Journal of Marine Science and Technology

Volume 24 | Issue 3 Article 12

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Recommended Citation
Cho, Yoon-Ok; Ha, Sol; and Park, Kwang-Phil (2016) "VELOCITY-BASED EGRESS MODEL FOR THE ANALYSIS OF EVACUATION PROCESS ON PASSENGER SHIPS," *Journal of Marine Science and Technology*: Vol. 24: Iss. 3, Article 12.
DOI: 10.6119/JMST-015-1012-1
Available at: https://jmstt.ntou.edu.tw/journal/vol24/iss3/12

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Acknowledgements

This work was partially supported by (a) Daewoo Shipbuilding and Marine Engineering Co., Ltd., (b) the Human Resource Training Program for Regional Innovation and Creativity through the Ministry of Education and National Research Foundation of Korea (2014H1C1 A1073060), and (c) the MKE through the fostering project of Daebul IndustryUniversity Convergence, Mokpo National University, Korea.

Journal of Marine Science and Technology, Vol. 24, No. 3, pp. 466-483 (2016)
DOI: 10.6119/JMST-015-1012-1

VELOCITY-BASED EGRESS MODEL FOR THE ANALYSIS OF EVACUATION PROCESS ON PASSENGER SHIPS

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Key words: evacuation analysis, passenger ship, velocity-based egress model, human behavior.

ABSTRACT

This study presents a velocity-based egress model, which takes into account different aspects of human behavior in an emergency situation, for the evacuation analysis on passenger ships. It was supposed that the egress model consists of three behaviors: individual, crowd, and emergency behavior. The individual behavior was represented by the body shape, walking speed, walking direction, and rotation of each passenger. The basic walking direction of each passenger was obtained as a solution to the shortest distance route to a destination using a visibility graph. The crowd behavior of the passengers was composed of two components: one is a flock behavior, a form of collective behavior of a large number of interacting passengers with a common group objective, and the other is a leader-following behavior, which causes one or more passengers to follow another moving passenger who is designated as the leader. The emergency behavior of the passengers was represented by a counterflow-avoiding behavior to avoid collision with other passengers walking in the opposite direction. Eleven basic tests and 2 examples specified in International Maritime Organization Maritime Safety Committee/Circulation 1238 were conducted, and it was confirmed that all the requirements of such tests had been met.

I. INTRODUCTION

1. Research Background

The Titanic was the largest passenger ship in the world when she set off on her maiden voyage from Southampton to New York City on 10 April 1912. At 11:40 p.m. on the fourth day of her crossing, she struck a huge iceberg and sank at 2:20 the following morning. The accident resulted in the deaths of 1,513 people, one of the deadliest catastrophes in history. No one could have imagined that such a huge ship - 269 meters long, 28 meters wide, 53.3 meters high, and 10.5 meters draft - would ever sink. Many unfortunate factors, especially an insufficient number of life-saving appliances (LSAs) made the accident all the more tragic. Following the disaster, the International Conference on the Safety of Life at Sea (SOLAS) was established. SOLAS specifically addressed this issue by the adoption of a new regulation stating that all escape routes onboard should be evaluated early in the design stage.

The ro-ro (roll-on/roll-off) passenger ship Estonia sank in the Baltic Sea on 28 September 1994, resulting in the deaths of 852 people. The ro-ro passenger ship is vessels designed to carry wheeled cargo, such as automobiles, trucks, semi-trailer trucks, and trailers, which are driven on and off the ship on their own wheels or using a platform vehicle, such as a self-propelled modular transporter. In the wake of the Estonia tragedy, evacuation was carefully considered and the International Maritime Organization (IMO)'s Maritime Safety Committee (MSC) promulgated a regulation in 1995 requiring ro-ro passenger ship to undertake an analysis early in the design stage in order to identify and solve the potential critical points in the escape routes and life-saving appliances by design. In January 1999, the MSC of the IMO developed guidelines for the evacuation analysis. However, recognizing that a very limited experience and data were available on the matter, the MSC considered these guidelines as "interim" for their improvements and further development. The latest set of guidelines produced is the IMO MSC/Circulation 1238 (Circ. 1238), Guidelines for evacuation analysis for new and existing passenger ships; its latest revision was in 2007 (IMO, 2007). Both regulations regarding passenger evacuation, "Means of Escape" from SOLAS and "Evacuation Analysis" from IMO MSC/Circ. 1238, must be executed. Each regulation is summarized in Fig. 1. Both regulations will be discussed in detail after reviewing the stages of passenger evacuation.

In accordance with the International Maritime Organization (IMO) Maritime Safety Committee (MSC)'s Circulation 1238

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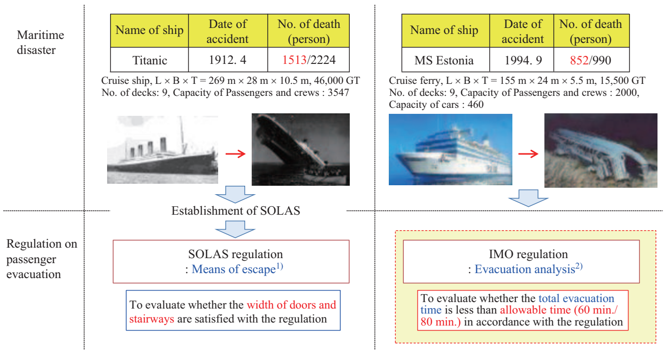


Fig. 1. Establishment of regulations on passenger evacuation.

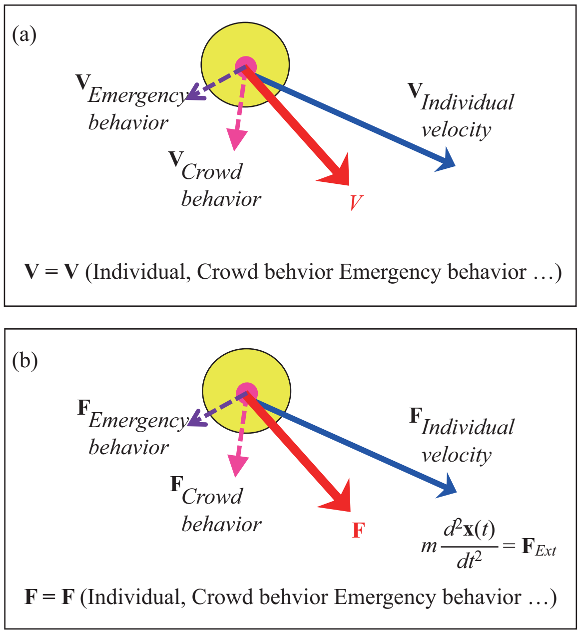


Fig. 2. Passenger behavior models: (a) velocity-based model and (b) acceleration-based model.

(Circ. 1238), entitled "Guidelines for Evacuation Analysis for New and Existing Passenger Ships," a mandatory regulation issued by the IMO, evacuation analysis should be performed for all passenger ships. The purpose of this regulation is meant to determine if the total evacuation time for a vessel is less than the allowable time according to the regulation. The maximum allowable time is 60 minutes for ro-ro passenger ships and 80 minutes for passenger ships.

The guidelines offer the possibility of using two distinct methods for evacuation analysis: A *simplified evacuation analysis* and an *advanced evacuation analysis*. The former is a deterministic method in which the total evacuation time is calculated through a simple hydraulic scheme by considering that all passengers have identical characteristics. The total evacuation time can be calculated using a simple formula provided by the IMO, and the results should be submitted to ship owner and classification society. An advanced evacuation analysis, on the other hand, is a stochastic method in which the total evacuation time is estimated through microscopic approach "by considering each characteristic of every passenger. In this analysis method, the total evacuation time is estimated via computer-based simulations representing each passenger and the detailed layout of the vessel. An advanced evacuation analysis is currently not mandatory, but it is expected to be required in the future. Thus, a study on an advanced evacuation analysis is carried out in this paper.

The remainder of this paper is as follows. Rest of this section reviews previous works related to this study. In Section 2, an evacuation sequence and its regulations in a passenger ship are introduced. Section 3 explains passenger behavior in an emergency used in this study. Its applications and the simulation results follow in Section 4. The last section summarizes this study and briefly discusses the next study.

2. Related Works

The main object of the simulation program for evacuation analysis in emergency situations is the evacuation from buildings (Tomomatsu et al., 2001); evacuation programs for ships have been in development since early 2000. For the purpose of simulating evacuation situations, it is important to comprehend the factors affecting passenger behavior, and to consist of the passenger behavior model with considering those factors. The egress model considering passenger behavior is the most important part of the evacuation program (Kim et al., 2001).

According to the method to consider the movement of each person, the egress model is divided into three categories; a continuous network model, a coarse network model, and a fine network model (Kuligowski and Peacock, 2005). A continuous network model applies a 2D (continuous) space to the floor plans of the structure, allowing the occupants to walk from one point in space to another throughout the space. A fine network model divides a floor plan into a number of small grid cells that the occupants move to and from. The coarse network models divide the floor plan into rooms, corridors, stair sections, etc. and the occupants move from one room to another. Fine and continuous networks have the ability to simulate the presence of obstacles and barriers in spaces that influence individual path route choice, whereas the coarse networks move occupants only from one portion of a space to another. Compared to the fine network model, the continuous network model represents the position of each person much precisely, but it consumes more computational time than the fine network model. In this paper, the continuous networks are chosen to represent the exact position of each passenger.

In the range of the continuous networks, the egress model is divided into two categories according to the consideration of the factors affecting passenger behavior. The velocity-based model considers passenger behaviors as walking velocities, whereas the acceleration-based model considers the passenger behaviors as the motion of the particle or rigid body affected by external forces. Two kinds of the passenger behavior model are shown in Fig. 2.

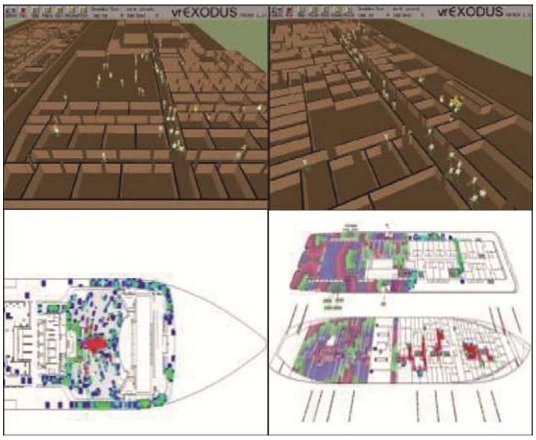


Fig. 3. maritimeEXODUS.

