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A SYSTEM SIMULATION MODEL FOR A TRAINING SHIP EVACUATION PLAN

Chian Liou[1] and Ching-Wu Chu[2]

Key words: evacuation, system simulation, hydraulic model.

ABSTRACT

Evacuation techniques for land buildings have been applied to passenger ships in maritime transportation. However, real and full-scale evacuation drills on a passenger ship are difficult to execute because of their high cost. Therefore, the purpose of this study is to present a system simulation model for developing an evacuation plan of a training ship by minimizing the total evacuation time. In our model, evacuation time can be expressed as a function of three variables: (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. We propose modifications to existing hydraulic model to incorporate human factors. We use Intel Visual Fortran Compiler to code the proposed model which is applied to a case study to show the advantage of System Simulation. In addition, the results have been checked for validity. Thus, the implications of this study may be valuable for developing an evacuation plan for a passenger ship.

I. INTRODUCTION

In view of experience in maritime disasters, the International Maritime Organization (IMO) has addressed the safety of passenger ship through a number of rules and regulations. The International Convention for the Safety of Life At Sea (SOLAS) specifies the maximum times allowed for key evacuation phases on passenger ships. First, the maximum time allowed from releasing the abandon ship signal to having all survival crafts ready for evacuation is 30 minutes. Second, the maximum time allowed from giving an abandon ship order to mustering all passengers to the muster station is 30 minutes. SOLAS is a prescriptive code that IMO uses to assure the safety of occupants on passenger ships. The requirements of SOLAS are based on calm weather conditions and no effects of fire or listing. In harsh weather conditions, or hindrances such as listing or the effects of fire, it is difficult to achieve evacuation within the given requirements.

After many computer simulation techniques were developed, IMO was prompted to set standards to evaluate their effectiveness. In 2007, the Maritime Safety Committee (MSC) of IMO formally adopted the "*Guidelines for Evacuation Analysis for New and Existing Passenger Ships*" (MSC.1/Circ. 1238). These guidelines only address the mustering stage of the evacuation process, and define two scenarios, namely day and night conditions. However, the maritime safety code has changed from a prescriptive code to a performance-based one. During this transition, evacuation models can help ensure the solutions proposed by performance-based codes are feasible, and that performance-based codes are able to address maritime safety issues properly (Rodrigo, 2009).

Fahy (2002) indicated that evacuation models are important tools for evaluating engineering designs, because these evaluations must estimate the time required for the safe evacuation of the occupants. Bryan (2002) showed that the worldwide movement toward performance-based codes has created a demand for computer evacuation models that estimate the evacuation time. Galea (2003) showed that designers and regulators have turned to performance-based analysis and regulations facilitated by the new generation of people movement models. Ko et al. (2007) promoted the use of evacuation models to assess plans and provide sufficient time for the occupants to evacuate safely in the event of an emergency. Evacuation models have become important tools for the understanding the evacuation process in general. Unlike traditional hand calculations, evacuation models consider the occupants' interactions (i.e., congested areas, response times, decision making, and so on.) that significantly affect evacuation efficiency.

The main purpose of this study is to construct a simple and efficient system simulation model to develop a personnel evacuation method to increase the safety at sea. The proposed model different from previous simulation models, modifies a hydraulic model by incorporating the human behavior factor. In the simulation model, human behavior factors, such as route choice (left or right turn at junction), can be easily modeled by assigning corresponding random numbers. The proposed model can evaluate all possible evacuation routes and different

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numbers of people on the evacuation routes to find the fastest evacuation plan with a minimum evacuation time.

The rest of this paper is organized as follows. The next section is literature review. Section 3 describes the layout and the network of the training ship. Section 4 introduces the system simulation using a modified hydraulic model. Section 5 illustrates the case study and reports the experimental result, and the final section is conclusions.

II. LITERATURE REVIEW

To prevent disasters such as those of Titanic, Estonia and Herald of Free Enterprise from recurring, IMO has stipulated SOLAS, and repeatedly revised safety specification for personnel evacuation plans in the MSC.

The emergency evacuation of a ship is an important issue in case of an accident. Many studies have been conducted on building evacuation. Previous studies on evacuation models can be generally classified into two categories: analytical models and simulation models. Bakuli and Smith (1996) provided an overview of different ways in which the evacuation problem has been approached or formulated. The deterministic model is a simple and useful tool for building evacuation. If the evacuation problem is formulated by stochastic models, the results are not only more realistic but also more complicated. Major studies adopting this approach include those of Smith (1984, 1985) and Løvås (1995, 1998).

