dissertations are selected and reviewed between January 1999 and August 2022. Afterward, the authors analyzed the collected studies regarding evacuation factors, modeling approaches, and solution methods. Finally, future gaps and research opportunities are outlined in three aspects: uncertainty analysis of evacuation parameters, passenger characteristics, and digital transformation adaptation. Employing modeling approaches, including RO, stochastic optimization, BN, MC-based, AI-based, and hybrid approaches, are identified as future opportunities in formulating uncertainty. Accordingly, possible future directions are provided regarding algorithms for tackling the modeled evacuation problems under uncertainty. Other future suggestions include paying attention to multi-objective optimization problems and employing the corresponding approaches.

Further, mutual interrelations evacuation parameters propose future trends in the problem classifications. Also, surrogate-based models are recommended for estimating the underlying model to ease the complexity of evacuation problems. Moreover, opportunities associated with passengers' compliance psychology and risk perception are offered. Ultimately, the possibility of adapting the two latest enabling technologies named DT and VR is suggested for this research area. The authors attempt to conduct the current study as a comprehensive literature review as possible; however, there are still some shortcomings. For instance, the number of the collected publications is not large, and the results of the visual network analysis may not be comprehensive. Hence, scholars can also examine the released investigation report from different maritime accidents, such as the Costa Concordia disaster and the MV Viking Sky, and how the literature can study them from an advanced evacuation analysis perspective. Also, most non-English publications have an English summary section. Therefore, they can be represented in the review analysis.

CRediT authorship contribution statement

Hossein Arshad: Conceptualization, Investigation, Visualization, Methodology, Writing- original draft, review, and editing, Software. Jan Emblemsvåg: Conceptualization, Supervision, Resources, Writing-review and editing. Guoyuan Li: Supervision, Writing-review and editing. Runar Ostnes: Supervision, Writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

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Appendix A. Publishers

Table A.1
List of publishers.

Paper	Publisher
List of publishers with a minimum of two publications.	
(Azizpour et al., 2022; Balakhontceva et al., 2016; Fang et al., 2022a; Grandison et al., 2017; Ha et al., 2012; Lee et al., 2004, 2022; Liu et al., 2022; Park et al., 2004, 2015; Salem, 2016; Sun et al., 2018a, 2018b; Vanem and Ellis, 2010; Vanem and Skjong, 2006; Wang et al., 2020c, 2021a, 2021b, 2021c, 2022; Wu et al., 2018; Xie et al., 2020a, 2020b, 2020c; Yip et al., 2015; Yue et al. 2022)	Elsevier
(Balakhontceva et al., 2016; Boulougouris and Papanikolaou, 2002; Casareale et al., 2017; Chen et al., 2016; Fukuchi and Imamura, 2005; Galea et al., 2014a, 2011; Guarin et al., 2014; Gwynne et al., 2003; Hu et al., 2019; Jasionowski et al., 2011; Katuhara et al., 2003; K V Kostas et al., 2014; K V Kostas et al., 2014a; Kwee-Meier et al., 2017; Łozowicka, 2005; Luo, 2019; Meyer-König et al., 2002, 2007; Ng et al., 2021; Sarshar et al., 2014; Spanos and Papanikolaou, 2014; Sun et al., 2018b; Dracos Vassalos et al., 2002; Walter et al., 2017; Wang et al., 2013; Wang et al., 2020b)	Springer
(Chen and Lo, 2019; Ma et al., 2020; Qiao et al., 2014; Sarshar et al., 2013a, 2013b; Sun et al., 2019; Zhang et al., 2017)	IEEE
(Hu and Cai, 2020; Nevalainen et al., 2015; Sarvari et al., 2019)	Taylor & Francis
(Brumley and Koss, 2000; Ditlev Jorgensen and May 2002; Li et al., 2021; Rutgersson and Tsychkova, 1999)	Royal Institution of Naval Architects
(Hu et al., 2019; Hu and Cai, 2022; Kim et al., 2020; Liu et al., 2021; Lee et al., 2022a)	MDPI
(Cho et al., 2016; Chu et al., 2013; Liou and Chu, 2016)	National Taiwan Ocean University
(Galea et al., 2013; Wang and Wu, 2020a)	OnePetro
(Fang et al., 2022b; Montecchiari et al., 2018)	SAGE
(Ni et al., 2017b; Yuan et al., 2014)	Hindawi
List of publishers with one publication.	
Finiti (2021)	University of Huddersfield
Bellas et al. (2020)	Palmdale, CA: Tech Science Press
Brown (2016)	University of Greenwich
Vilen (2020)	Aalto University
Azzi et al. (2011)	Fire and Evacuation Modeling Technical Conference
Boulougouris and Papanikolaou (2002)	Proceedings of the 10th International Congress of the International Maritime Association of the Mediterranean
Brown et al. (2008)	International Conference on Ocean, Offshore, and Arctic Engineering
Kang et al. (2010)	Marine Technology Society
Łozowicka (2010)	Akademia Morska w Szczecinie
Miyazaki et al. (2004)	Maritime Research Institute, Japan

(continued on next page)

Table A.1 (*continued*)

Paper	Publisher
(A. López Piñeiro et al., 2005)	Spanish Society of Maritime Research
(D. Vassalos et al., 2002)	Safety at Sea and Marine Equipment exhibition (SASMEX)
Liu and Luo (2012)	Shanghai Maritime University
Lozowicka (2021)	the Public Library of Science
Na et al. (2019)	Medico Legal Update
Murayama et al. (2000)	Research Institute of Marine Engineering, Japan
Zhang et al. (2016)	ORES
Deere et al. (2006)	International Journal of Maritime Engineering
Galea et al. (2014b)	State Key Laboratory of Fire Science
Hu and Cai (2017)	Atlantis Press
Luo (2019)	NHH Norwegian School of Economics
Deere et al. (2012)	RINA SAFEGUARD Passenger Evacuation Seminar
Meyer-König et al. (2002)	Gerhard-Mercator-Universität
Ruponen et al. (2015)	University of Strathclyde
Ni et al. (2017a)	Gdansk University of Technology
Vukelic et al. (2021)	Scientific Journals Zeszyty Naukowe of the Maritime University of Szczecin
Ni et al. (2018)	IOPScience
Montecchiari et al. (2021)	IOS Press

Appendix B. Journals and conferences

Table B.1
List of journals, conferences, and master/doctoral publications by paper.