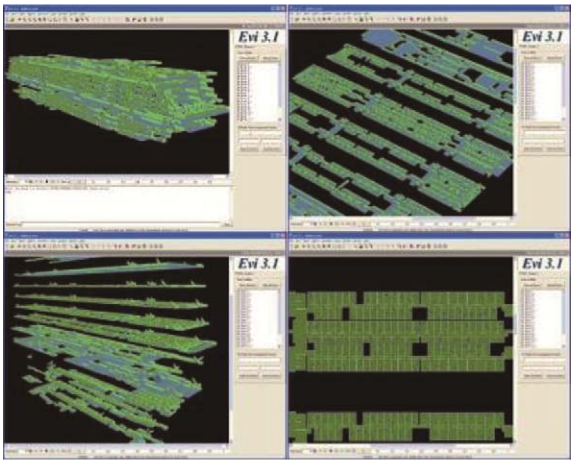


Fig. 4. EVacuation Index (EVi).

"maritimeEXODUS", shown in Fig. 3, is a commercial software for the evacuation analysis on passenger ships using the velocity-based egress model (Galea and Perez Galparsoro, 1994; Gwynne et al., 2003). The geometries of the spaces such as spaces and obstacles are represented based on discrete cells, which are occupied by individuals or regions with other environmental attributes. The default route is determined by the potential map (marking 0 as the exit and all other nodes as higher number the further away the node is from the exit), which leads passenger to the nearest available exit. The passengers always move onto a cell with a lower potential than the one they are presently occupying. Interactions between passengers are represented based on rules, probabilities and the emptiness of the cell around their position. The effects of the ship's attitude are reflected in the program as a reduction factor over the normal movement rates at of heel, but the body size and rotation of the passengers are not considered.

A commercial software "EVacuation Index (EVi)", shown in Fig. 4, is a software tool used to simulate pedestrian movement in any environment (Guarin et al., 2004; Vassalos et al., 2001). It has been used extensively to model circulation and evacuation of persons from ships, offshore structures and buildings. The egress model in EVi is based on velocity. The geometries of target environment are modeled based on continuous coordinates, with passengers moving on the continuous spaces. The walking direction of passengers is determined along the shortest distance route in a graph connecting each destination to each door, and the interaction between passengers is represented by the reduction factor for walking speed according to the population density in the region. The effect of the ship heeling angle is included in walking speed of passenger by reduction factor which is calculated by analytically derived function. But the rotation of the passengers is not considered because the passengers are represented as circles.

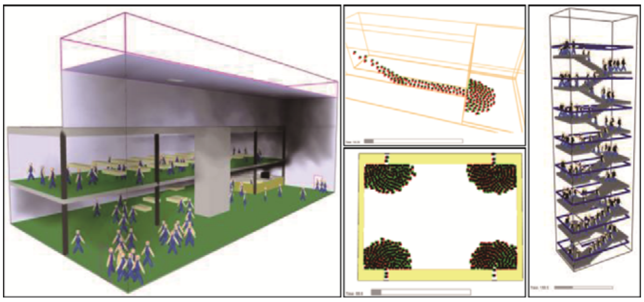


Fig. 5. FDS + Evac.

"FDS + Evac", shown in Fig. 5, is the evacuation simulation module for Fire Dynamics Simulator (FDS). The software is used to simulate the movement of people in evacuation situations. This software adopted the acceleration-based egress model (Korhonen and Hostikka, 2009; Heliövaara et al., 2012), and also considered the social forces suggested by Helbing et al. (2000, 2002). The geometries of the space are modeled based on continuous coordinates, and the walking direction is determined by a flow field which is made by placing a virtual exhaust fan at the exit door and sucking virtual fluid out of the domain; the direction which the fluid takes creates a flow field. Interactions between passengers are modeled by external forces, considering physical and psychological effects. Although the rotation of the passengers is considered in FDS + Evac, the effect of the attitude of the ship is not included.

In this study, a velocity-based egress model is suggested with modeling spaces based on continuous coordinates. Walking direction is pre-determined and stored in the basic walking direction grid, which is decided by using a visibility graph. Interactions between passengers are modeled based on flock algorithms, and realistic body shapes and the rotational of passengers are also considered. Related works described above are summarized and compared with this study in Table 1.

II. INTRODUCTION TO EVACUATION IN A PASSENGER SHIP

1. Stages of Evacuation

The passenger evacuation steps specified in IMO MSC/Circ. 1238 go through several stages, and each stage is covered se-

Table 1. Related works.

	This study	maritime EXODUS	EVi	FDS+Evac
Egress model	Velocity-based	Velocity-based	Velocity-based	Acceleration-based
Geometry Representation	Continuous network	Fine network (Discrete cell)	Continuous network	Continuous network
Determination of Walking Direction	Basic walking direction grid (by visibility graph)	Potential of grid	Shortest path to nearest destination (graph)	Flow field
Movement Model	Inter-person Distance (Flocking Algorithm)	Potential, Emptiness of next grid cell	Density correlation	Equation of motion
Leader-Following Behavior	O	O	O	△[1)]
Counterflow-Avoiding Behavior	O	△[2)]	△[2)]	O
Body Shape	O	X	X	O
Rotation of Passenger	O	X	X	O

1) In FDS + Evac, it contains a group behavior, not a leader-following behavior.
2) Different counterflow - avoiding behavior is applied. Passengers exchange their position with the neighbor in front of them.

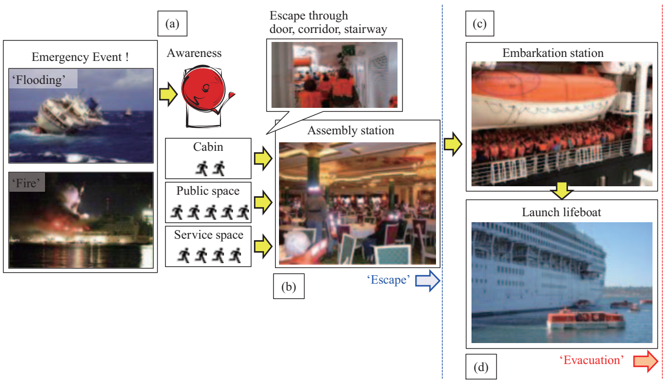


Fig. 6. Summary of stages of passenger evacuation.

quentially (Schreckenberg and Sharma, 2002). Among the stages of passenger evacuation, gathering in assembly stations for an evacuation is called "escape," and finishing the evacuation by launching lifeboats is called "evacuation" as shown in Fig. 6. In this section, each step of the evacuation shown in Fig. 6 are noted in detail.

If an accident such as flooding or fire happens, the alarm goes off and passengers recognize the emergency situations, and they are ready to escape as shown in Fig. 6(a). At this moment, some of the crews are posted at strategic position to guide passengers in preparation for a possible emergency situation. When the emergency situation happens, the captain should determine whether muster the passenger or not. When the captain has decided to muster the passengers, the alarm will be activated and public address (PA) announcements will inform passengers and crew about the situation. Being warned by an announcement, passengers begin to leave their cabins and walk along the marked escape ways to pre-defined assembly stations, where the crew will support them in wearing their life vests and guiding them to the assembly stations as shown in Fig. 6(b). Some of the crews systematically search the cabins to find passengers who are still in the cabin.

Passengers are guided by crew to move to assembly stations. After all passengers have been gathered in assembly stations, the crew distributes additional life jackets to passengers and assigns the passengers to life boats. If the situation deteriorates, the captain of the ship gives the command to abandon ship after deciding that the ship cannot be saved. Then embarkation of the lifeboats will be started. Passengers move to embarkation stations, following the crew's instructions, as shown in Fig. 6(c). Passengers arriving at embarkation stations board life boats according to priority, and finish evacuating by launching the life boat as shown in Fig. 6(d).

Actual evacuation stages can be more complex than described above. For example, life jackets usually are stocked in each cabin for the purpose of space-saving, so passengers who do not wear life jackets must return to their cabin. When passengers who have to return to their cabins to get their life jackets encounter passengers who already have their life jackets, there can be massive confusion. Even though multiple scenarios are possible, only the evacuation scenarios specified in the IMO regulations are considered.

2. Regulations of Evacuation Analysis

Evacuation analysis is a process for calculating evacuation time, confirming that the total evacuation time is less than the allowable evacuation time, and identifying congestion points throughout the escape route. The guidelines, IMO MSC/Circ. 1238, offer the possibility of using two distinct methods for evacuation analysis. A simplified evacuation analysis, is a deterministic method that the total evacuation time is calculated through a simple hydraulic scheme by considering that all passengers have identical characteristics. The total evacuation

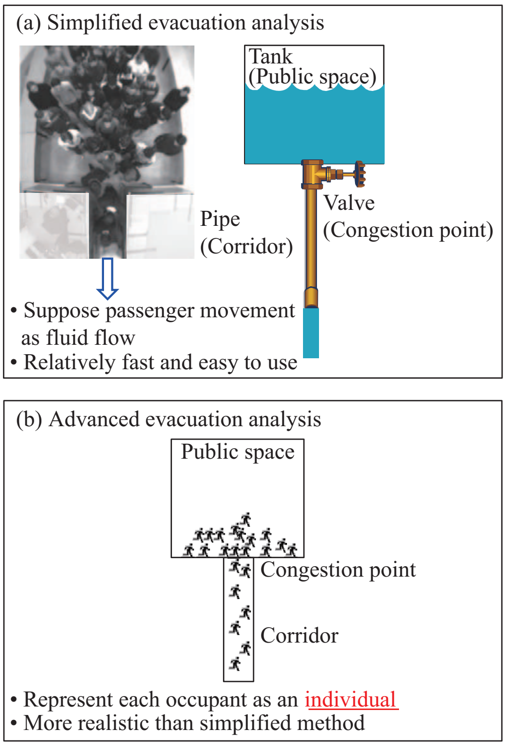


Fig. 7. Passenger evacuation methods.

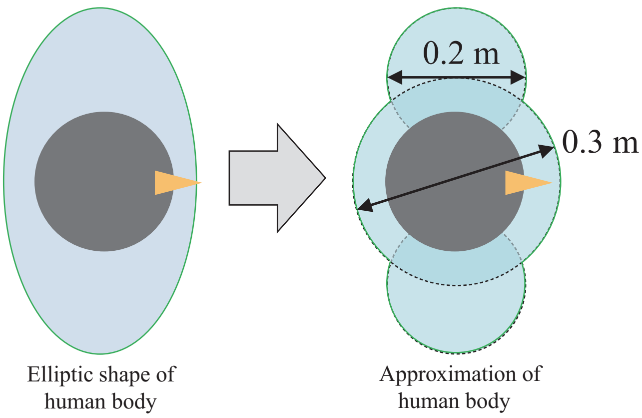


Fig. 8. Approximation of the elliptical shape of the human body.

time can be calculated by a simple formula provided by the IMO. An advanced evacuation analysis is a stochastic method that the total evacuation time is estimated through microscopic approach by considering each characteristic of every passenger. Total evacuation time in an advanced evacuation analysis is estimated by computer-based simulations that represent each passenger and the detailed layout of the vessel. The characteristic of each method is represented in Fig. 7.