A simulation is the imitation of a real-world process or system over time. Simulations have been used frequently in emergency evacuation analysis. Weinorth (1989) used GPSS to write a MOBILIZE model for evacuating a complex building on a large campus. Fahy (1991) used the EXIT89 model to study the evacuation process in high-rise buildings. Thompson and Marchant (1994) developed SIMULEX to evaluate the potential evacuation of a complex building with a high degree of accuracy. The most-recent contribution was made by Galea (2001) who used the EXODUS program.

Despite these investigations, little research has been conducted on the evacuation of ships. Researchers have recently transferred the methodology of building evacuation to ship evacuation, considering the special circumstances such as ship motion and human behaviors. The EU research project was launched in 1997. The mustering simulation program EVAC was developed to simulate the mustering operation on passenger vessels based on a microscopic method. This program considers the motions of all passengers and their interactions with other evacuees. However, this model does not include the dynamic effect and the listing of the ship.

Galea (2003), professor of the University of Greenwich, also developed the maritimeEXODUS which is a computer based laboratory for evaluating the emergency and non-emergency movement of passenger and crew. MonteDEM was developed by the Korean Research Institute of Ships and Ocean Engineering and Seoul National University to assess the fire safety of ships. The MonteDEM model specified the physical characteristics of each person and personal reaction caused by ship's motions. There are some key ship evacuation models that comply with the IMO requirements, such as AENEAS (Germanisher Lloyd AG), ODIGO (France) or EVI (British).

Chu et al. (2013) formulated a mathematical model using a minimum cost flow to calculate the personnel evacuation route and examine different evacuation scenarios. They compared the results with the original evacuation plan and found some mistakes in the original plan. They suggested a system for monitoring the number of people in a room and solved the optimal evacuation route in real time.

Researchers have also explored factors affecting human behavior in ship evacuation, such as ship listing and motion, crowd density, and psychological responses. Lee et al. (2003) provided a detailed explanation of the current status and future issues in human evacuation from ships. Park et al. (2004) presented an intelligent model for extrication simulation (IMEX), which combined a dynamics model and human behavior model to overcome some limits of current evacuation models.

An evacuation model that does not reflect crowd behavior is incomplete. Jorgensen and May (2002) discussed a number of important issues related to crowd behavior. They defined the concept of group-binding, which expressed that people both rationally and emotionally have a strong desire to find their relatives before being evacuated. The degree of group-binding is a function of the social composition of the passengers: singles, couples, families, and groups of friends. An average of 30% of passengers disobeys crews' instructions to find family members and other people they feel closely connected or related to. Berlonghi (1995) classified passengers into two groups, the passive crowd (e.g., watching) and active crowd (e.g., violence, panic, craze, hysteria). Pan (2006) investigated the psychological and sociological characteristics of human behaviors in terms of three aspects (individual, interaction among individuals, and group) to establish a generalized process model of the emergence of non-adaptive crowd behavior.

This literature review indicates that planning the movement of people is critical for safety measures. Therefore, an appropriate tool is necessary to analyze the fastest evacuation route problem. Important factors, such as human behavior should be incorporated into the model. The main advantage of the system simulation is that it can handle complex scenarios and run full-scale evacuation exercise without actual people in ships. This study builds a system simulation model that modifies the hydraulic model by considering human behavior.

III. DESCRIPTION OF THE TRAINING SHIP

The case study was based on the general arrangement of a training ship for cadets called "Yu-Ying No. 2". Her home port is Keelung, Taiwan. Yu-Ying No. 2 was launched in 1994. Every year, she carried about 800 cadets sailing between Taiwan and Japan. Table 1 gives the particulars of the ship.

The training ship has five decks, including 3rd Deck, 2nd

Table 1. The particulars of motor ship "Yu-Ying No. 2".

Principal particulars of MS "Yu-Ying No. 2"			
L.O.A.	72.85 m	Main engine	
L.B.P.	66.00 m	Type:	MITSUI MAN
Breath molded	12.60 m		B&W 8S26MC
Depth molded	5.70 m	Speed	
Draft molded	5.00 m	Max. trail speed	14.8 knot
Deadweight	1109 tons	Service speed	13.7 knot
Gross tonnage	1846 tons		
Type	Training ship		
Crew capacity		Classification	
VIP room	4	China Corporation Register of Shipping	
Officer's room	6	CR 100 + E	
Crew's room	12	American Bureau of Shipping	
Cadets' room	80	A1	
Teachers' room	6		
Total	108		

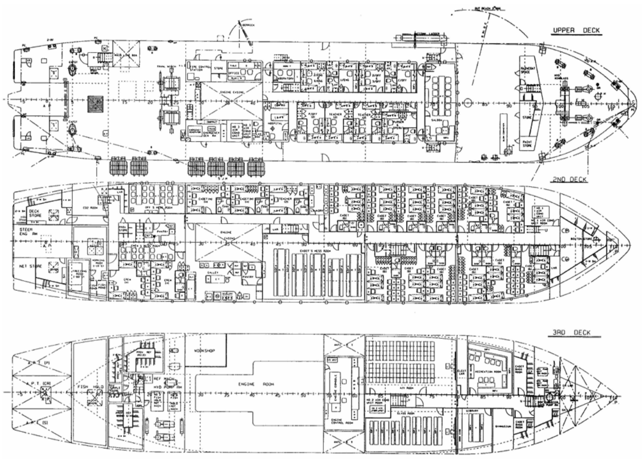

Fig. 1. General arrangement chart.

