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Passengers and Crew's Evacuation from Passenger Ships Under Fire: An Agent-Based Model Simulation Study

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Abstract

The characteristics of the passengers have a significant impact on how the evacuation procedures are carried out. During an evacuation, the amount of time it takes depends on how quickly passengers move. There is a correlation between age and travel speed, but not always. As a result of this problem, a significant number of passengers were unable to make it to the assembly point in time for the evacuation, which may have resulted in fatalities. An evacuation simulation will be carried out aboard passenger ships in the event of a fire. This research will employ agent-based modeling to perform the simulation, and it will include modifications for day and night, as well as for the number of emergency stairs used. The findings of this study are the simulation times for the evacuation of passengers and crew for each scenario, with the shortest time for evacuation occurring during the daytime with operational emergency stairs, clocking in at 36.51 minutes, and the longest time for evacuation occurring during the night with damaged emergency stairs, clocking in at 47.43 minutes. Both times are given in minutes. According to the findings, the evacuation circumstances satisfied the standards set by the IMO, which demanded that the entire amount of time spent evacuating be less than or equivalent to sixty minutes.

1. Introduction

As part of various community activities in Indonesia, sea transportation is a major means of transportation, including passenger ships and cargo ships. There are many risks associated with shipping. It is well known to all crews and shipping companies alike that human failures play a significant role in accidents. Even though shipping companies make every effort to make sure work safety is assured, they are not completely successful in eliminating human failures [1]. Around 80% of maritime accidents are caused by human error, according to several studies [2–5]. Since then, most studies on maritime accidents have concluded that human error is the primary cause of marine accidents [6].

Indonesia has experienced several marine accidents. According to data compiled by Indonesia's National Transportation Safety Committee (KNKT) in 2022, 13 separate cruise ship accidents occurred in the country that year. Five vessels (the Dumai Line 5, Belt Nusantara 91, Lit Enterprise, Mutiara Timur ships I, and Express Cantika 77) were involved in fires or explosions, accounting for 38 per cent of the total number of mishaps [7,8]. On June 8, 2022, a fire broke out on a ship operated by Dumai Line in Sekupang Port, Batam, affecting six people [9]. In North Sulawesi, a KM Prince Soya passenger ship recently caught fire at Nusantara Port, Pare-pare City, and emitted thick smoke. Passengers were evacuated safely with 200 on board [10]. Thus, evacuation analysis is regarded as one of the most important factors to consider when designing an evacuation route in the first place. Passengers' lives can be saved by evacuation as a last resort.

The characteristics of passengers have a crucial role in evacuation processes. The time required to evacuate a building is related to the average walking speed of its inhabitants. There is a difference in the charges paid to male and female passengers of the same age, depending on their gender. Due to this issue, a significant number of passengers could not reach the assembly point during the evacuation operation, increasing the number of wounded or dead [11]. The International Maritime Organization (IMO), responsible for maritime safety and security as well as the protection of marine pollution, has established evacuation analysis guidelines for new and current passenger ships. The IMO MSC 1238 specifies conventional running or walking speed passenger assumptions that may be utilized to analyze passenger evacuation [12].

The Fire Dynamic Simulator is a system for simulating fires onboard ships (FDS). According to Rinnie et al. [13], FDS can occasionally anticipate CO, CO^2, and O^2 smoke concentration simulations. When there are frequent fires, a person's walking pace is slowed due to behaviours like walking in a zigzag pattern and walking slowly near walls [14]. The higher the attention devoted to the smoke created by numerous fires, the slower the walking pace. The results of Rudianto, which aims to study and provide recommendations on evacuating a ship, indicating that the time necessary to evacuate the ship during the day runs from 32 to 48 minutes, while the time required at night goes from 35 to 48 minutes [15].

There might be differences in the characteristics of walking speed among Indonesians and people in other countries. Praditya et al. and Arfi et al. have conducted several studies pertaining to pedestrian evacuation in Indonesia [16, 17]. Based on IMO, the minimum speed of crossing male pedestrians under 30 years was 1.11 m/s, and a woman under 30 years was 0.93 m/s. Furthermore, the minimum rate for men between 30-50 years is 0.97 m/s, while for women aged between 30-50 years is 0.71 m/s [12].