An advanced evacuation analysis considers each characteristic of a passenger when estimating evacuation time. Because a lot of passenger characteristics are considered through the analysis, the total evacuation time in an advanced evacuation analysis is calculated by the computer-based simulation that represents each passenger and ship layout. In the regulation of IMO MSC/Circ.1238 ANNEX 1, the total evacuation time in an evacuation analysis is defined as

$$1.25(A+T)+\frac{2}{3}(E+L)\leq n \text{ and } E+L\leq 30. \qquad (1)$$

where A is awareness time, T is travel time, E is embarkation time, L is launching time, and n is allowable evacuation time (See Fig. 8).

Awareness time (A) is the time it takes for people to react to a situation. This time begins at the initial notification of an emergency (e.g., alarms) and ends when passengers have begun to move towards an assembly station. A satisfactory time during the day is five minutes, and ten minutes at night. *Travel time* (T) is the time it takes for all persons on board to move from where they are at notification to assembly stations and then to embarkation stations. *Embarkation and launching time* ($E + L$) is the time required for abandonment using the total number of persons on board. *Allowable evacuation time* (n) is the upper limit of total evacuation time according to the type of passenger ships. Allowable evacuation time of ro-ro passenger ships are allotted 60 minutes and that of passenger ships other than ro-ro passenger ships are allotted 80 minutes if the ship has more than three main vertical zones (only 60 minutes are allotted if the ship has no more than three main vertical zones).

Both the awareness and traveling time are included in traveling time (T) in an advanced evacuation analysis. And the evacuation time is estimated by a computer-based simulation using advanced evacuation analysis. This means that each passenger has different characteristics and awareness times that must be accounted for in order to simulate the traveling time from their initial position to the assembly stations.

III. PASSENGER BEHAVIOR IN EMERGENCY

This study proposes the passenger behavior according to velocity-based model, which takes into account for different aspects of human behavior in emergency situation. In this study, passenger behavior model consists of three components: individual behavior, crowd behavior, and emergency behavior. The following assumptions are made regarding the passenger behavior model:

1. Each behavior is modeled as the factors affecting passenger velocity (velocity-based model).
2. Passenger behavior is represented based on two-dimensional motions.
3. Geometry is represented by two-dimensional polygons on continuous coordinates.

Based on these assumptions, individual behavior, crowd behavior, and emergency behavior are modeled. Each behavior is expressed as a velocity vector. To express the behavior of each passenger, they are summarized with weight factors, so a

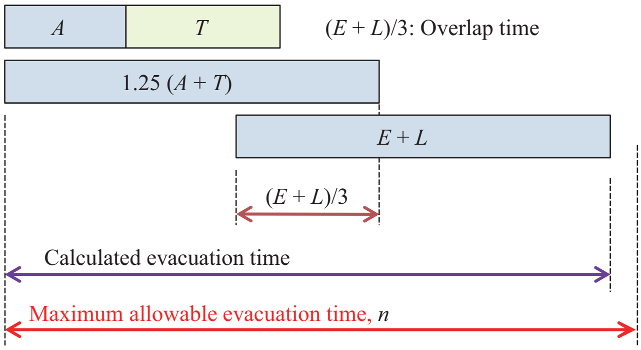


Fig. 9. Total evacuation time in an evacuation analysis.

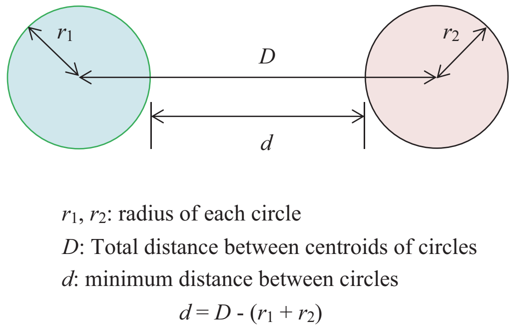


Fig. 10. Calculation of the minimum distance between two circles.

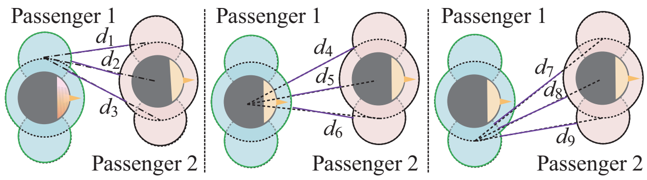


Fig. 11. Example of the inter-person distance between two bodies.

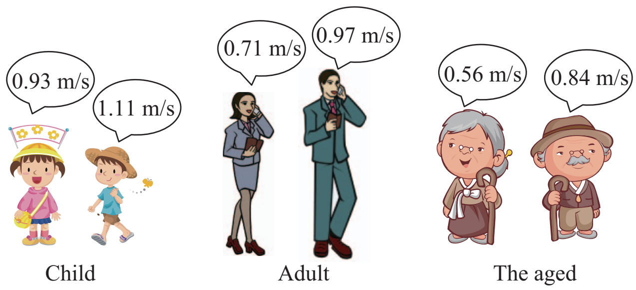


Fig. 12. Examples of walking speed according to age and gender.

final velocity vector represents current behavior of each passenger every moment.

1. Individual Behavior

We model individual behavior by sequentially defining the body shape, walking speed, walking direction and rotation of a passenger. Body shape is defined before describing and representing passenger behavior. To represent the passenger behavior using a velocity-based model, the individual walking velocity will have to be determined. The walking velocity of a passenger consists of walking speed (v_w) and basic walking direction ($\mathbf{u}_0$), as in the following Eq. (2). The rotation of passengers is changed toward the basic walking direction of the passengers.

$$\mathbf{v} = v_w \cdot \mathbf{u}_0 \tag{2}$$

The individual behavior does not consider any interaction between oneself and other passengers nearby. This behavior only deals how to escape to the final destination, i.e. an assembly station, as soon as possible. The interaction with other passengers nearby will be considered by a crowd behavior in the following subsection.

1) Body Shape

Each passenger in the model is represented by three overlapping circles at a position (x, y) at time t. These circles approximate the elliptical shape of the human body, which is similar to one used by Thompson and Marchant (1995a, 1995b), Langston et al. (2006), Singh et al. (2009), and Smith et al. (2009) as shown in Fig. 9. The body dimension is determined by the stochastic data of the passengers referred to by Thompson and Marchant (1995a, 1995b) and Heliövaara et al. (2012).

The use of an elliptical form gives rise to very complex calculations when calculating the distance between two bodies. The "three-circle body" is used for approximately representing the human body, because such body uses very simple calculation principles to assess the interperson distance. The assignment begins by calculating the nine distances between the two sets of three circles, representing the bodies. For two circles, the "minimum distance" is defined as the total distance between the circle centroids minus the sum of the two-circle radius, as shown in Fig. 10. The "interperson distance" is the minimum distance, which represents the smallest distance between the envelopes of the two bodies. An example of the calculation of the nine distances between two sets of three circles is shown in Fig. 11. The interperson distance was used in this study for applying the separation and counterflow-avoiding behaviors, which will be discussed in the next section.

2) Walking Speed

Individuals of varying age and gender may also vary in the walking speed as shown in Fig. 12, other passenger and the environment also have an effect on the walking speed. In addition to those, the walking speed often has relation to whether or not an individual is disabled or impaired. In this study, walking speed according to age and gender, which is recommended by IMO MSC/Circ. 1238, is applied for each passenger. Walking speed according to age and gender is listed in Table 2 to Table 3, and walking speed is different according to age in the case of the crew.

Table 2. Walking speeds on stairs in IMO MSC/Circ. 1238 according to age and gender.

Population groups - passengers	Walking speed on stairs (m/s)			
	Stairs down		Stairs up	
	Min.	Max.	Min.	Max.
Females younger than 30 years	0.56	0.94	0.47	0.79
Females 30-50 years old	0.49	0.81	0.44	0.74
Females older than 50 years	0.45	0.75	0.37	0.61
Females older than 50, mobility impaired (1)	0.34	0.56	0.28	0.46
Females older than 50, mobility impaired (2)	0.29	0.49	0.23	0.39
Males younger than 30 years	0.76	1.26	0.5	0.84
Males 30-50 years old	0.64	1.07	0.47	0.79
Males older than 50 years	0.5	0.84	0.38	0.64
Males older than 50, mobility impaired (1)	0.38	0.64	0.29	0.49
Males older than 50, mobility impaired (2)	0.33	0.55	0.25	0.41
Population groups - crew	Walking speed on stairs (m/s)			
	Stairs down		Stairs up	
	Min.	Max.	Min.	Max.
Crew females	0.56	0.94	0.47	0.79
Crew males	0.76	1.26	0.5	0.84

Table 3. Walking speeds on flat in IMO MSC/Circ. 1238 according to age and gender.

Population groups - passengers	Walking speed on flat terrain (eg., corridors)	
	Minimum (m/s)	Maximum (m/s)
Females younger than 30 years	0.93	1.55
Females 30-50 years old	0.71	1.19
Females older than 50 years	0.56	0.94
Females older than 50, mobility impaired (1)	0.43	0.71
Females older than 50, mobility impaired (2)	0.37	0.61
Males younger than 30 years	1.11	1.85
Males 30-50 years old	0.97	1.62
Males older than 50 years	0.84	1.4
Males older than 50, mobility impaired (1)	0.64	1.06
Males older than 50, mobility impaired (2)	0.55	0.91
Population groups - crew	Walking speed on flat terrain (eg., corridors)	
	Minimum (m/s)	Maximum (m/s)
Crew females	0.93	1.55
Crew males	1.11	1.85

3) Walking Direction

In this section, the method for determining the walking direction of the passenger is detailed. The advanced evacuation analysis is intended for thousands of passengers. Because manually designating the escape route for thousands of passengers will consume much time, methods to designate escape route automatically are required. In this study, it is assumed that passenger determine their escape route as the shortest distance route to destination. The basic walking direction is obtained as a solution to the shortest distance route to a destination using a visibility graph. If the escape route is determined, the walking direction can be decided along the escape route. A combination of the visibility graph and of the Dijkstra algorithm was used to calculate the shortest-distance route to a destination considering the obstacles in the compartment of the passenger ship, referring to the study of Nishinari et al. (2004). This study calculated the shortest distance to the destination using these combined algorithms.

The sequence of determining the basic walking direction by visibility graph is summarized as follows. The configuration of the example is shown in Fig. 13.