Paper	Journal Title
List of journals with a minimum of two publications.	
(Grandison et al., 2017; Ha et al., 2012; Lee et al., 2004; Park et al., 2004; Salem, 2016; Sun et al., 2018a; Wang et al., 2021a; Wu et al., 2018; Xie et al., 2020b, 2020c)	Ocean Engineering
(Azizpour et al., 2022; Fang et al., 2022a; Vanem and Ellis, 2010; Vanem and Skjong, 2006; Wang et al., 2021c; Wang et al., 2020c)	Safety Science
(Cho et al., 2016; Chu et al., 2013; Liou and Chu, 2016)	Journal of Marine Science and Technology
(Sun et al., 2018b; Wang et al., 2021b)	Physica A: Statistical Mechanics and its Applications
Balakhontceva et al. (2016)	Procedia Computer Science
(Ha et al., 2012; Park et al., 2015)	Computers in Industry
(Fukuchi and Imamura, 2005; Spanos and Papanikolaou, 2014)	Journal of Marine Science and Technology
(Ni et al., 2017b; Yuan et al., 2014)	Mathematical Problems in Engineering
List of conferences with a minimum of two publications.	
(Galea et al., 2014a, 2011, 2003; K V Kostas et al., 2014; Meyer-König et al., 2007; Sun et al., 2018b; Dracos Vassalos et al., 2002)	Pedestrian and Evacuation Dynamics
(Brumley and Koss, 2000; Ditlev Jorgensen and May 2002)	International Conference on Human Factors in Ship Design and Operation
(Guarin et al., 2014; K V Kostas et al., 2014b)	International Conference on Virtual, Augmented, and Mixed Reality
(Liu et al., 2022; Wang et al., 2022)	Reliability Engineering & System Safety
(Chen et al., 2016; Katuhara et al., 2003)	Traffic and Granular Flow Conference
List of university publications.	
(Brown, 2016; Finiti, 2021)	Doctoral Dissertation
(Luo, 2019; Vilen, 2020)	Master Thesis
List of journals/conferences with one publication.	
Kim et al. (2019)	International Journal of Naval Architecture and Ocean Engineering
Ng et al. (2021)	Annals of Operations Research
Park et al. (2015)	Procedia Engineering
Sarshar et al. (2013a)	IEEE Symposium on Computational Intelligence in Dynamic and Uncertain Environments
Casareale et al. (2017)	Building Simulation
Zhang et al. (2017)	IEEE International Conference on Networking, Sensing, and Control
Qiao et al. (2014)	IEEE International Conference on Systems, Man and Cybernetics
Montecchiari et al. (2018)	Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability
Bellas et al. (2020)	Computer Modeling in Engineering & Sciences
Liu et al. (2021)	Journal of Marine Science and Engineering
Sun et al. (2019)	International Conference on Fire Science and Fire Protection Engineering
Sarvari et al. (2019)	Maritime Policy & Management
Azzi et al. (2011)	Fire and Evacuation Modeling Technical Conference
Boulougouris and Papanikolaou (2002)	Proceedings of the 10th International Congress of the International Maritime Association of the Mediterranean
Brown et al. (2008)	International Conference on Ocean, Offshore, and Arctic Engineering
Galea et al. (2013)	Journal of Ship Research
Kang et al. (2010)	Marine Technology Society Journal
Klüpfel et al. (2001)	Theory and Practical Issues on CA
Łozowicka (2010)	Akademia Morska w Szczecinie
Miyazaki et al. (2004)	Maritime Research Institute, Japan

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Table B.1 (*continued*)

Paper	Journal Title
Nevalainen et al. (2015)	Proceedings of Marine Design
(A. López Piñeiro et al., 2005)	Journal of Maritime Research
(D. Vassalos et al., 2002)	Safety at Sea and Marine Equipment Exhibition (SASMEX)
Rutgersson and Tsychkova (1999)	Proceedings of RINA Conference on Learning from Marine Incidents
Liu and Luo (2012)	Journal of Shanghai Maritime University
Sun et al. (2020)	International Conference on Big Data Analytics for Cyber-Physical-Systems
Wang et al., 2020b	Journal of Shanghai Jiaotong University (Science)
Chen et al. (2011)	Journal of Marine Science and Application
Gwynne et al. (2003)	Fire Technology
Łozowicka (2005)	International Journal of Automation and Computing
Couasnon et al. (2019)	International Symposium on Web and Wireless Geographical Information Systems
Sarshar et al. (2014)	Transactions on Engineering Technologies
Kwee-Meier et al. (2017)	Advances in Human Aspects of Transportation
(K V Kostas et al., 2014a)	Virtual Realities
Jasionowski et al. (2011)	Contemporary Ideas on Ship Stability and Capsizing in Waves
Xie et al. (2020a)	Applied Ocean Research
Lozowicka (2021)	Plos One
Na et al. (2019)	Medico Legal Update
Walter et al. (2017)	Experimental Brain Research
Murayama et al. (2000)	Research Institute of Marine Engineering, Japan
Zhang et al. (2016)	Xitong Gongcheng Lilun yu Shijian/System Engineering Theory and Practice
Deere et al. (2006)	International Journal of Maritime Engineering
Wang et al. (2013)	China Ocean Engineering
Sarshar et al. (2013b)	International Conference on Innovative Computing Technology
Galea et al. (2014b)	Fire Safety Science
Hu and Cai (2020)	International Journal of Computers and Applications
Hu and Cai (2017)	Advances in Computer Science Research
Hu et al. (2019)	Symmetry
Kim et al. (2004)	Computers & Industrial Engineering
Deere et al. (2012)	RINA SAFEGUARD Passenger Evacuation Seminar
Yip et al. (2015)	Accident Analysis & Prevention
Meyer-König et al. (2002)	Gerhard-Mercator-Universität
Ruponen et al. (2015)	Stability of ships and ocean vehicles
(Wang and Wu, 2020a)	Journal of Ship Production and Design
Ni et al. (2018)	Journal of Statistical Mechanics: Theory and Experiment
Ni et al. (2017a)	Polish Maritime Research
Li et al. (2021)	International Journal of Maritime Engineering
Montecchiari et al. (2021)	International Shipbuilding Progress
Chen and Lo (2019)	International Conference on Fire Science and Fire Protection Engineering
Yue et al. (2022)	Process Safety and Environmental Protection
(Lee et al., 2022a)	Journal of Marine Science and Engineering
Kim et al. (2020)	International Journal of Environmental Research and Public Health
Ma et al. (2020)	IEEE Access

Appendix C. Abbreviations

Table C.1
Journal and conference title abbreviations.

Journal/conference	Abbreviation
Ocean Engineering	Ocean Eng.
International Journal of Naval Architecture and Ocean Engineering	Int. J. Nav. Archit. Ocean Eng.
Annals of Operations Research	Ann. Oper. Res.
Safety Science	Saf. Sci.
Procedia Engineering	Procedia Eng.
IEEE Symposium on Computational Intelligence in Dynamic and Uncertain Environments	IEEE CIDUE
Physica A: Statistical Mechanics and its Applications	Phys. A: Stat. Mech. Appl.
Procedia Computer Science	Procedia Comput. Sci.
Building Simulation	Build. Simul.
Journal of Marine Science and Technology (Taiwan)	JMST
IEEE International Conference on Networking, Sensing, and Control	IEEE ICNSC
IEEE International Conference on Systems, Man and Cybernetics	IEEE SMC
Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	Proc Inst Mech Eng
Computer Modeling in Engineering & Sciences	Comput Model Eng Sci
Reliability Engineering & System Safety	Reliab. Eng. Syst. Saf.
Journal of Marine Science and Engineering	J. Mar. Sci. Eng.
International Conference on Fire Science and Fire Protection Engineering	ICFSFPE
Maritime Policy & Management	Marit. Policy Manag.
Fire and Evacuation Modeling Technical Conference	FEMTC

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Table C.1 (*continued*)

Journal/conference	Abbreviation
International Conference on Ocean, Offshore, and Arctic Engineering	OMAE
Journal of Ship Research	J. Sh. Res.
Marine Technology Society Journal	Mar. Technol. Soc. J.
Journal of Maritime Research	JMR
Mathematical Problems in Engineering	Math. Probl. Eng.
International Conference on Big Data Analytics for Cyber-Physical-Systems	BDCPS
International Conference on Virtual, Augmented, and Mixed Reality	VAMR
Journal of Shanghai Jiaotong University (Science)	J. Shanghai Jiaotong Univ. (Sci.)
Pedestrian and Evacuation Dynamics	PED
Journal of Marine Science and Application	JMSA
Fire Technology	Fire Technol.
International Journal of Automation and Computing	Int. J. Autom. Comput.
Journal of Marine Science and Technology (Springer)	J Mar Sci Technol
International Symposium on Web and Wireless Geographical Information Systems	W2GIS
Transactions on Engineering Technologies	Trans. Eng. Technol.
Advances in Human Aspects of Transportation	AHFE
Traffic and Granular Flow Conference	TGF
Virtual Realities	Virtual Real.
Applied Ocean Research	Appl. Ocean Res.
Computers in Industry	Comput Ind
Plos one	Plos one
Medico Legal Update	Med.-Leg. Update
Experimental Brain Research	Exp. Brain Res.
International Journal of Maritime Engineering	IJME
China Ocean Engineering	China Ocean Eng.
International Conference on Innovative Computing Technology	ICICC
Fire Safety Science	Fire Saf. Sci.
International Journal of Computers and Applications	Int. J. Comput. Appl.
Advances in Computer Science Research	Adv. Comput. Sci. Res.
Symmetry	Symmetry
Computers & Industrial Engineering	Comput Ind Eng
Process Safety and Environmental Protection	Process Saf Environ Prot
Accident Analysis & Prevention	Accid Anal Prev
Journal of Ship Production and Design	J. Ship Prod. Des.
Journal of Statistical Mechanics: Theory and Experiment	JSTAT
Polish Maritime Research	Pol. Marit. Res.
International Journal of Maritime Engineering	IJME
International Shipbuilding Progress	Int. Shipbuild. Prog
International Conference on Fire Science and Fire Protection Engineering	ICFSFPE
International journal of environmental research and public health	Int. J. Environ. Res. Public Health
Journal of Statistical Mechanics: Theory and Experiment	J. Stat. Mech. Theory Exp.
Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment	P I MECH ENG M-J ENG
Journal of Marine Science and Engineering	J. Mar. Sci. Eng.
Applied Sciences	Appl. Sci