Based on previous research and existing problems regarding the evacuation process on ships, this study will conduct an evacuation simulation on passenger ships when there is a fire relating to walking speed and passenger distribution using agent-based modeling with variations in the case of day and night and the number of emergency stairs used. Therefore, it is shown the importance of this study. The simulation results obtained in the form of the length of the evacuation process will be validated based on the regulations from IMO as a standard of safety.

2. Methods

The method in this study is to simulate the evacuation process on passenger ships by entering related data that will be needed and performing simulations to show the conditions and time required to save all agents, both ferries and crew members, in the event of a fire on board. Problem identification and data collection of walking speed will be performed through field observations; a model will be developed for passenger evacuation, and a conclusion will be made. This study focused on identifying problems related to the realization of research, such as observing, measuring, and modelling the evacuation. The research's second step was modelling passenger evacuation using an Agent-Based Model (ABM) and a Fire Dynamic System (FDS) to analyze fire control and smoke dissipation in various structures for fire safety or investigation [18], [19]. Several earlier research [11], [16–18], [20] have used an Agent-Based Model to simulate harsh situations during an evacuation with excellent outcomes because ABM can comprehend pedestrian egress and congestion threats for fire prevention and safety.

Data collection is done by seeking information through the agency related to the specified ship, namely PT Citra Bahari Shipyard, located in Tegal City, Indonesia, which is one of the companies engaged in marine transportation on a national scale. The ship used for this research object is the 750 DWT pioneer ship. The ship sails through the Tarakan route in North Kalimantan – Paleleh Port in Buol and Toli-Toli in Central Sulawesi – Kwandang Port in Gorontalo (or vice versa), Indonesia. The ship model used in this study is a 750 DWT passenger ship with a total number of passengers and a crew is 285 people. The main size details can be seen in Table 1.

Table 1. Small Fishing Hull Specification

Dimension	Value
LOA	58.50 m
LPP	52.30 m
B	12.00 m
D	4.50 m
T	2.90 m
Velocity Service	12knot

The hybrid (PV/ Gasoline) model is to be described by simulation. Small fishing hull is the object in this study that has specification as Table 1. Specification and power requirement calculation are generally discussed on [9]. Solar panels were installed as hull rooftops, as shown in Figure 1.

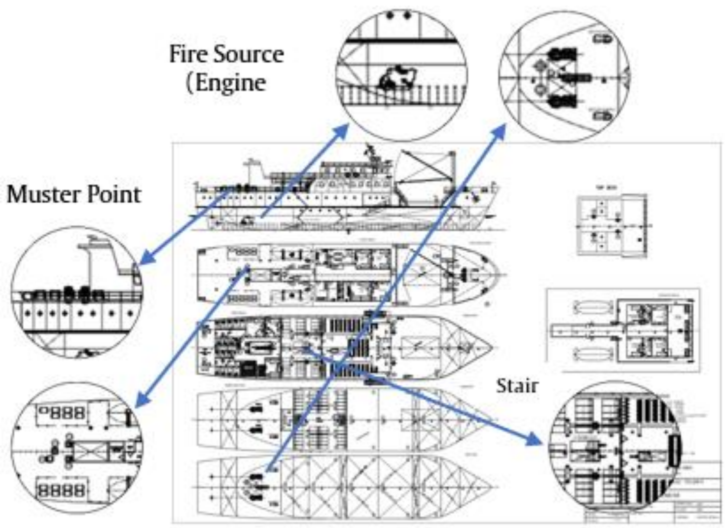


Figure 1. General arrangement of passenger ships used in the simulation in this study

It is well known that the IMO has set assessment requirements for the evacuation procedure, and these standards may be found in the document titled IMO MSC.1/Circ.1238 [2]. According to IMO MSC.1/Circ.1238, the performance standard for evacuation time on Ro-Ro passenger ships is n = 60; for passenger ships other than RoRo passenger ships, it is n = 60, and if the ship has no more than three main vertical zones; and n = 80 if the vessel has more than three main vertical zones [15]. n = 80 is the performance standard for evacuation time on passenger ships that have more than three main vertical zones. Guidelines for Evacuation Analysis for Passenger Ships, Both New and Existing IMO (International Maritime Organization), has stated the findings of his investigation on the pace at which people walk, as seen in Table 2 and Table 3 [12].