(1) Create the vertices of the graph: the vertices for the graph are created in the center of the door, the corners of obstacles and the center of the passenger (Fig. 13(a)).
(2) Bond the vertices that are visible to each other by line: the vertices which are visible to each other are bonded by line. The line has its own weight which corresponds to the distance of line (Fig. 13(b)).

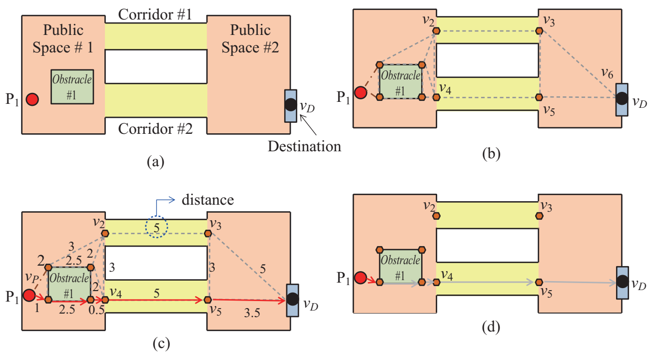


Fig. 13. Steps in calculating the shortest distance. (a) Create the vertices of the graph. (b) Bond the vertices with lines that are visible to one another. (c) Determine the shortest-distance route in the graph. (d) Calculate the shortest distance.

(3) Determine the shortest distance route in the graph. The shortest distance route in the graph is decided by the Dijkstra algorithm (Fig. 13(a)).
(4) Determine the basic walking direction. The basic walking direction is determined as the direction from current position to the closest vertex of the shortest distance route in the graph (Fig. 13(b)).

As described above, determining the walking direction considering the visibility of the passenger stands for determining

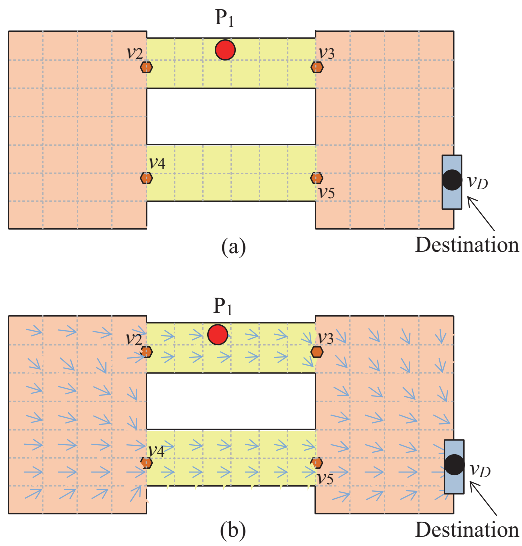


Fig. 14. Example for basic walking direction grid: (a) discretization of the compartment by cell, and (b) an example of a basic walking direction grid.

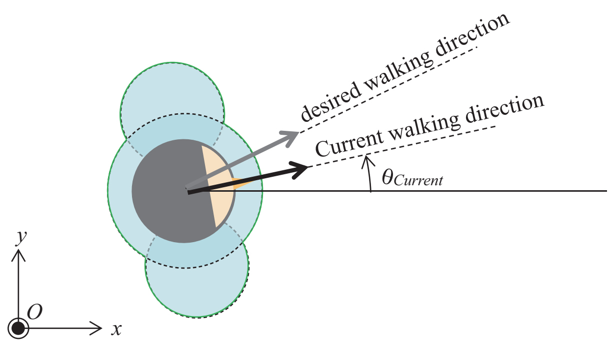


Fig. 15. Change in the walking direction.

compartments are discretized into uniform cells, shown in Fig. 14(a), and the representative basic walking direction for each cell is determined and stored in cells as shown in Fig. 14(b). The grid consisting of the cells containing basic walking directions is called as basic walking direction grid in this study. This study also considered the cases that a passenger passes through multiple spaces with arbitrary shape containing arbitrary-shaped obstacles.

4) Rotation of Passenger

This study also considered the rotation of a passenger. For example, if the current walking direction differs from the desired walking direction, a passenger turns to face the desired walking direction by change current body angle ($\theta_{Current}$) to desired walking direction as shown in Fig. 15. The desired walking direction is a unit vector of the resultant walking velocity of passenger.

The heading angles of the passengers' bodies have an effect on the other passengers' behaviors. As the distance between the passengers affects the passengers' behaviors, the distance

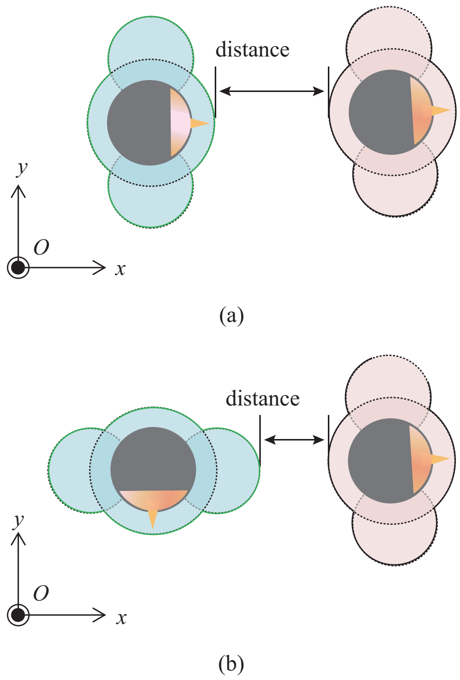


Fig. 16. Comparison of the distance between the passengers according to a change in a passenger's body angle.

the walking direction by creating a new visibility graph for every unit-time. It is very expensive and time-consuming work to perform this procedure for thousands of passengers, so the between each passenger changes according to the angles of the passengers' bodies. If a passenger's body angle changes, the distance between the passengers will change even though the passengers' positions remain the same, as shown in Fig. 16.

In this study, it was assumed that a passenger's body angle changes due to the previous behavior when the next behavior is applied. For example, if the counterflow behavior of a passenger after the application of individual and flock behaviors will be considered, it can be assumed that the passenger's body angle will change due to the previous behavior, such as the passenger's individual behavior or the flock behavior. It also means that the sequence of applying each behavior will cause different passenger behaviors. In this study, the individual-passenger velocity was first applied, then the crowd behavior was considered, and finally, the emergency behavior was applied along with each behavior, with the assumption that the body angle changes due to the previous behaviors.

2. Crowd Behavior

Crowd behavior is represented by "flock behavior", which are used for modeling the tendency that people want to act together considering other passengers and the "leader-following behavior" which is used for modeling the tendency of passengers to follow the leader like a crew would.

1) Flock Behavior

In an emergency situation, passengers have a tendency to

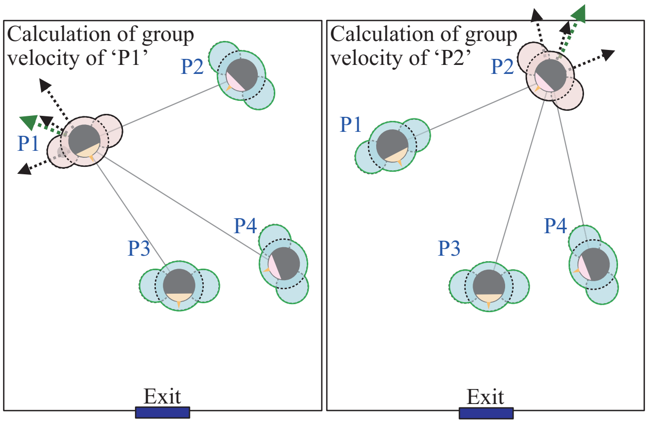


Fig. 17. Separation behavior as a component of the flock behavior.

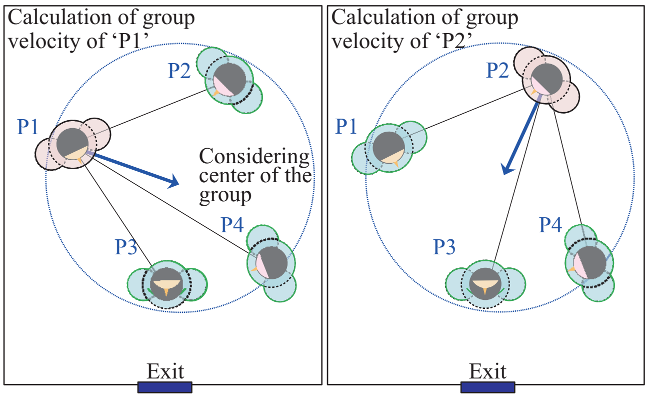


Fig. 18. Cohesion behavior as a component of the flock behavior.

act together with other people. For example, passengers want to use same exit that other passengers pass through even though there are other exits. The flock algorithm suggested by Reynolds (1987, 1999) and Hartman and Benes (2006) is used for modeling flock behavior of passenger. This study adapts the flock behavior used on the study of Hartman and Benes. Flock behavior is used to represent a form of collective behavior of large number of interacting passengers with a common group objective. Flock behavior is a result of the motion and interaction of passengers. Each passenger has three local rules of behavior: cohesion, separation, and alignment. These behaviors are described in the following section. Another important aspect of the flock algorithm is the passenger's visibility. With limited vision, every passenger considers others around him when applying the flock algorithm. The detecting radius of flock behavior is important and can be set by the user.

(a) Separation behavior

Every passenger in a crowd tends to avoid collision with his neighbors. This tendency is called separation or collision avoidance, which signifies striving to avoid overcrowding local neighbors. There are many ways in which this vector can be implemented. In this study, as shown in Fig. 17, the steering vector v_S for separation against neighbors are calculated by using the Eq. (3).

$$\mathbf{v}_S = -\sum_i^n k_S \cdot \mathbf{u}_{S,j} \tag{3}$$

n is the number of the visible neighbors which are within the detecting radius, and j is the index of neighbor passenger. $k_S = c_S/d$ is magnitude of steering vector for separation behavior. d is the inter-person distance considering body shape and body angle of passenger which was described in section 3.1. c_S is the proportional coefficient to make k_S to be 1 when the passengers are in contact. $\mathbf{u}_{S,j}$ is the direction vector of separation behavior against j-th visible neighbor passenger Pj within the detecting radius, and calculated by using the Eq. (4).

$$\mathbf{u}_{S,j} = \left(\mathbf{x}_{\min,i} - \mathbf{x}_{\min,j}\right) / \left|\mathbf{x}_{\min,i} - \mathbf{x}_{\min,j}\right| \tag{4}$$

$\mathbf{x}_i$ is the position of the body or shoulder of the ith passenger (P_i) and $\mathbf{x}_j$ is the position vector the body or shoulder of j-th visible neighbor passenger (P_j). $\mathbf{x}_{min,i}$ and $\mathbf{x}_{min,j}$ are determined according to the position and heading angle of each passenger. For instance, if the distance between the left shoulder of P_i and the body of P_j is a minimum distance, then $\mathbf{x}_{min,j}$ is the center of the left shoulder of P_i, and $\mathbf{x}_{min,j}$ is the center of the body of P_j.