Appendix D. Modeling approach

Table D.1
List of publications categorized by modeling approach analytical category.

Paper	Modeling Approach
(Azizpour et al., 2022; Azzi et al., 2011; Balakhontceva et al., 2016; Bellas et al., 2020; Boulougouris and Papanikolaou, 2002; Brumley and Koss, 2000; Chen and Lo, 2019; Cho et al., 2016; Couasnon et al., 2019; Deere et al., 2006; Ditlev Jorgensen and May 2002; Fang et al., 2022b, 2022a; Fukuchi and Imamura, 2005; Galea et al., 2013, 2003; Ha et al., 2012; Hu and Cai, 2022, 2017; Katuhara et al., 2003; Kim et al., 2019, 2020; Klüpfel et al., 2001; K V Kostas et al., 2014a; Lee et al., 2022; Li et al., 2021; Liou and Chu, 2016; Liu et al., 2022; Łozowicka, 2010; Meyer-König et al., 2002; Montecchiari et al., 2018; Ni et al., 2018, 2017b, 2017a; Park et al., 2004; Piñeiro et al., 2005; Roh and Ha, 2013; Ruponen et al., 2015; Rutgersson and Tsychkova, 1999; Salem, 2016; Sarshar et al., 2014, 2013a; Spanos and Papanikolaou, 2014; Sun et al., 2020; Vanem and Skjong, 2006; Vassalos et al., 2002; Vassalos et al., 2002; Vilen, 2020; Wang et al., 2013, 2014, 2022; Wang et al., 2020b; Wu et al., 2018; Xie et al., 2020b; Yuan et al., 2014; Zhang et al., 2017, 2016)	Simulation
(Bles et al., 2001; Deere et al., 2012; Galea et al., 2014b, 2014a, 2011; Grandison et al., 2017; K V Kostas et al., 2014; Kwee-Meier et al., 2017; Lee et al., 2004; Meyer-König et al., 2007; Na et al., 2019; Park et al., 2015; Sun et al., 2019, 2018b, 2018a; Walter et al., 2017; Wang and Wu, 2020a; Wang et al., 2021a, 2021b; Yip et al., 2015)	Experimental
(Brown, 2016; Brown et al., 2008; Casareale et al., 2017; Chen et al., 2011, 2016; Gwynne et al., 2003; Hu et al., 2019; Hu and Cai, 2020; Jasionowski et al., 2011; Kang et al., 2010; Luo, 2019; Ma et al., 2020; Miyazaki et al., 2004; Montecchiari et al., 2021; Murayama et al., 2000; Qiao et al., 2014; Sarshar et al., 2013b; Sarvari et al., 2019; Xie et al., 2020a)	Hybrid (Simulation/Mathematical, Simulation/Experimental, Simulation/Questionnaire, and Experimental/Questionnaire)
(Chu et al., 2013; K V Kostas et al., 2014b; Liu and Luo, 2012; Liu et al., 2021; Lozowicka, 2021; Łozowicka, 2005; Ng et al., 2021; Xie et al., 2020c)	Mathematical
(Guarin et al., 2014; Kim et al., 2004; Nevalainen et al., 2015; Vanem and Ellis, 2010; Vukelic et al., 2021)	Analytical
(Finiti, 2021; Wang et al., 2021c; Wang et al., 2020c)	Questionnaire and Interview

Appendix E. Traffic assignment formulation

Table 6
List of publications categorized by traffic assignment formulation analytical category.

Paper	Model type
User equilibrium formulation	
(Azizpour et al., 2022; Bellas et al., 2020; Bles et al., 2001; Brown et al., 2008; Brumley and Koss, 2000; Casareale et al., 2017; Chen et al., 2016; Cho et al., 2016; Chu et al., 2013; Couasnon et al., 2019; Deere et al., 2006, 2012; Ditlev Jorgensen and May 2002; Fang et al., 2022a, 2022b; Finiti, 2021; Fukuchi and Imamura, 2005; Galea et al., 2014a, 2014b, 2013; Ha et al., 2012; Hu et al., 2019; Hu and Cai, 2022, 2020; Kang et al., 2010; Katuhara et al., 2003; Kim et al., 2019, 2020; K V Kostas et al., 2014a; Kwee-Meier et al., 2017; Lee et al., 2004, 2022; Liou and Chu, 2016; Liu et al., 2021; Lee et al., 2022a; Liu et al., 2022; Meyer-König et al., 2002; Miyazaki et al., 2004; Montecchiari et al., 2021; Murayama et al., 2000; Na et al., 2019; Ng et al., 2021; Ni et al., 2018; Park et al., 2015; Qiao et al., 2014; Roh and Ha, 2013; Rutgersson and Tsychkova, 1999; Sarshar et al., 2013b, 2013a; Sun et al., 2020, 2019, 2018a; Walter et al., 2017; Wang et al., 2020b; Wang et al., 2022; 2021a, 2021c; X. Wang et al., 2020c; Wu et al., 2018; Yue et al. 2022; Zhang et al., 2017)	Microscopic
(Azzi et al., 2011; Balakhontceva et al., 2015, 2016; Brown, 2016; Chen et al., 2011; Gwynne et al., 2003; Hu and Cai, 2017; Klüpfel et al., 2001; Li et al., 2021; Montecchiari et al., 2018; Ni et al., 2017a, 2017b; Sarshar et al., 2014; Sarvari et al., 2019; Sun et al., 2018b; Vassalos et al., 2002; Vilen, 2020; Wang et al., 2014, 2021b; Yuan et al., 2014)	Microscopic and Macroscopic
System-optimal formulation	
(Chen and Lo, 2019; Galea et al., 2003, 2011; Grandison et al., 2017; Jasionowski et al., 2011; Lozowicka, 2021; Łozowicka, 2005; Luo, 2019; Ma et al., 2020; Park et al., 2004; Ruponen et al., 2015; Salem, 2016; Spanos and Papanikolaou, 2014; Vanem and Skjong, 2006; Wang and Wu, 2020a; Wang et al., 2013; Xie et al., 2020a, 2020c, 2020b)	Macroscopic
Not available	
(Boulougouris and Papanikolaou, 2002; Guarin et al., 2014; Kim et al., 2004; K V Kostas et al., 2014; K V Kostas et al., 2014b; Liu and Luo, 2012; Łozowicka, 2010; Meyer-König et al., 2007; Nevalainen et al., 2015; Piñeiro et al., 2005; Vanem and Ellis, 2010; Vassalos et al., 2002; Yip et al., 2015; Zhang et al., 2016)(Vukelic et al., 2021)	NA

Appendix F. Model parameter

Table F.1
List of publications categorized by model parameter analytical category.