Table 1. Data on walking speed of ship passengers and

Population-Passenger Group		Walking Speed on Flat Terrain based on IMO		Passenger Percentage (%)	Number of Passengers (person)
		Min (m/s)	Max (m/s)		
Female	<30 y.o	0.93	1.55	7	20
	30-50 y.o	0.71	1.19	7	20
	> 50 y.o	0.56	0.94	16	46
	>50 y.o, impaired mobility (1)	0.43	0.71	10	28
	>50 y.o, impaired mobility (2)	0.37	0.61	10	28
Male	<30 y.o	1.11	1.85	7	20
	30-50 y.o	0.97	1.62	7	20
	> 50 y.o	0.84	1.4	16	46
	>50 y.o, impaired mobility (1)	0.64	1.06	10	28
	>50 y.o, impaired mobility (2)	0.55	0.91	10	29

The simulation modelling stage has been divided into several scenarios using software assistance, namely the simulation of evacuation, fire, sinking, and the capsizing of a ship resulting from a ship running aground. The analysis and discussion results contain the final part that achieves the research results or the conclusion obtained in research with the goals set at the beginning. The final result is obtained from data analysis with objects and situations carried out and the IMO MSC.1/Circ.1238 standard with the existing safety plan design with the condition of the ship being on fire until it capsized.

Table 3 population of passengers and crew on board passenger ships

Population-Crew Group	Walking Speed on Flat Terrain based on IMO		Passenger Percentage (%)	Number of Crew (person)
	Min (m/s)	Min (m/s)		
Female crew	0.93	1.55	50	12
Male crew	1.11	1.85	50	13
Overall Total (Passengers and Crew)				310

In this study, there were four variations of the simulation conditions carried out, namely the simulation of case I with case II, which had stairs in normal conditions, for the time in case 1, namely at night, and case II during the day, then there was case III with case IV which had the condition the stairs are damaged and the time for case III is at night and case IV is during the day.

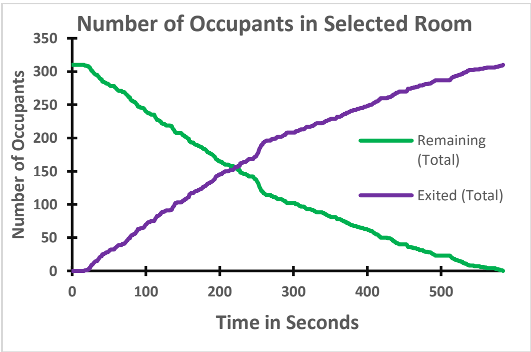
Table 4. Variation of evacuation simulation case conditions

Item	Time	Emergency Stair Condition
Case I	Night	All Available
Case II	Day	All Available
Case III	Night	One not working
Case IV	Day	One not working

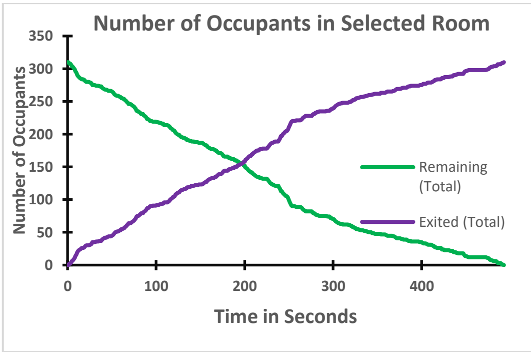
3. Results and Discussion

3.1. Simulation

The evacuation simulation that will be carried out in this study is based on four pre-determined cases. Each case will be simulated from these cases according to the identification on a case-by-case basis. Evacuation simulation in this study uses Agent-Based Modelling Simulation-based modeling pathfinder software. This evacuation simulation is based on IMO MCS.1/Circ.1238 with a full load condition. This evacuation simulation process produces an output in the form of a total travel time (T) value. For each case in this study, one evacuation simulation modelling will be made, the results of which can be seen in Figure 2.