(b) Cohesion behavior

Passengers have the tendency to stay close to the center of the local group formed by neighbors and to find comfort within the group. This tendency is called cohesion, or flock centering. The steering vector for cohesion behavior $\mathbf{v}_C$ makes that a passenger moves toward the center of the visible neighbor group. As shown in Fig. 18, $\mathbf{v}_C$ is calculated by following Eq. (5).

$$\mathbf{v}_C = \mathbf{x}_C - \mathbf{x}_i \tag{5}$$

$\mathbf{x}_C$ is the center of visible neighbor passengers of the ith passenger P_i. The cohesion behavior is applied among group members like family and friends, because passengers do not want to move together with neighbors whose walking directions are different. The group is defined before starting the simulation.

(c) Alignment behavior

Passengers have a tendency to match the direction and speed of their neighbors; this is the factor causing passengers to follow each other. The steering vector for alignment behavior ($\mathbf{v}_A$) makes that the passenger follows toward the average bearing of the neighbor passengers. As shown in Fig. 19, $\mathbf{v}_A$ is calculated by following Eq. (6).

$$\mathbf{v}_A = \frac{1}{n}\sum_{j=1}^n \mathbf{v}_j \tag{6}$$

As shown in Eq. (6), $\mathbf{v}_A$ is same as the average velocity of

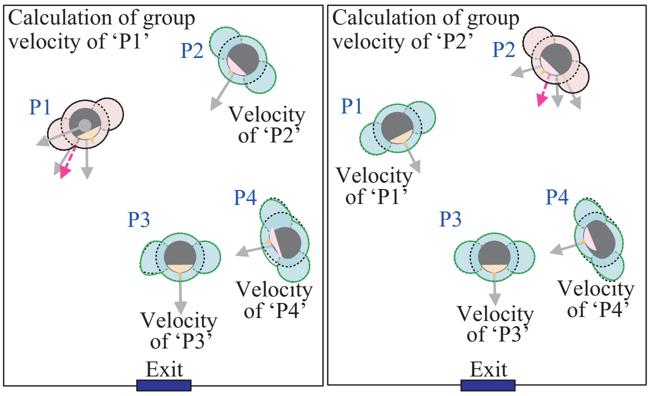


Fig. 19. Alignment behavior as a component of the flock behavior.

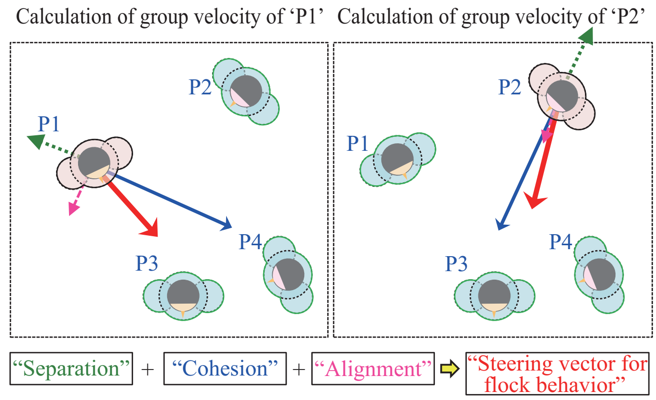


Fig. 20. Flock behavior: the combination of the separation, cohesion, and alignment behavior.

the neighbor passengers. The alignment is applied among group members because of the same reason for cohesion behavior.

All the steering vectors are combined into a resulting influence as shown in Fig. 20. Let us recall that the steering vectors for separation ($\mathbf{v}_S$), cohesion ($\mathbf{v}_C$), and alignment ($\mathbf{v}_A$). The steering vector for flock behavior is the resultant vector, which is the combination of the three steering vectors (cohesion, alignment, and separation) where K_S, K_C, K_A are weight factors for each steering vector.

$$\mathbf{v}_F = K_S \cdot \mathbf{v}_S + K_C \cdot \mathbf{v}_C + K_A \cdot \mathbf{v}_A \tag{7}$$

Thus, considering the flock behavior, the resultant walking velocity of each passenger in the Eq. (2) is modified as

$$\mathbf{v} = v_w \left(\mathbf{u}_0 + \mathbf{v}_F \right), \tag{8}$$

where $\mathbf{u}_0$ is the basic walking direction and $\mathbf{v}_F$ is the steering vector due to the flock behavior in Eq. (7).

2) Leader-Following Behavior

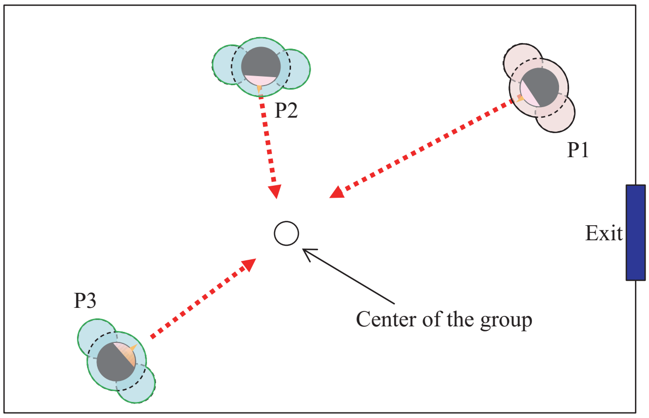


Fig. 21. Gathering stage as the first stage of the leader-following behavior.

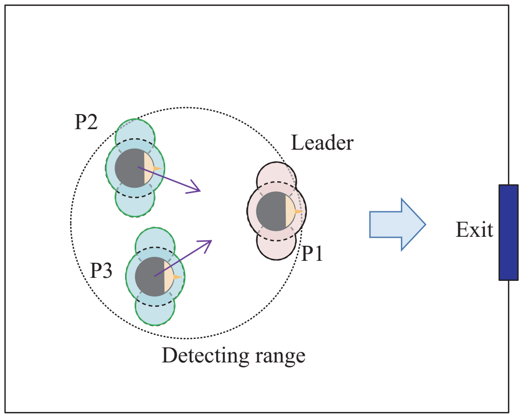


Fig. 22. Evacuation state as the second stage of the leader-following behavior.

In the passenger behavior model of this study, the passengers are assumed to consist of groups of passengers, and these groups are considered to be families or friends that have boarded the ship together. Such group members also tend to escape the ship together, and to follow the leader of the group in an emergency situation. This section describes the modeling of leader-following behavior causing one or more passengers to follow another moving passenger who is designated as the leader referring to the group model by Heliövaara (2007) and Singh et al. (2009). This study follows the algorithms in their study.

The actions of leader-following behaviors are divided into two stages: the first state is gathering stage where the group members walk towards each other to gather the group (Fig. 21). The second stage is evacuation stage where the group members escape the ship and follow the leader (Fig. 22). The behavior in these two stages is modeled separately, and the leader-following behavior of the passengers can be modeled by changing the basic walking direction $\mathbf{u}_0$.

In the gathering stage as the first stage of the leader-following behavior, each passenger attempts to move towards the center of the group and, thus, the basic walking direction ($\mathbf{u}_0$) of each group member points to the center of the group. The gathering continues until all members of a group are within a certain radius $r(n)$ from the center. It is assumed that the radius depends on n, which denotes the number of the group member. This dependence is modeled with the function

$$r(n) = r_0 + n \cdot r_1, \tag{9}$$

where n is the number of the group member and r_0 and r_1 are constants.

Once the group has been gathered, it begins to evacuate from the ship. This stage is called the evacuation stage in leader-following behavior. In the evacuation stage, each follower has two objectives: one is to move toward the destination along the basic walking direction of the grid, and the other is to follow the leader. Thus, the modified basic walking direction $\tilde{\mathbf{u}}_0$ is denoted as

$$\tilde{\mathbf{u}}_0 = (1-\alpha)\mathbf{u}_0 + \alpha\mathbf{u}_{LF}, \tag{10}$$

where $\mathbf{u}_{LF}$ is a unit vector pointing to the leader of the group and the parameter α is the leader-following parameter and ranged as $0 \leq \alpha \leq 1$. The larger the leader-following effect parameter α is, the more eagerly the group members try to follow the leader.

When the group starts to move towards the exit, the walking speeds v_w are set equally for all group members. The faster group members would run away from the others without equalizing the speed. It was assumed that the walking speed of each group member is set to be equal to the walking speed of the slowest member of the group.

Actually, the leader-following behavior is similar to the cohesion and alignment behaviors. In cohesion behavior, the passengers converge at the center of the group, and in leader-following behavior, the passengers converge towards the leader, which are almost the same. Further, in alignment behavior, the passengers align their speed with the average speed of the group, and in leader-following behavior, the passengers align their walking speed with that of the slowest group member. The two behaviors are thus almost the same. Thus, the leader-following behavior can be considered as a kind of flock behavior. Therefore, when the leader-following behavior is applied, it is assumed that the cohesion and alignment behaviors will be converted into the leader-following behavior. Thus, the leader-following behavior was applied with only the separation behavior among the flock behaviors. The resultant velocity of the passenger considering the individual behavior, the separation behavior, and the leader-following behavior was denoted as

$$\mathbf{v} = v_G\left[(1-\alpha)\mathbf{u}_0 + K_S \cdot \mathbf{v}_S + \alpha \cdot \mathbf{u}_{LF}\right], \tag{11}$$

where v_G is the walking speed of the slowest group member.

Fig. 23. Movement of people with counterflow in case of a dense crowd.

3. Emergency Behavior

When an emergency situation occurs, passengers move to pre-assigned assembly station. Actual evacuation situations can be more complex, however. For example, some passengers can go back to their cabins to find one's belongings, or to find one's family or friends. The characteristic of passenger that wants to avoid passengers walking in the opposite direction is modeled by counterflow-avoiding behavior.

As described in section 3.2, if we consider the separation behavior of flock behavior, passengers can keep their distance with each other. However, if the passengers are located in an area with a high population density and apply separation behavior without distinguishing whether the neighbor is walking in the same or opposite direction, passengers can be congested and stuck in a crowd. They need to change their walking direction to directions aimed at avoiding passengers walking in the opposite direction as well as for following passengers walking in same direction as shown in Fig. 23. Counterflow-avoiding behavior is not affected by the flock behavior, especially the separation behavior, and these two behaviors are exist together in the behavior of a person at the same time. The counterflow-avoiding behavior described above is modeled in reference to Korhonen and Hostikka (2009).

The objective of counterflow-avoiding behavior is to modify the direction with the largest forward flow. In this case, counterflow is considered as negative forward flow, and thus the passengers also tend to avoid directions with counterflow. Each time passengers have three options: keep going forward, change the walking direction to the right, or to change the walking direction to the left.