Paper	Parameter
Xie et al. (2020c)	• Fire (heat, smoke, and toxic gases) and • ship layout (stairs, assembly stations, and different functional zones including seating zone, general area, bar zone, locker zone, restaurant zone, and retail zone)
Azizpour et al. (2022)	•Ship stability (heeling angle (0, 10, 15, and 20°), •passenger age (18–72), •passenger gender (male and female), •passenger height (154–195), • passenger weight (48–123), •other forces (thermal protective immersion suits)
Fang et al. (2022a)	•Ship stability (trim angles from −30 to 30° and heeling angles from 0 to 30°)
Wang et al., (2022)	• Passenger age, •passenger gender, •passenger physical condition, • exit and staircase layout
Kim et al. (2019)	•Ship stability (heeling angle (0,30,52.2°)), •passenger load (human density) • passenger gender (crew, male, female), and • crowd behavior (counter flow)
Liu et al., (2022)	• Ship layout (passage, exit, and number of corners in a deck)
Fang et al. (2022b)	•Ship stability (inclination angles (0,5,10,15,20°), •passenger gender (male, female), • passenger age
Yue et al. (2022)	•Passenger gender, •passenger age, •passenger size, •passenger mass, •other factors (neighborhood radius, information value, information threshold, information attenuation ratio, location in a two-dimensional (2D) environmental network, physical quality, and psychological quality)
Hu and Cai (2022)	•Passenger age, •passenger gender
Lee et al. (2022)	•Passenger age, •passenger gender, •passenger physical condition, •ship layout, •ship stability (heel and trim angle (0–30°))
Ng et al. (2021)	•Passenger age (children, women, and seniors)
Wang et al. (2021b)	•Ship stability (heeling angle of 15–20°), •ship motion (ship berthing and sailing operations), •passenger age (25.8+-10,5), •passenger height (175.3 cm ± 6.6 cm), • passenger weight (71.3 kg ± 8.6 kg), and • passenger physical condition
Ha et al. (2012)	•Ship layout (corridors, staircase),

(continued on next page)

Table F.1 (*continued*)

Paper	Parameter
	• crowd behavior (counter flow), and • passenger behavior
Finiti (2021)	•Passenger age, • passenger gender, and • passenger behavior (individually based on companions and experience)
Vanem and Skjong (2006)	•Fire (starting point of fire within each fire zone), •ship stability (list direction), • ship layout, and • passenger and crew load
Wang et al. (2014)	•Ship layout (staircase and restaurant)
Sun et al. (2018a)	•Ship stability (heeling (between −15 and + 15°), trimming (−20 and 20°), and both), •ship layout (corridors (10m1.8m2.2m)), •passenger age (24.6+-1.45), •passenger gender, • passenger weight (60.5+-9.1), and • passenger height (167.7+-6.4 cm)
Sarshar et al. (2013a)	•Fire (fire location, fire condition (controllable/uncontrollable), •ship stability (trim and heel) •passenger age, • passenger gender, and • passenger physical condition
Sun et al. (2018b)	•Ship stability (trim and heeling), •ship layout (corridors (10m (Length)*1.8m (Width)*2.2m (Height))), •passenger age (23–26), •passenger gender, •passenger weight (45–72 kg), and • passenger height (157–185 cm)
Balakhontceva et al. (2015)	•Passenger age, • passenger gender, and • passenger physical condition, and • other external forces (intensity of waves (5, 7, 9 sea forces), rate of sailing (0, 5, 15, 25 knots))
Casareale et al. (2017)	• Passenger behavior (familiarity with emergencies, such as disaster and drills experience, seek for emergency procedures information (e.g., emergency plan, emergency signs, and path escape routes), interacting with unknown people (e.g., social attachment), leaving immediately after the alarm or ignore it (risk denial))
Chu et al. (2013)	•Ship layout (corridors, doorways, and stairs)
Zhang et al. (2017)	•Ship motion (rolling), •passenger age (21–40), •passenger gender, •passenger height (160–187 cm), • passenger weight (50–95 kg), and • other external forces (wind-wave dynamics)
Wu et al. (2018)	• Fire (smoke and temperature (fire growth rate is 0.0029,0.0117,0.0469,0.1846 kw/s^2) and • ship layout (corridors (initial speed is 1.2 m/s), stair descent (1.0 m/s), stair ascent (0.8 m/s))
Qiao et al. (2014)	•Ship layout (stairs, corridors, and doorways), •passenger age (23–26), •passenger gender, • passenger height (157–185 cm), and • passenger weight (45–72 kg),
Liou and Chu (2016)	•Ship layout (corridors and stairway), •passenger behavior (walking speed), • passenger age, and • passenger gender
Montecchiari et al. (2018)	•Crow behavior (counter flow)
Bellas et al. (2020)	•Ship layout (the location of corridors, doors, stairways, and ladders along with the ship), • passenger age, and • passenger gender •passenger behavior (walking speed)
Brown (2016)	•Fire (heat, smoke, toxic products), •ship stability (heel and trim), •passenger age, •passenger gender, •passenger physical condition (agility and mobility impairment), •passenger behavior (experience and walking speed)
Liu et al. (2021)	• Crowd behavior (crowd density) and • passenger behavior (passenger walking speed)
Vilen (2020)	•Ship layout (the topology and geometry of the ship), • passenger age, and • passenger gender
Sun et al. (2019)	•Passenger stability (heeling (−15 to +15°), trim (−20 to +20°), •passenger age (21–26), • passenger height (157–173 cm), and • passenger weight (45–78)
Sarvari et al. (2019)	•Ship stability (trim and heel −20 to +20°)
Azzi et al. (2011)	•NA
Cho et al. (2016)	•Crowd behavior (flock behavior, emergency behavior (counter flow), and other is a leader following behavior), •passenger behavior (and individual behavior (body shape, walking speed, walking direction, and rotation of each passenger),

(continued on next page)

Table F.1 (*continued*)