(a)



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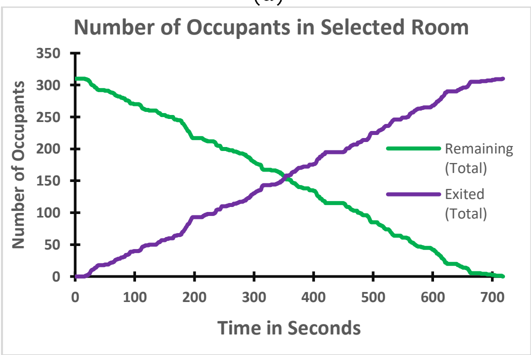

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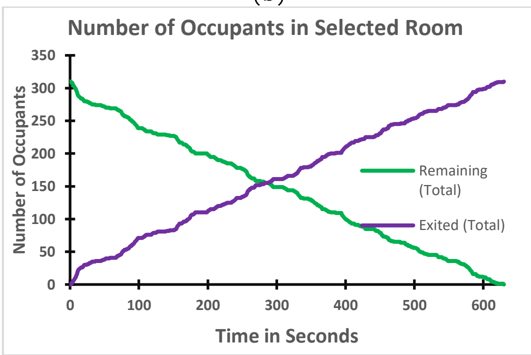
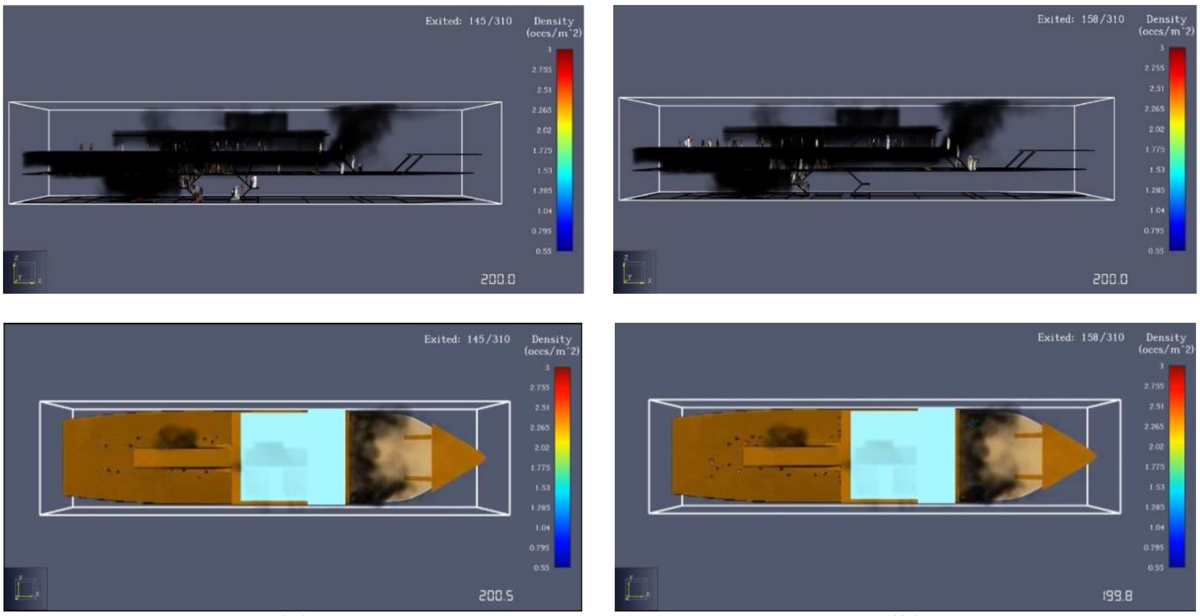


(d)