The sequence of the counterflow-avoiding behavior is as follows: the basic idea of the counterflow-avoiding behavior is to choose the sector with the least counterflow. If the passenger P_i needs to choose the direction to avoid counterflow among left ($\mathbf{u}_L$), center ($\mathbf{u}_C$), and right ($\mathbf{u}_R$) as shown in Fig. 24, he/she would choose the right direction ($\mathbf{u}_R$) as we can expect.

This is formulated as a problem, where each passenger lying within a sector either increases or decreases the score of

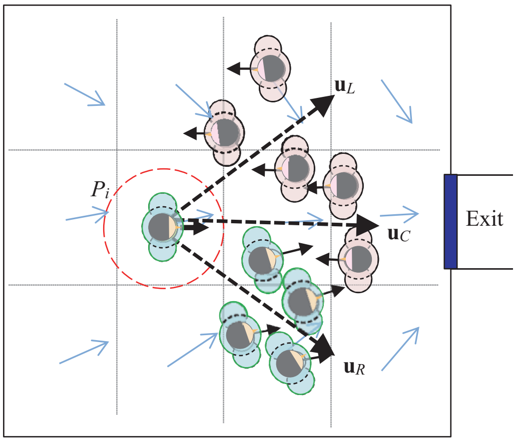
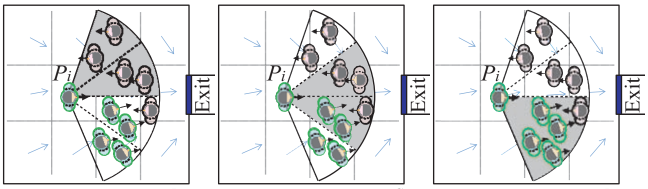
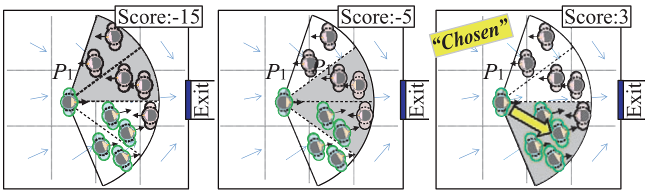


Fig. 24. Choosing a direction to avoid the counterflow.



(a) Left Sector S_i^L (b) Center Sector S_i^C (c) Right Sector S_i^R

Fig. 25. First stage of counterflow-avoiding behavior: dividing the area in front of the passenger into three overlapped sectors.



(a) Left Sector S_i^L (b) Center Sector S_i^C (c) Right Sector S_i^R

Fig. 26. Second stage of counterflow-avoiding behavior: scoring each sector.

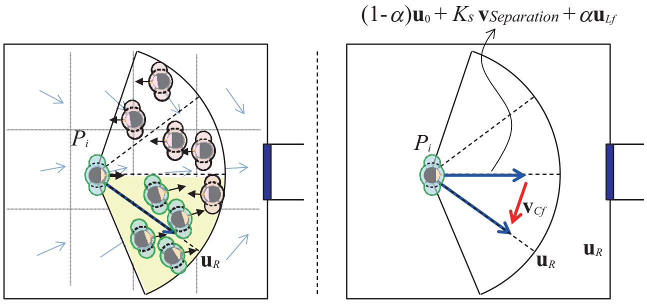


Fig. 27. Third stage of counterflow-avoiding behavior: modifying walking direction toward the center of the sector with the highest score.

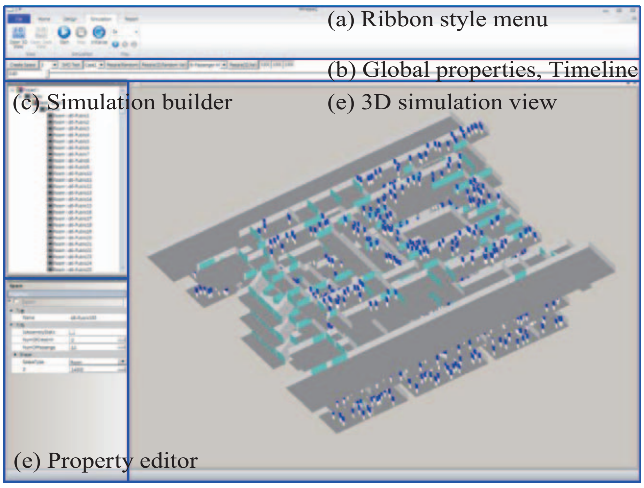


Fig. 28. Screenshot of the developed program for the evacuation analysis in a passenger ship: (a) ribbon style menu, (b) global properties & timeline, (c) simulation builder, (d) property editor, and (e) 3-dimensional simulation view.

the sector depending on its location and velocity. To calculate a score for each section, the area in front of the passengers P_i is divided into three overlapping sectors as shown in Fig. 25.

The score is calculated for each sector depending on the neighbor's location and moving velocity lying within a sector. If the distance between the passenger and neighbor is small or the velocity of the neighbor is high, then the score becomes large. The score is subtracted if the neighbor is walking in a counterflow direction, otherwise the score is added. For example, the score is calculated as -15 for the left sector, -5 for the center sector, and +3 for the right sector as shown in Fig. 26.

After calculating sector scores, the walking direction is modified toward the center of the sector with highest score as shown in Fig. 27. Thus, the steering vector for counterflow-avoiding behavior ($\mathbf{v}_{CF}$) is added to the Eq. (11), then the resultant velocity considering the individual, crowd, and emergency be haviors is

$$\mathbf{v} = v_G\left[\left(1-\alpha\right)\mathbf{u}_0 + K_S \cdot \mathbf{v}_S + \alpha \cdot \mathbf{u}_{LF} + \mathbf{v}_{CF}\right]. \quad (12)$$

If there is no counterflow in the front sector of passenger P_i, the passenger will keep their walking direction.

Three behaviors to represent the behavior of passengers in an emergency situation is explained until now. Each behavior is expressed as a velocity vector, and only the vector of the individual behavior is used to the crowd behavior and emergency behavior. The crowd behavior is not correlated with the emergency behavior. The velocity expressing the behavior of each passenger was expressed by summarizing the velocity vector of each behavior as shown in Eq. (12).

IV. VERIFICATION OF THE PASSENGER BEHAVIOR MODEL THROUGH IMO TESTS

In this study, a simulation program for the evacuation analysis in a passenger ship has been developed based on the behaviors aforementioned in Section 3. Fig. 28 shows a screenshot

Table 4. Tests for verification of an advanced evacuation analysis programs recommended by IMO MSC/Circ. 1238.

Test	Description
Test 1	Maintaining the set walking speed on a corridor
Test 2	Maintaining the set walking speed up a staircase
Test 3	Maintaining the set walking speed down a staircase
Test 4	Exit flow rate
Test 5	Response time
Test 6	Rounding corners
Test 7	Assignment of population demographic parameters
Test 8	Counterflow: two rooms connected via a corridor
Test 9	Crowd dissipation from a large public room
Test 10	Exit route allocation
Test 11	Staircase

of the developed program in this study. This program is developed using C# and Windows Presentation Framework (WPF) programming language in the environment of Microsoft Visual Studio 2010. As shown in Fig. 28, the program provides various types of a graphical user interface (GUI) to support the user make an evacuation easily. The developed program has six components: ribbon style menu, global property & timeline, simulation builder, property editor, and 3-dimensional simulation view. These components has the functions of pre-processor or post-processor for the evacuation analysis in a passenger ship, and also developed based on open source libraries, free libraries, or in-house codes. The egress model in Section 3 is implemented as a kernel function, and it is located on the background of these GUIs.

To verify the egress model developed in this study, 11 tests are implemented that are noted in IMO MSC/Circ. 1238 Annex 3 guidance on validation/verification of evacuation simulation tools. The tests include checking that the various components of the software perform as intended. This involves running the software through elementary test scenarios to ensure that the major sub-components of the model are functioning as intended. Also, the tests concern the nature of predicted human behavior with informed expectations.

The 11 tests recommended by IMO are listed in Table 4.

The results of the 11 tests verified the validity of the proposed passenger behavior model. In this paper, the detailed results of tests 4, 6, 8 and 10 are described.

1. IMO Test 4: Exit Flow Rate

Fig. 29 shows the configuration of IMO test 4. In IMO test 4, one hundred passengers in 8 × 5 meter with one meter wide exit located centrally on the five meter wall. The flow rate over the entire period should not exceed 1.33 person/s.

It takes 160 seconds for all passengers to escape the room, confirming a flow rate over the entire period of 0.625 person/s, which is lower than 1.33 person/s (Figs. 30 and 31).

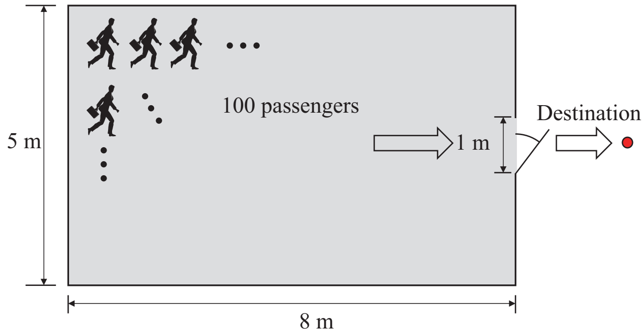


Fig. 29. Configuration of IMO test 4: exit flow rate.

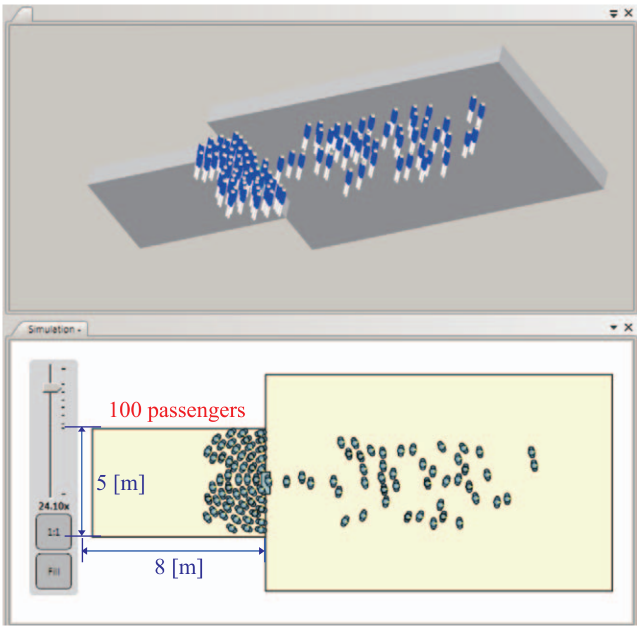


Fig. 30. Simulation result of IMO test 4.