Paper	Parameter
	•ship layout (corridor and staircase), • passenger age (around 30 to older than 50), and • passenger gender
Boulougouris and Papanikolaou (2002)	•Passenger age (children, adults, and elderly)
Brown et al. (2008)	•Passenger age, •passenger gender, •passenger height, •passenger weight
Brumley and Koss (2000)	•Ship layout (ship corridors and on stairs), •passenger age, • passenger gender, and • passenger physical condition (degree of handicap)
Galea et al. (2013)	•NA
(Ditlev Jorgensen and May, 2002)	•Ship layout, • passenger behavior (non-compliance with instructions), and • passenger physical condition (disabled, asthmatic, heart trouble, and hearing impaired)
Kang et al. (2010)	•NA
Klüpfel et al. (2001)	•Crowd behavior (crowd motion)
Łozowicka (2010)	•Crowd behavior (counter flow)
Miyazaki et al. (2004)	•Passenger gender, •passenger physical condition (disabled people and wheelchair), •passenger behavior (kind mental state, (non-)competitive spirits or mean mental state)
Nevalainen et al. (2015)	•Ship layout (spaces such as staircases, objects such as escape routes), •passenger behavior (perception, decision making, passenger activities)
Piñeiro et al. (2005)	•Passenger age, •passenger gender, •passenger behavior (walking speed), •passenger and crew load
Vanem and Ellis (2010)	•NA
Vassalos et al. (2002)	•Passenger behavior
Rutgersson and Tsychkova (1999)	• Passenger behavior (Human factors) and • other external forces (environment factors, guidance systems, arrangements onboard, and technical equipment)
Ni et al. (2017b)	•Ship layout (interior layout of passenger ship cabins (tables and stools) and obstacles) •passenger behavior (interaction forces between the individual and crew)
Liu and Luo (2012)	•NA
Sun et al. (2020)	•Passenger age (30–50)
Guarin et al. (2014)	•Other external forces (sea State, time of day) •human and organizational factors and crew emergency)
Wang et al., 2020c	•NA
Galea et al. (2014a)	•NA
Chen et al. (2011)	•NA
Gwynne et al. (2003)	•Ship stability (tilting (20° left), listing (20° right)), •crowd behavior (contra-flow situation) •passenger physical condition
Łozowicka (2005)	•NA
Spanos and Papanikolaou (2014)	•Ship layout (hull breach and ship's loading)
Fukuchi and Imamura (2005)	•Fire (smoke and fire) •ship layout (enclosure layout, the number and type of exits, corridor widths, and travel distances) •passenger age (children, youth, elderly) •passenger behavior (evacuation movements and the reaction of emotions and action)
Couasnon et al. (2019)	•Passenger behavior (crew members, disoriented passengers, and "normal" passengers)
Galea et al. (2011)	•Passenger age (exclude children under the age of 12)
Sarshar et al. (2014)	•Ship layout (the structure of the ship), •passenger age •passenger gender, •passenger behavior (panic)
Kwee-Meier et al. (2017)	•Passenger age (mean age = 24.31), •ship stability (a treadmill at 0°, 7°, and 14° with and without applied mental and emotional stressors, i.e., time limit and acoustic background noise)
Katuhara et al. (2003)	•Passenger behavior (getting information using a sense of sight, hearing, and smell), Influence of Imaginary •distances, and walking speed) •passenger age (an adult, a child, an elderly), •passenger physical condition (disabled persons)
(K V Kostas et al., 2014b)	•NA
(K V Kostas et al., 2014a)	•Fire (with and without a concurrent fire event), •ship motion (and 90-degree ship heading (beam seas)) •crow behavior (with and without crew assistance) •other external forces (No Waves, 4 m significant wave height, 11 s peak period)
Jasionowski et al. (2011)	•Other external forces (wave (length, amplitude, elevation), flooding), • ship stability (heel and trim), and • ship motion (water accumulation and heave motion)
(K V Kostas et al., 2014)	•Ship motion (with and without ship motions), •crowd behavior
Xie et al. (2020a)	•NA
Balakhontceva et al. (2016)	•Ship motion (ship roll and pitch angles under the influence of sea waves),

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Table F.1 (*continued*)

Paper	Parameter
	•passenger age, •passenger gender, • passenger physical condition, and • other external forces (sea waves dynamics)
Park et al. (2015)	•Ship layout (corridors, staircase, ship layout, (11 tests specified in IMO MSC/Circ. 1238 were performed), •passenger age (age (younger than 30 and older than 50))
Grandison et al. (2017)	•NA
Roh and Ha (2013)	•Ship layout (corridors, staircase, ship layout, (11 tests specified in IMO MSC/Circ. 1238 were performed), •passenger age (age (younger than 30 and older than 50)), • crowd behavior (counterflow-avoiding behavior), and • passenger behavior
Lozowicka (2021)	• NA
Wang et al. (2021a)	• Ship motions (rolling (0,1,3,5,9) & pitch (less than 1)), • ship layout (flat terrains and staircases, corridors (L7.4m, W5.4m, H1.2m)), • passenger age (20–53), • passenger weight (55–96 kg), and • passenger gender
Bles et al. (2001)	• Ship motion (dynamic ship motion) • ship layout (stairs and corridors), • ship stability (ship listing), and • passenger age (age (18–83))
Lee et al. (2004)	• Ship motion (roll angle between 3 and 4° and pitch motions), • passenger behavior, • crowd behavior, • ship layout (corridors (10m*1.2m*1.9m)), and • ship stability (trim angle between −20 and + 20 and heel angle between 0 and 20)
Meyer-König et al. (2007)	• Ship stability (heel (0–15 and 15–35°)) and • ship motion (roll motion)
Na et al. (2019)	• Ship motion (roll angular magnitude (1°)), • ship stability (berthing), • passenger age, and • passenger gender
Walter et al. (2017)	• Ship motion (roll and pitch), • passenger age (20–72), and • passenger gender
Wang et al. (2021c)	• Passenger age (16–61 and above), • passenger gender, • passenger behavior (educational level, mobility level, experience on board), • crowd behavior (family group experience in evacuation education)
Wang et al., (2020b)	• Passenger age (16–61 and above), • passenger gender, • passenger behavior (educational level, mobility level, experience on board), • crowd behavior (family group experience in evacuation education)
Xie et al. (2020b)	• Passenger load (initial passenger density) and • ship layout (stairs, different functional zones in this passenger ship including bar, general area, retail, seating, restaurant, and locker zone)
Murayama et al. (2000)	• Ship stability (fore and aft inclination (+20 to −20°)) and • ship motion (roll and pitch cycle (10° and for 5 and 10 s), • passenger height (1.56–1.81 cm), and • passenger weight (51–90 kg)
Zhang et al. (2016)	• Ship motion (different rolling angle) and • other external forces (wave scales)
Chen et al. (2016)	• Ship motion (water motion)
Deere et al. (2006)	• NA
Vassalos et al. (2002)	• Ship motions
Wang et al. (2013)	• Fire (oxygen concentration, smoker layer height, and temperature)
Sarshar et al. (2013b)	• Fire (fire location, hat, and smoke exposure), • passenger age, • passenger gender, and • passenger physical condition
Galea et al. (2014b)	• NA
Hu and Cai (2020)	• Ship layout (cabins)
Yuan et al. (2014)	• Ship stability (heel (0–35°) and trim (−20 to 20°) • ship layout (door sizes (0–8m))
Hu and Cai (2017)	• Crowd behavior (the attraction of the mainstream crowd and the repulsion impact and static and dynamic floor fields)
Luo (2019)	• Ship layout (cabin, a hall, a doorway, and an intersection of corridors), • passenger load, and • passenger behavior
Hu et al. (2019)	• Ship stability (listing, trimming (−30 to +40°), and heeling), • passenger age (30 and younger to 50 and older), • passenger gender, • passenger behavior (walking speed), and • passenger physical condition (mobility-impaired people)
Galea et al. (2003)	• Fire (smoke)
Kim et al. (2004)	• Ship stability (listing), • ship motion, • crowd behavior (crowd density),

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Table F.1 (*continued*)

Paper	Parameter
	• passenger behavior (cultural differences and behavior under panic), • passenger age, and • passenger gender
Park et al. (2004)	• Ship motion, • ship layout (exit doors width), and • passenger behavior
Deere et al. (2012)	• NA
Salem (2016)	• Fire (fire toxicity, heat, and smoke) and • ship layout (stairwell, corridor, and cabin)
Yip et al. (2015)	• NA
Meyer-König et al. (2002)	• Passenger age, • passenger gender, and • passenger behavior (the patience and stamina)
Ruponen et al. (2015)	• Ship stability (heeling angle (−5 to 20)),
Wang and Wu, (2020a)	• Ship layout (stairs, corridors, and doors)
Ni et al. (2018)	• Crowd behavior (counter flow)
Ni et al. (2017a)	• Crowd behavior (crowd movement), • passenger behavior (agent (perception, decision-making, walking speed, and locomotion)), • passenger gender (male and female), and • passenger age
Li et al. (2021)	• Ship layout (stairs, corridors, and doors) and • passenger behavior (layout familiarity and social relationship)
Montecchiari et al. (2021)	• Crowd behavior (counter flow), • passenger age, and • passenger gender
Chen and Lo (2019)	• Ship stability (trim angle (−0.38,0, +0.38°), rolling rate, and Influence of fore-aft direction) and • ship motion (pitching rate and yaw rate, and sway)
Kim et al. (2020)	• Ship stability (heeling angle (0, 5, 10, 15, 20, 25, and 30°), • passenger age, and • passenger gender
Ma et al. (2020)	• Ship stability (heeling angle and trim angle) and • passenger behavior (passenger walking speed and reduction factor of the walking speed)

Appendix G. Hazard type

Table G.1
List of publications categorized by hazard type analytical category.