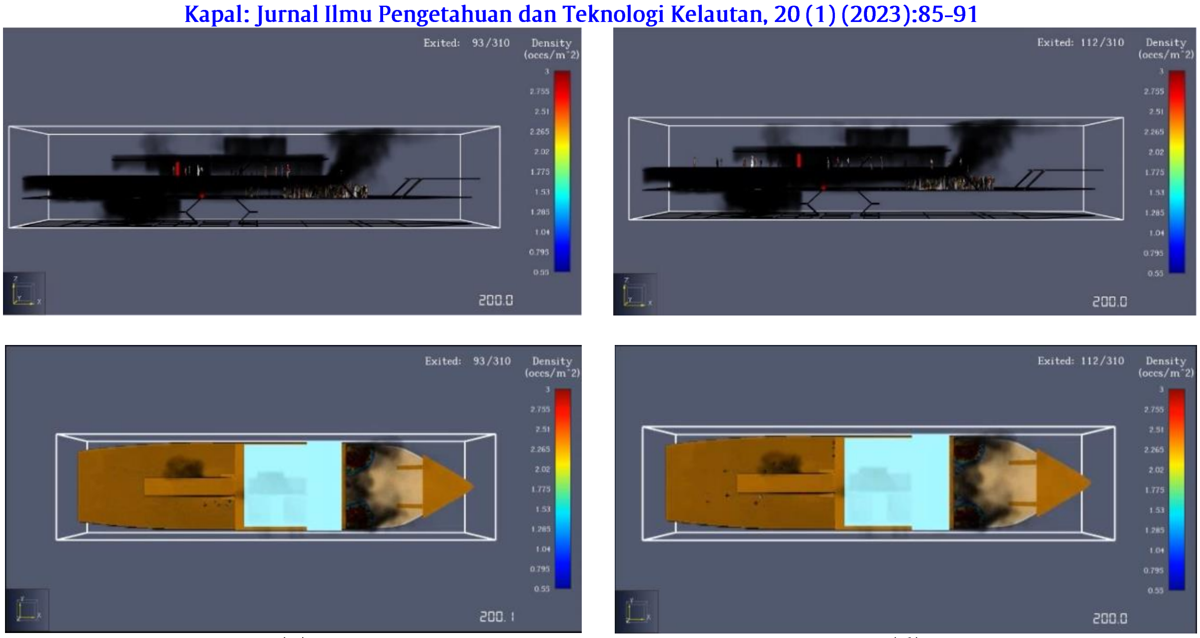
Figure 1. Evacuation Simulation results in the form of a graph of the function of the total number of passengers against the evacuation time in several cases where (a) in case I, (b) is case II, (c) in case III, and (d) in case IV

Figure 2 (a)-2(d) is a graph of the function of the total number of passengers against the evacuation time where the green line (Remaining) in the picture is the number of passengers still in the room and the purple line (Exited) in the picture is the number of passengers. Who had managed to evacuate themselves out of the room to the muster point. Based on the simulation results of the evacuation time in Figure 2(a)-2(d), at night conditions with emergency stairs functioning normally (Figure 2(a)), all agents, both passengers and crew members, can reach the evacuation end point in time (T) 583.5 seconds. While in Figure 2(b), namely Daytime Time and Normal Stair Conditions, all agents, passengers, and crew, can reach the evacuation endpoint in (T) 492.8 seconds. For scenarios of fires that occur at night and during the day with the condition that the emergency stairs are not functioning, as shown in Figures 2(c) and 2(d), it takes 717 seconds and 629.5 seconds, respectively.

The picture below compares the evacuation process between conditions with the fastest evacuation time, Case II, where Daytime Time and Stairs Conditions work well, with the longest evacuation time, and Case III, where Night Time and Conditions fail on one of the emergency stairs



(a) (b)



(c) (d)

Figure 2. The evacuation simulation process in cases I to IV is sequentially shown from above and sides in Figures (a) to (d) at the 200-second condition

It can be seen in Figure 3 that the comparison between Case II and Case III shows that in Figures 3(b) and 3(c), at 200 seconds for the normal staircase case, the number of passengers who were successfully evacuated amounted to 158 out of a total of 310 people, while in the case of a failure in one of the emergency stairs only 93 out of 310 people with a passenger density of +maximum $3m^2$, 40% lower than optimal conditions. Even so, the time required for the evacuation process is still below the standard set by IMO, which is less than 60 minutes. The results seen from all the images in figure 3 follow several previous studies where time affects the behaviour of passengers during evacuation [11, 21].