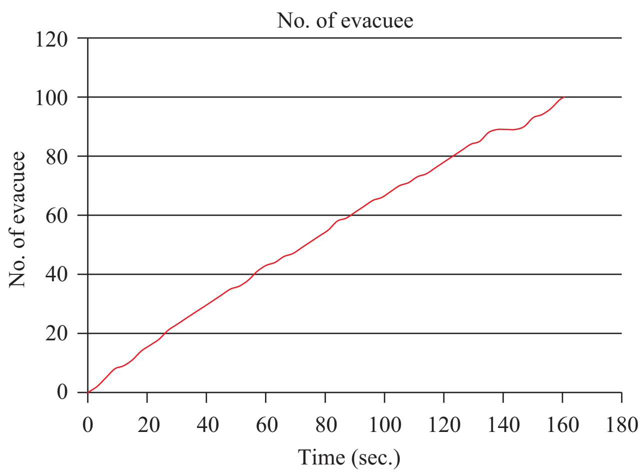


Fig. 31. Number of total evacuees at each time in IMO test 4.

2. IMO Test 8: Counterflow - Two Rooms Connected via a Corridor

Fig. 32 shows the configuration of IMO test 8. As shown in

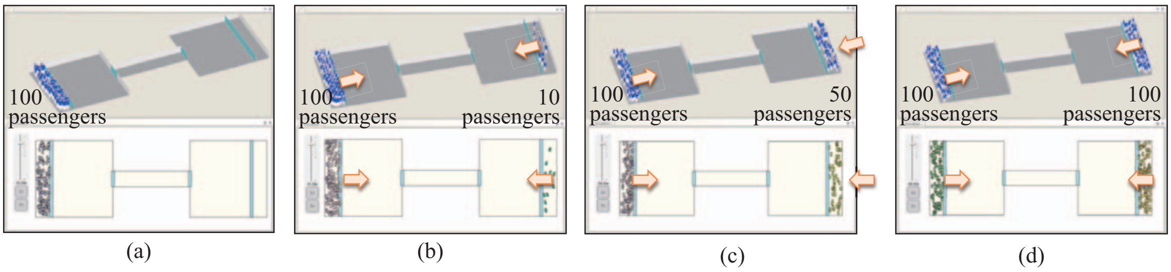


Fig. 32. Initial distribution of passengers at each room: (a) step 1 - 100 passengers in room 1, (b) step 2 - additional 10 passengers in room 2, (c) step 3 - additional 50 passengers in room 2, (d) step 4 - additional 100 passengers in room 2.

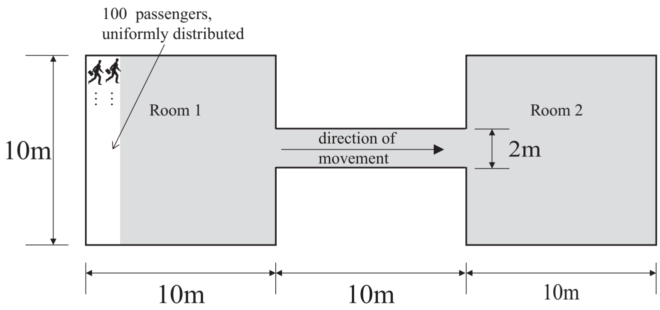
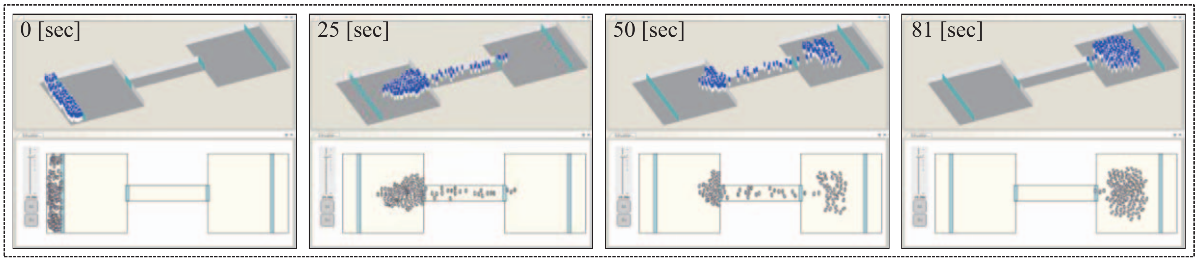
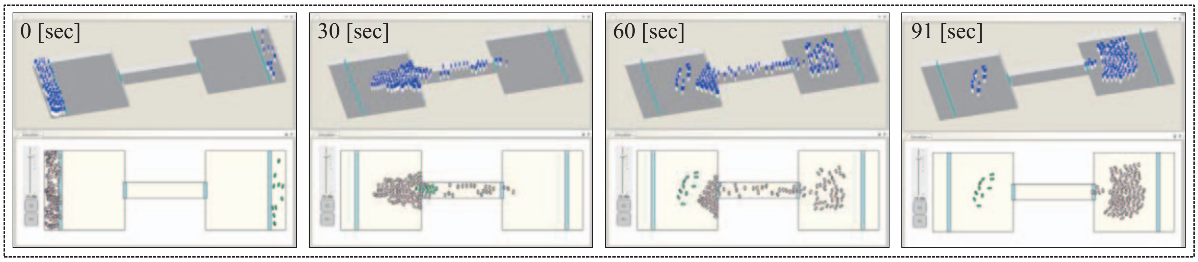


Fig. 33. Configuration of IMO test 8: counterflow - two rooms connected via a corridor.



(a) Simulation result of IMO test 8: step 1-100 passengers in room 1

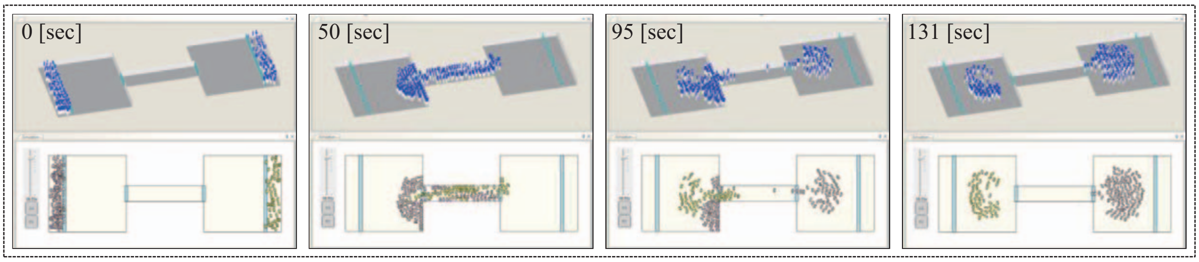


(b) Simulation result of IMO test 8: step 2-100 passengers in room 1 and additional 10 passengers in room 2

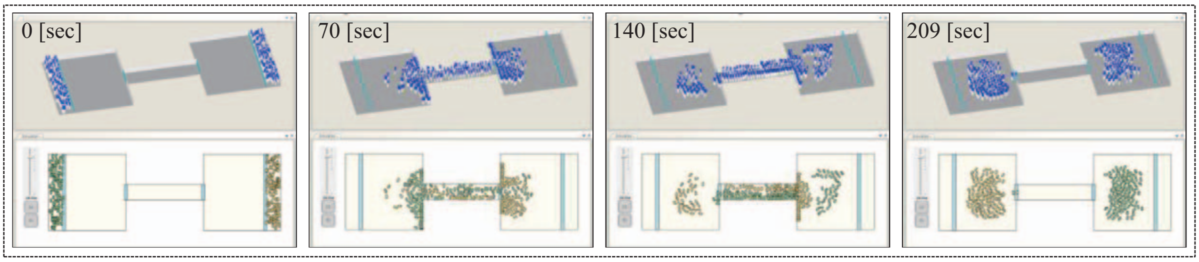
Fig. 34. Simulation results of IMO test 8: (a) step 1 - 100 passengers in room 1, (b) step 2 - additional 10 passengers in room 2.

Fig. 32, two rooms, each 10 meters wide and long, were connected via a corridor with 10 meters long and 2 meters wide, starting and ending at the center of one side of each room. It was supposed that the passengers were 30- to 50-years old males on a flat terrain, as mentioned in the appendix to the IMO Guidelines, and that their walking speeds were distributed over a population of 100 persons with instant response time.

For the first step of this test, one hundred passengers move from Room 1 to Room 2, where the initial distribution is such that the space of Room 1 is filled from the left with maximum possible density, as shown in Fig. 33(a). Then, step 1 is repeated with an additional 10, 50, and 100 passengers in Room 2 in step 2, as shown in Fig. 33(b)-(d). These passengers should have identical characteristics to those in Room 1. Both rooms move off simultaneously and the time for the last passengers in



(a) Simulation result of IMO test 8: step 2-100 passengers in room 1 and additional 50 passengers in room 2



(b) Simulation result of IMO test 8: step 2-100 passengers in room 1 and additional 100 passengers in room 2

Fig. 35. Simulation results of IMO test 8: (a) step 2 - additional 50 passengers in room 2, (b) step 2 – additional 100 passengers in room 2.

Table 5. Tests for verification of an advanced evacuation analysis programs recommended by IMO MSC/ Circ. 1238.

Number of passengers in room 2 (persons)	Total evacuation time (second)
0	83.2
10	90.8
50	129.4
100	201.4

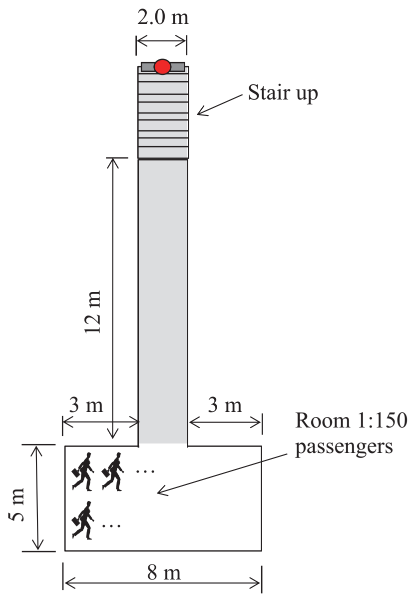


Fig. 36. Configuration of IMO test 11: staircase.

Room 1 to enter Room 2 is recorded. The expected result is that the recorded time increases with the number of passengers.

As shown in Fig. 34 and Fig. 35, it is confirmed that the total evacuation time increases relative to the increase of the number of passenger in Room 2 (Table 5).