Paper	Hazard Type
(Azzi et al., 2011; Bellas et al., 2020; Brown, 2016; Fukuchi and Imamura, 2005; Galea et al., 2003; K V Kostas et al., 2014a; Liu and Luo, 2012; Lee et al., 2022a; Łozowicka, 2010; Luo, 2019; Miyazaki et al., 2004; Salem, 2016; Sarshar et al., 2014, 2013a, 2013b; Sarvari et al., 2019; Wang et al., 2013; Wu et al., 2018; Xie et al., 2020b, 2020c, 2020a)	Fire
(Casareale et al., 2017; Finiti, 2021; Kim et al., 2019, 2020; Ma et al., 2020; Piñeiro et al., 2005)	Foundered (capsizing and sinking)
(Jasionowski et al., 2011; Ruponen et al., 2015; Spanos and Papanikolaou, 2014)	Flooding
(Balakhontceva et al., 2015, 2016; Zhang et al., 2016)	Storm
Vanem and Skjong (2006)	Fire and sinking
Vassalos et al. (2002)	Fire and flooding
Yip et al. (2015)	Fire, grounding, flooding, and sinking
(Azizpour et al., 2022; Bles et al., 2001; Boulougouris and Papanikolaou, 2002; Brown et al., 2008; Brumley and Koss, 2000; Chen et al., 2016, 2011; Chen and Lo, 2019; Cho et al., 2016; Chu et al., 2013; Couasnon et al., 2019; Deere et al., 2006, 2012; Ditlev Jorgensen and May 2002; Fang et al., 2022b, 2022a; Galea et al., 2014a, 2014b, 2013, 2011; Grandison et al., 2017; Guarin et al., 2014; Gwynne et al., 2003; Ha et al., 2012; Hu et al., 2019; Hu and Cai, 2022, 2020, 2017; Kang et al., 2010; Katuhara et al., 2003; Kim et al., 2004; Klüpfel et al., 2001; K V Kostas et al., 2014; K V Kostas et al., 2014b; Kwee-Meier et al., 2017; Lee et al., 2004, 2022; Li et al., 2021; Liou and Chu, 2016; Liu et al., 2021; Liu et al., 2022; Lozowicka, 2021; Łozowicka, 2005; Meyer-König et al., 2007, 2002; Montecchiari et al., 2021, 2018; Murayama et al., 2000; Na et al., 2019; Nevalainen et al., 2015; Ng et al., 2021; Ni et al., 2018, 2017a, 2017b; Park et al., 2004, 2015; Qiao et al., 2014; Roh and Ha, 2013; Rutgersson and Tsychkova, 1999; Sun et al., 2020, 2019, 2018a, 2018b; Vanem and Ellis, 2010; Vassalos et al., 2002; Vilen, 2020; Vukelic et al., 2021; Walter et al., 2017; Wang and Wu, 2020a; Wang et al., 2020b; Wang et al., 2014, 2022, 2021c, 2021a, 2021b; Wang et al., 2020c; Yuan et al., 2014; Yue et al., 2022; Zhang et al., 2017)	NA

Appendix H. Solution method

Table H.1
List of publications categorized by solution method analytical category.

Paper	Objective
Velocity-based Model	
Kim et al. (2019)	Analyzing the influence of heel angle on passenger walking speed during the sinking
Vilen (2020)	Calculating reaction time, travel time, congestion time, and completion time
Sun et al. (2019)	Calculating the correlation between passenger walking speed and gait parameters of individuals on board

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Table H.1 (*continued*)

Paper	Objective
Sarvari et al. (2019)	Designing real-time decision support for estimating evacuation time and the death toll
Azzi et al. (2011)	Evacuation time minimization
Cho et al. (2016)	Passenger behavior analysis during ship evacuation
Boulougouris and Papanikolaou (2002)	Route finding
Brown et al. (2008)	Abandonment of passenger vessels with untrained and ambulatory subjects
Sun et al. (2018a)	Analyzing the influence of heel/trim angle on passenger walking speed during ship evacuation
Bellas et al. (2020)	Evacuation time minimization
Brown (2016)	Data production, human performance understanding, and passenger response time calculation
Galea et al. (2013)	Finding passenger response times, starting locations, end locations, and arrival times in the assembly stations
Vassalos et al. (2002)	Calculating the cumulative probability distribution (CDF) of evacuation time under uncertainties regarding human behavior
Sun et al. (2020)	Determining the number of passengers assembled
Guarin et al. (2014)	Developing a pedestrian dynamics simulation tool
Galea et al. (2014a)	Determining response time, starting locations, arrival time at the designated assembly stations, and the paths taken
(K V Kostas et al., 2014b)	Description of the enhanced crowd modeling approaches in VELOS
(K V Kostas et al., 2014a)	Description of VELOS′ components and functionalities
Deere et al. (2006)	Passenger response time calculation
Vassalos et al. (2002)	Passenger behavior and movement analysis
Galea et al. (2014b)	Data validation related to response times, starting locations, end locations, and arrival times in the assembly stations
Galea et al. (2003)	Assembly time determination
(K V Kostas et al., 2014)	Analyzing the effect of ship motions on passengers and/or crew movements
Kim et al. (2004)	Meeting requirements of IMO and current research works for evacuation from the ship
(Park et al., 2004)	Distance walking time determination
Gwynne et al. (2003)	Number of evacuees calculation, evacuation time minimization, and data collection
Cell-based Model	
Ha et al. (2012)	Passenger behavior understanding
Klüpfel et al. (2001)	Crowd motion description
(A. López Piñeiro et al., 2005)	Conceptual design, evacuation models during ship emergency
Hu and Cai (2020)	Evacuation time minimization
Hu and Cai (2017)	Evacuation time minimization
Meyer-König et al. (2007)	Analyzing the influence of ship motion on passenger walking speed
Hu et al. (2019)	Evacuation time minimization
Wang et al., (2020b)	Path planning of passenger ships
Chen et al. (2011)	Continuity of the passengers' track and evacuation time steps
Meyer-König et al. (2002)	Pedestrians' movements analysis
Roh and Ha (2013)	Evacuation time minimization
Social Force-based Model	
Ni et al. (2017b)	Evacuation time minimization
Fang et al. (2022a)	Pedestrians' movements analysis
Fang et al. (2022b)	Evacuation time calculation in the presence of inclination angle
Balakhontceva et al. (2016)	Estimating evacuation time under environmental conditions
Chen et al. (2016)	Analyzing the effect of ship swaying on pedestrian evacuation efficiency
Ni et al. (2018)	Life jacket's location determination
Ni et al. (2017a)	Agent's target and shortest path determination
Balakhontceva et al. (2015)	Estimating evacuation time under ship motions
Montecchiari et al. (2021)	Real-time human participation implementation using virtual reality
Acceleration-based Model	
Casareale et al. (2017)	Risk perception analysis, passenger behavior analysis, and finding the similarities between building and cruises evacuation processes
Zhang et al. (2017)	Human behavior under different ship rolling angles, the data on adjustment actions, walking pauses, and the influence of rolling angle on walking speed.
Montecchiari et al. (2018)	Testing real-time people participation through immersive virtual reality during ship evacuation
Zhang et al. (2016)	Analyzing the impact of adjustment action, pause phenomenon, and linear velocity on pedestrian walking speed