3.2. Calculation of Total Evacuation Duration

Performance standards published by IMO MSC.1/Circ.1238 are as seen in Figure 4. Where T is the total evacuation simulation time, $E + L$ is a maximum of 30 minutes according to SOLAS Regulation III/21.14, and $E + L/3$ is the overlap time. The time required for passengers and crew as a whole or the total travel time (T) to change positions from where they are to the final point of evacuation. After obtaining the value of the travel time (T), which is the result of the evacuation simulation, then it needs to be recalculated using the standard performance formula as follows:

$$1{,}25(A + T) + \frac{2}{3}(E + L) \leq 60\ minute \qquad (1)$$
$$(E + L) \leq 30\ minute$$

In the above formula, A is awareness time, T is travel time, and E and L are Embarkation and Launching time, respectively. Calculations using the above procedure must be carried out to produce a total evacuation duration value. This value will be analyzed to determine whether it meets the IMO MSC.1/Circ.1238 performance standards.

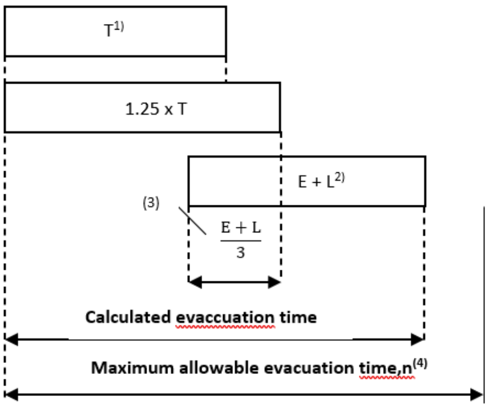


Figure 4. Standard Perform IMO MSC.1/Circ.1238

An example of the calculation in case 1, the evacuation simulation, produces a T value of 583.5 seconds, equivalent to 9,725 minutes. After obtaining the T value, then the next step is to enter the T value into the standard performance formula with the value of awareness duration (A) as follows:

Table 5. Calculation Results of Total Evacuation Duration

Evacuation Condition	Total Evacuation Duration (minute)	
	Working Emergency Stairs	One emergency stair is not working
Night Time	44,656	47,438
Day Time	36,517	39,365

3.3. Validation of Simulation Calculation Results

Validation is a measurement in a research test or proof of the truth of data obtained. According to IMO's Interim Guidelines MSC/Circ. 1238, it is explained that in the evacuation system, a minimum ship using four scenarios, namely Case I (night) and Case II (day), is the primary evacuation case, and Case III (night) and Case IV (day) are secondary evacuation case [12]. The error results are obtained from the largest Total Travel Time, where the largest overall time is on the main deck, which is then reduced by the pathfinder travel time. It can be seen in Table 6 the validation results for each case in this study with an error proportion ranging from 2% - 9% for all cases, this value has the same trend of time needed to extract according to previous research [20]

Table 6. Comparison of Total Travel Time from software simulation with an approach based on the IMO formula

Case	Total Travel Time (sec)	Travel Time Pathfinder (sec)	Percentage Error (%)
I	527.7	583.5	9.56
II	514.0	492.8	4.30
III	701.9	717	2.11
IV	701.9	629.5	8.44

4. Conclusion

In this research, an Agent-Based Model (ABM) and Fire Dynamic System (FDS) were used to simulate the evacuation of cruise ship passengers utilizing a variety of scenarios, including those with staircases in both normal and damaged states, both at night and during the day. Based on the outcomes of the simulation of the evacuation and the analysis of the overall time of the evacuation that has been carried out, as well as the information provided in IMO MSC.1/Circ.1238. In this research, The characteristics of the ship's passengers and crew regarding walking speed can be grouped based on the age and physical condition of each passenger, while the characteristics of the crew members have been determined according to the standards in IMO MSC.1/Circ.1533. The longest evacuation simulation time for passengers and crew members was 47,438 minutes in case 3 where the evacuation occurred at night and one connecting ladder between decks was not working, and the fastest was 36,517 minutes in case 2 where the evacuation occurred during the day, and all connecting ladders were working. Maximum evacuation time in each scenario that has been studied based on IMO MSC.1/Circ.1238 with a total evacuation time for passenger boats of 750 DWT within 60 minutes

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