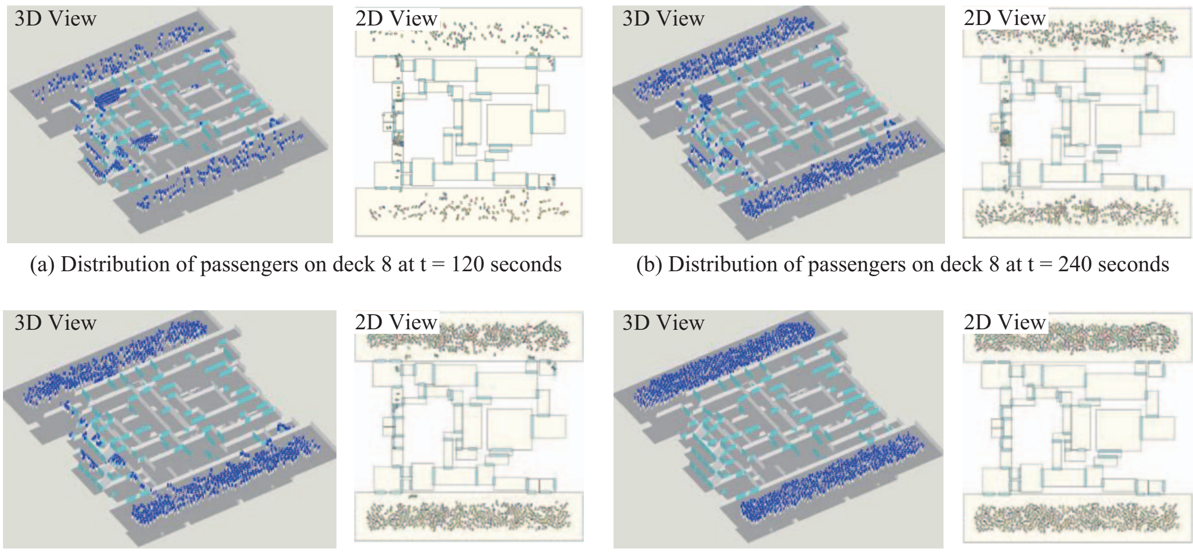
3. IMO Test 11: Staircase

Fig. 36 shows the configuration of IMO test 11. In IMO test 11, a room was connected to a stairway via a corridor as shown in Fig. 36. It was supposed that 150 passengers were 30-50 years old males, and their properties were distributed as indicated in the appendix to the IMO Guidelines for the advanced evacuation analysis of new and existing ships. The expected result is that congestion appears at the exit from the room, which produces a steady flow in the corridor with the formation of congestion at the base of the stairs.

It is confirmed that congested passengers are identified around the entrances to the corridor and bottom of the stairs as shown in Fig. 37.

V. EXAMPLE OF MAIN VERTICAL ZONE 1 IN IMO/MSC CIRC.1238 ANNEX 1

In this section, an advanced evacuation analyses for two MVZ (Main Vertical Zone) of a passenger ship in IMO/MSC Circ. 1238 ANNEX 1 are carried out by the egress model developed in this study. The results of implementation are compared with the results by EVi, a commercial software for the evacuation analysis in a passenger ship. Since EVi and the developed program does not have same algorithm to express the passenger behavior, they may not produce the same results actually. Anyway, EVi is a software that has the records of the application to the evacuation simulation, so this study com-



(a) Distribution of passengers on deck 8 at t = 120 seconds (b) Distribution of passengers on deck 8 at t = 240 seconds

(c) Distribution of passengers on deck 8 at t = 360 seconds (d) Distribution of passengers on deck 8 at t = 481 seconds

Fig. 37. Example of main vertical zone 1 in IMO/MSC Circ. 1238 ANNEX 2: simulation result.

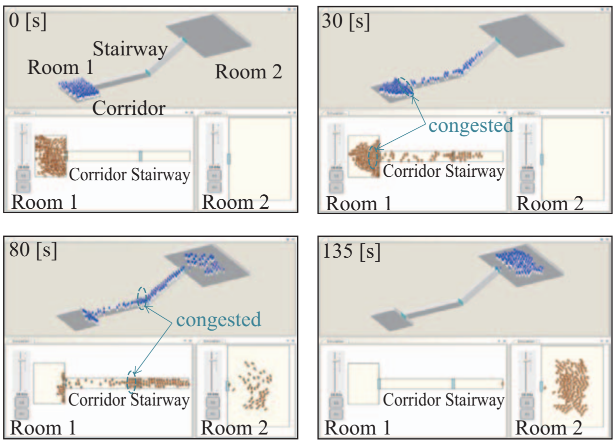


Fig. 38. Simulation result of IMO test 11.

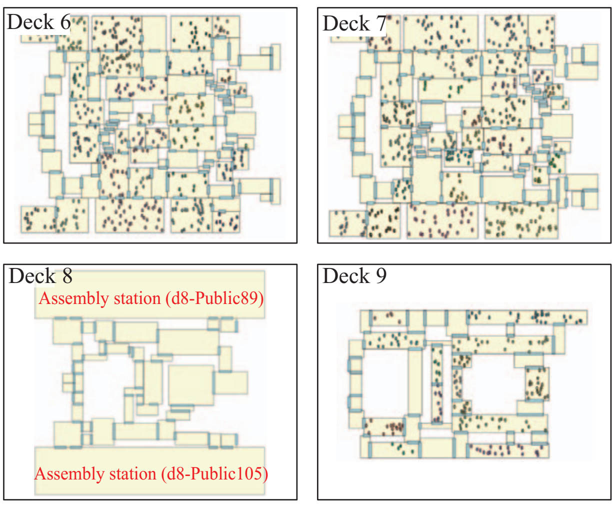


Fig. 39. Example of main vertical zone 1 in IMO/MSC Circ. 1238 ANNEX 2: initial distribution of passengers for each deck.

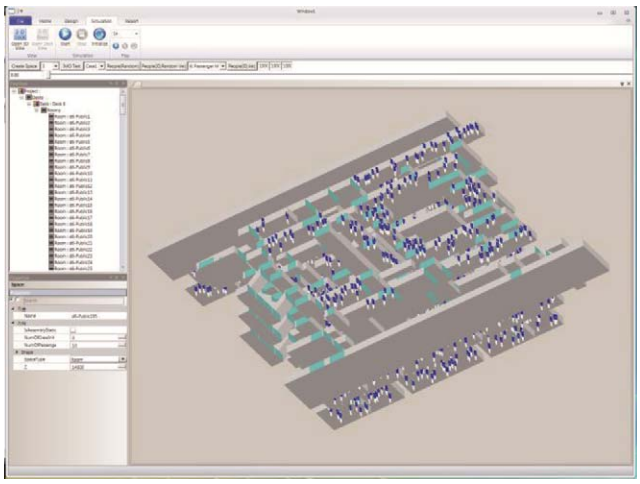


Fig. 40. Example of main vertical zone 1 in IMO/MSC Circ. 1238 ANNEX 2: 3D view.

pared the results of EVi and the developed program, and it was assumed that the proposed algorithm is verified if the results are similar.

There are four decks and two assembly stations on Deck 8. The initial distribution corresponds to a total of 1138 persons located in the public spaces as follows: 469 on Deck 6, 469 on Deck 7, and 200 on Deck 9. Deck 8 (assembly station) is empty.

- Length: about 40 meters, Breadth: about 26 meters
- Number of passengers: 1138
- Number of decks: 4 (deck6 ~ deck9)- Number of assembly stations: 2 (2 assembly stations in Deck 8)

The initial distribution of the passengers is shown in Fig. 38 in a 3D view, and in Fig. 39 in a 2D view.

The 3D and 2D view of simulation results are indicated in Fig. 40.

Table 6. Example of main vertical zone 1 in IMO/MSC Circ. 1238 ANNEX 2: comparison of the travel time and total evacuation time in this study and that in EVi.

Simulation results	This paper	EVi
Travel time	481 seconds	513 seconds
Total evacuation time	1801 seconds	1841 seconds

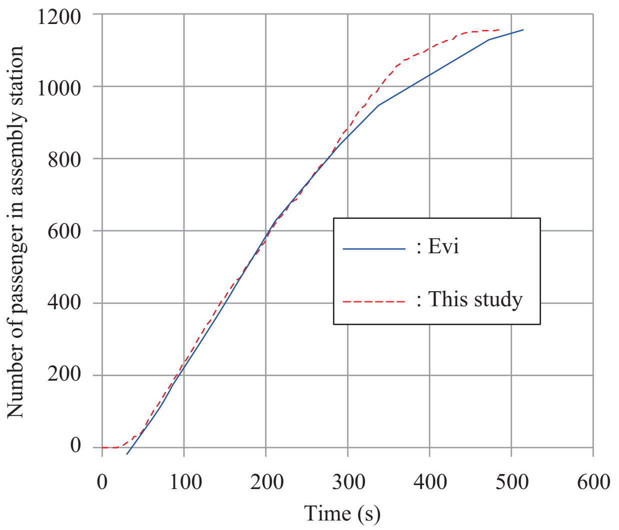


Fig. 41. Example of main vertical zone 1 in IMO/MSC Circ. 1238 ANNEX 2: comparison of the number of passengers at assembly stations in this study and that in EVi.

As a result of the simulation, the number of passengers at assembly stations in the allotted time is plotted in Fig. 41. The total calculation time for this case was about 7 minutes: 5 minutes to calculate basic walking direction grid and 2 minutes for the simulation. The total travel time is 8 minutes, 1 second by the egress model proposed in this study, where the results by EVi were 8 minutes and 33 seconds. The difference of the travel time is 6%, which can be considered to be small. The total evacuation time is calculated and specified in Table 6. It is confirmed that the requirement by IMO which is given in Eq. (1) is satisfied.

V. CONCLUSION

In this study, an advanced evacuation analysis considering passenger behavior in an emergency is performed. The passenger behavior in an emergency is represented by the velocity-based model consisting of individual behavior, crowd behavior, and emergency behavior. The advanced evacuation analysis program was developed based on the passenger behavior model. To verify the proposed egress model, 11 tests and 2 examples specified in IMO MSC/Circ. 1238 were implemented and confirmed that all requirements are satisfied. The simulation result is compared with that obtained by EVi.

The function of the advanced evacuation analysis program in this study needs to be developed further, and research with more realistic passenger evacuation analysis should be performed in the future. One of the main reasons for needing to escape a ship is due to fire. The commercial evacuation analysis programs maritimeEXODUS, Evi, and FDS+Evac can be linked with the fire-related data of the fire simulation programs. The effects of the dynamic motion of the ship on passengers walking may be a future research focus. The validation of a full-scale evacuation experiment on a ship may also be a future research focus.

ACKNOWLEDGMENTS

This work was partially supported by

(a) Daewoo Shipbuilding and Marine Engineering Co., Ltd.,
(b) the Human Resource Training Program for Regional Innovation and Creativity through the Ministry of Education and National Research Foundation of Korea (2014H1C1 A1073060), and
(c) the MKE through the fostering project of Daebul Industry-University Convergence, Mokpo National University, Korea.

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