Other Techniques		
Xie et al. (2020c)	Passenger Response Time Calculation under ship Fires	PC expansion and GA
Li et al. (2021)	Route choice	Agent-based modeling technique
Azizpour et al. (2022)	Assessing the impact of survival suit on passenger walking speeds	Regression analysis
Yue et al. (2022)	Evaluation of passenger evacuation capacity	AnyLogic software
(Lee et al., 2022a)	Evacuation time minimization	PyroSim software
Wang et al., (2022)	Assessing the effects of the passenger population composition on evacuation time	FDS + EVAC
Liu et al., (2022)	Realizing spatial modeling of the spatial-temporal characteristics of evacuation	Geographic information system
Hu and Cai (2022)	Analysis of the passenger characteristics	AnyLogic software
Lee et al. (2022)	Passenger walking speed calculation and analysis	UNITY engine
Vukelic et al. (2021)	Assessing the possibility of adopting new technologies to the human evacuation process	Literature analysis method
Ng et al. (2021)	Evacuation time minimization	Dynamic programming
Wang et al. (2021b)	Analyzing the influence of ship motion on passenger walking speed	Collecting data with a camera
Finiti (2021)	Data production and understanding of human performance	Behavioral sequence Analysis, talk-through, and comparison methods
Vanem and Skjong (2006)	Evacuation time minimization and number of fatalities calculation	Risk-based technique
Wang et al. (2014)	Finding the number of the assembled passengers	An agent-based microscopic evacuation model—city flow-M
Sarshar et al. (2013a)	Evacuation time minimization under ship fire	Simulation tool
Sun et al. (2018b)	Analyzing the influence of heel/trim angle on passenger walking speed during ship evacuation (athwartship and fore-aft walking)	Electrical monitoring system with four cameras (AVI format, 25 fps)
Chu et al. (2013)	finding Evacuation route, travel distance, the number of people moving from node i to node j	Mathematical tool

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Table H.1 (*continued*)

Wu et al. (2018)	ASET and RSET calculation	Simulation tool
(Qiao et al., 2014)	Finding optimum evacuation route	Simulation tool
Liou and Chu (2016)	Evacuation time minimization ((1) walking speed, (2) the number of cadets turning to the left or right at T junctions, and (3) the number of cadets moving forward or aft in the corridors.)	Developed program
Liu et al. (2021)	Evacuation time minimization and Developing Evacuation route planning	Improved ant colony system and flow method-based cardinal number
(Brumley and Koss, 2000)	Observations on passenger walking speed in ship corridors and on stairs	Simulation tool
(Ditlev Jorgensen and May 2002)	Analyzing the attitudes and behavior of passengers about wayfinding, reactions to alarms, effects of "group binding," and non-compliance with instructions on assembly time	Simulation tool
Kang et al. (2010)	Real-time location recognition and escape route determination	Simulation tool
Łozowicka (2010)	Opposite flow analysis	GA
Miyazaki et al. (2004)	Estimating Evacuation time and optimal evacuation routes	Video camera for collecting data
Nevalainen et al. (2015)	Human-environment interaction investigation (Source of stimuli, human behavior, Spatial environment, social environment)	NA
Vanem and Ellis (2010)	Evaluation of a Monitoring System according to RFID technology in terms of the cost-effectiveness for passenger ships	Risk-based
Rutgersson and Tsychkova (1999)	Simulate the mustering operation	NA
Liu and Luo (2012)	Evacuation routes determination	Mathematical tool
Łozowicka (2005)	Finding evacuation time as a function of the initial distribution of passengers and Evacuation routes	GA
Spanos and Papanikolaou (2014)	Estimation of the probability to capsize	MC method
Fukuchi and Imamura (2005)	Analyzing smoke diffusion state, evacuation movements, and risk index analysis under ship fires	Analytical model
Couasnon et al. (2019)	Developing an evacuation simulation model	Mathematical tool
Galea et al. (2011)	Determining response time, starting locations, arrival time at the designated assembly stations, and the paths taken	31 Infra-Red beacons
Sarshar et al. (2014)	Congestion prediction	Simulation tool
Kwee-Meier et al. (2017)	Analyzing the influence of physical demands on escape routes, i.e., uphill grades, and mental and emotional stress influence decision-making in terms of decision times?	Analysis of variance
Katuhara et al. (2003)	Evacuation route selection and evacuation time minimization	Twenty video cameras
Jasionowski et al. (2011)	Predicting ship survival time	Envelope process technique
Xie et al. (2020a)	Analysis of evacuation time, travel time, and safety factor	PC expansion
Park et al. (2015)	Evacuation time minimization	Simulation tool
Couasnon et al. (2019)	Developing an evacuation simulation model	Mathematical tool
Grandison et al. (2017)	Determining the confidence interval of evacuation time	Binomial-distribution technique
Lozowicka (2021)	Analyzing the arrangement of evacuation routes, and evacuation time minimization	GA
Wang et al. (2021a)	Analyzing the influence of ship rolling on passenger walking speed	Video camera for collecting data
Bles et al. (2001)	Analyzing the influence of ship motion on passenger walking speed	TNO ship motion simulator
Lee et al. (2004)	Passenger walking speed analysis	Camera and ship motion measuring for collecting data
Na et al. (2019)	Passenger walking speed analysis	CCTV cameras for collecting data
Walter et al. (2017)	Passenger walking speed analysis in athwart and fore-aft directions	Video camera for collecting data
Wang et al. (2021c)	Illustrating the status of ship passengers' safety awareness, the perception of Evacuation wayfinding tools, and the demographic differences regarding safety awareness and perception.	Regression model
Wang et al., 2020c)	Passenger behavior according to demographic differences during the human evacuation	Regression model
Xie et al. (2020b)	Travel time determination under ship fires	PC expansion
Murayama et al. (2000)	Determining assembly time and passenger walking speed	27 Video cameras for collecting data
Wang et al. (2013)	Uncertainty analysis for ASET under ship fire	MC method
Sarshar et al. (2013b)	Panic quantification and modeling	Simulation tool
Yuan et al. (2014)	Evacuation time minimization	Mathematical tool
Deere et al. (2012)	Data collection related to response times, Starting locations, end locations, and arrival times in the assembly stations	Infra-red and video cameras
Salem (2016)	ASET calculation	MC method
Yip et al. (2015)	Determinants of the crew and passenger injuries in passenger vessel accidents	Regression model
Ruponen et al. (2015)	Assessment of the survivability of the people onboard, evaluation of the survivability of the people onboard, breach detection	124 level sensors for collecting data
Wang and Wu (2020a)	Total evacuation time and congestion points determination	NA
Chen and Lo (2019)	Determining pedestrian movement dynamics subject to ship motion	NA
Kim et al. (2020)	Analyzing the occupants' moving speeds according to the inclination of the ship, and evacuation time minimization	Mathematical tool
Ma et al. (2020)	Determining path length, user escape time, navigation success ratio, and minimum distance to hazardous regions	26 sensors for collecting data, and ANT (a deadline-aware adaptive emergency navigation strategy)

Appendix I. Evacuation tools

Table I
1 Evacuation simulation tools

Name	Year	Field	Space representation	Purpose	Reference
Simulex	1995	• Maritime, • Civil Engineering	• Discrete	• Evacuation time estimation • Calculation of individuals' walking speed	Thompson and Marchant (1995)

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Table I (*continued*)

Name	Year	Field	Space representation	Purpose	Reference
EVAC	1999	• Maritime	• Continuous	• Simulation of mustering operation	Rutgersson and Tsychkova (1999)
AnyLogic	2000	• A broad range, including maritime	• Hybrid	• Combined discrete-continuous simulation, • Agent-based modeling, • System dynamic simulation	AnyLogic (2000)
SMARTFIRE		• Maritime, • Aerospace, and • Civil Engineering	• Continuous	• Simulation of the fire environment	Galea et al. (2004)
MaritimeEXODUS	2003	• Maritime	• Discrete	• • Simulation of evacuation behaviors and Pedestrian dynamics	Gwynne et al. (2003)
IMEX	2004	• Maritime, • • Aerospace, and Civil Engineering	• Discrete	• • Pedestrian dynamics and Human behavior simulation	Park et al. (2004)
ODIGO	2000–2005	• Maritime, • • Aerospace and Civil Engineering	• Continuous	• Crowd motion simulation	Pradillon (2004)
FDS + Evac	2007	• Civil Engineering	• Continuous	• Simultaneous simulation of fire and Evacuation process	Korhonen et al. (2010)
AENEAS/PedGo	2007	• Maritime	• Discrete	• • Distribution of passengers and Route definition/ evacuation simulation	Meyer-König et al. (2007)
UNITY engine	2008	• A broad range, including maritime	• Hybrid	• Simulation	Unity (2008)
VELOS	2010	• Maritime	• Continuous	• Assessment of passenger and crew activities	Ginnis et al. (2010)
Pathfinder	2011	• Civil Engineering	• Continuous	• Simulation of human behavior and interactions	(Thunderhead Engineering, 2021)
EVI	2011	• Maritime	• Hybrid	• Pedestrian movement simulation	Guarin et al. (2014)
SIMPEV	2012	• Maritime	• Discrete	• Evacuation analysis based on human behavior	Roh and Ha (2013)
EvacSim	2013	• Civil Engineering	• Hybrid	• Simulation of pedestrian egress	Murphy et al. (2013)

Appendix J. Problem type

Table J.1
List of publications categorized by problem type.

Paper	Category
(Azzi et al., 2011; Balakhontceva et al., 2016, 2015; Bellas et al., 2020; Boulougouris and Papanikolaou, 2002; Chen et al., 2011; Chu et al., 2013; Deere et al., 2006; Fang et al., 2022b; Galea et al., 2003, 2013; Grandison et al., 2017; Gwynne et al., 2003; Hu et al., 2019; Hu and Cai, 2020, 2017; Jasionowski et al., 2011; Kang et al., 2010; Katuhara et al., 2003; Kim et al., 2020; Kwee-Meier et al., 2017; Li et al., 2021; Liou and Chu, 2016; Liu and Luo, 2012; Liu et al., 2021; Lee et al., 2022a; Liu et al., 2022; Lozowicka, 2021; Łozowicka, 2005; Luo, 2019; Ma et al., 2020; Miyazaki et al., 2004; Murayama et al., 2000; Ng et al., 2021; Ni et al., 2017a, 2017b; Park et al., 2015; Qiao et al., 2014; Roh and Ha, 2013; Rutgersson and Tsychkova, 1999; Salem, 2016; Sarshar et al., 2014, 2013a; Sarvari et al., 2019; Spanos and Papanikolaou, 2014; Sun et al., 2020; Vanem and Skjong, 2006; Vilen, 2020; Wang and Wu, 2020a; Wang et al., 2013, 2022; P. Wang et al., 2020b; Wu et al., 2018; Xie et al., 2020a, 2020b, 2020c; Yuan et al., 2014; Yue et al., 2022)	Evacuation time optimization
(Bles et al., 2001; Brown et al., 2008; Brumley and Koss, 2000; Casareale et al., 2017; Chen et al., 2016; Chen and Lo, 2019; Cho et al., 2016; Ditlev Jorgensen and May, 2002; Fang et al., 2022a; Fukuchi and Imamura, 2005; Ha et al., 2012; Hu and Cai, 2022; Kim et al., 2019; K V Kostas et al., 2014; Lee et al., 2004; Łozowicka, 2010; Meyer-König et al., 2007, 2002; Na et al., 2019; Nevalainen et al., 2015; Ni et al., 2018; Park et al., 2004; Sarshar et al., 2013b; Sun et al., 2019, 2018a, 2018b; Vassalos et al., 2002; Vassalos et al., 2002; Walter et al., 2017; Wang et al., 2021b, 2021a, 2021c; Wang et al., 2020c; Zhang et al., 2017, 2016)	Passenger behavior understanding
(Couasnon et al., 2019; Guarin et al., 2014; Kim et al., 2004; Klüpfel et al., 2001; Konstantinos V Kostas et al., 2014a, 2014b; Montecchiari et al., 2021, 2018; Piñeiro et al., 2005; Ruponen et al., 2015; Vanem and Ellis, 2010; Yip et al., 2015)	Evacuation models description
(Brown, 2016; Deere et al., 2012; Finiti, 2021; Galea et al., 2011, 2014a, 2014b; Wang et al., 2014)	Data collection and validation

Appendix K. Case studies

Table K.1
List of case studies.

Paper	Emergency evacuation environment
Fang et al. (2022a)	•Training vessel "YUKUN" of Dalian Maritime University
Wang et al., (2022)	•Ro-Ro passenger ship "Yong Xing Dao"
Liu et al. (2022)	•Training vessel "YUKUN" of Dalian Maritime University
Xie et al. (2020c)	•3-storey passenger ship
Finiti (2021)	•Costa Concordia cruise ship
Wang et al. (2014)	•3-storey passenger ship
Balakhontceva et al. (2015)	•MS Costa Allegra cruise ship
Casareale et al. (2017)	•Costa Concordia ccccruise ship (Deck 4)
Chu et al. (2013)	•Ro-Ro passenger ferry (TAI WHA)
Liou and Chu (2016)	•Training ship (Yu-Ying No. 2)
(Brown, 2016)	•Ferry without/with cabins (RoPax ferry) and •Cruise ship

(*continued on next page*)

Table K.1 (*continued*)

Paper	Emergency evacuation environment
Liu et al. (2021)	•3-tier cruise ship
Vilen (2020)	•Ferry without/with cabins (RoPax ferry) and •Cruise ship
Sarvari et al. (2019)	•Ro-Ro ferryboat (Osman Gazi)
(Galea et al., 2013)	•Ferry without/with Cabins (Ro-Pax ferry) and •Cruise ship
Ditlev Jorgensen and May (2002)	•MS Kronprins Frederik Ro-Ro ferry vessel
Miyazaki et al. (2004)	•Ferryboat (Yuukari)
Ni et al. (2017b)	•Restaurant area in a passenger ship
Sun et al. (2020)	•Ferry without/with cabins (Ro-Pax ferry) and •Cruise ship
Wang et al., (2020b)	•An exhibition hall in a large cruise ship
Galea et al. (2014a)	•Large RO-Pax ferry
Gwynne et al. (2003)	•Passenger/tour boat
Spanos and Papanikolaou (2014)	•Ro-Ro ferry and •Panamax cruise ship
Galea et al. (2011)	•RO-Pax ferry super speed
Katuhara et al. (2003)	•Training ship (Seiun-maru)
Xie et al. (2020a)	•Two hypothetical main vertical zones of passenger ships
Balakhontceva et al. (2016)	•MS Costa Allegra cruise ship
Park et al. (2015)	•Large RO-Pax ferry
Roh and Ha (2013)	•Car ferry
Na et al. (2019)	•Ro-Pax cruise ship
Walter et al. (2017)	•Research vessel (Thomas G. Thompson)
Wang et al. (2021c)	•Ro-Ro passenger vessel
Wang et al., (2020c)	•Ro-Ro passenger vessel
Xie et al. (2020b)	•3-storey passenger ship
Murayama et al. (2000)	•Passenger ferry
Vassalos et al. (2002)	•Ro-Pax cruise ship
Galea et al. (2014b)	•Ferry without/with cabins (Ro-Pax ferry) and •Cruise ship
Deere et al. (2012)	•Ferry without/with cabins (Ro-Pax ferry) and •Cruise ship
Salem (2016)	•Ro-Ro passenger ship and •Cruise ship
Ruponen et al. (2015)	•Large passenger ship
Wang and Wu, (2020a)	•Ro-Ro passenger ship (MV Tai Hwa)
Ni et al. (2018)	•Deck 5 of a passenger ship
Kim et al. (2020)	•MV Sewol vehicle-passenger ferry
Ma et al. (2020)	•Passenger ship (Yangtze Gold 7)

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