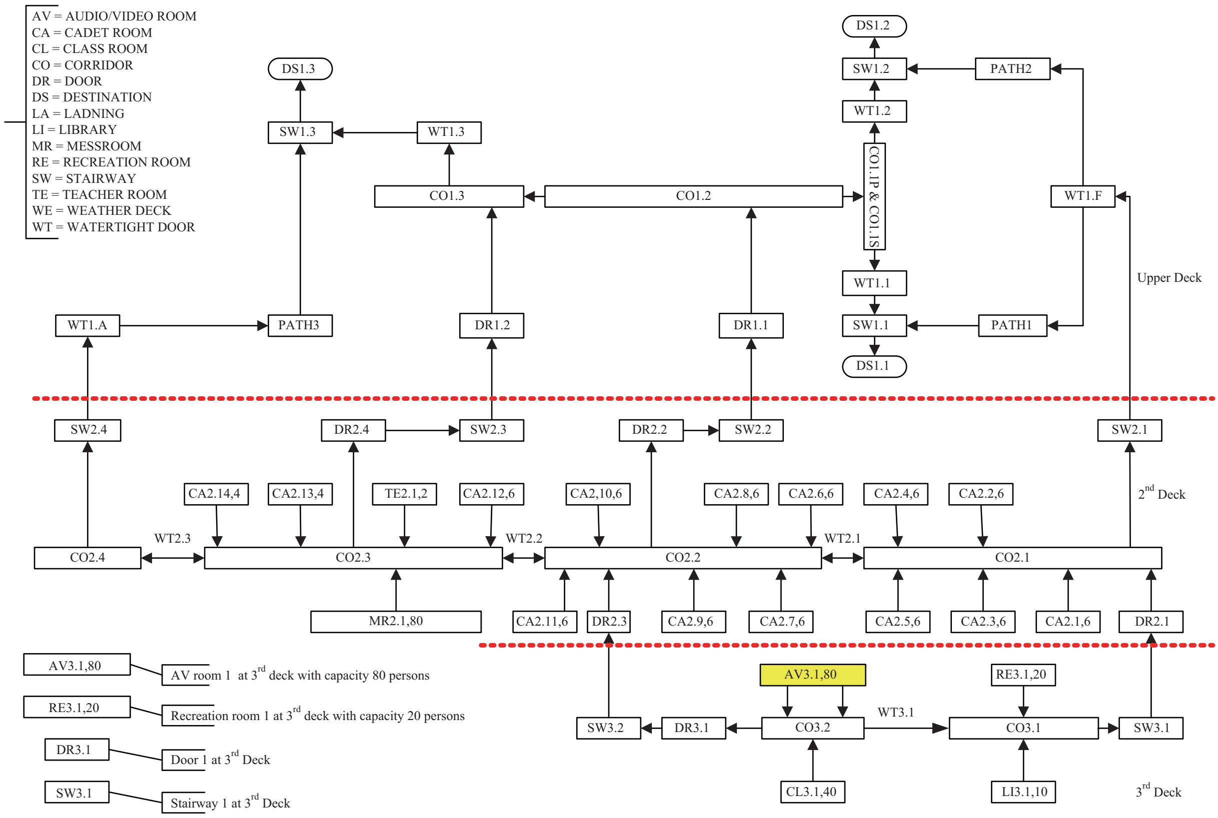

Fig. 2. Evacuation network diagram.

Deck, Upper Deck, Boat Deck and Bridge Deck. Fig. 1 shows the layout of the lower three decks considered in this study.

To simplify the explanation of the proposed system simulation model in the following section, this study transforms the layout of the lower three decks into a network graph as shown in Fig. 2. The upper left of Fig. 2 lists the abbreviations for the facilities. In the network diagram, the arrow on the line shows the direction of people movement between two facilities and the rectangle with yellow color (AV3.1, 80) shows the capacity of the source node. Table 2 shows the detailed information of the clear widths of stairs, corridors, and doors, which are important factors affecting evacuation effectiveness.

In Fig. 2, the lowest deck, namely the 3rd deck, includes the audio-video room 3.1 (AV3.1), which has a capacity of 80 persons, the library 3.1 (LI3.1) and the recreation room 3.1 (RE3.1). There is one watertight door (WT3.1) between the corridor 3.1 (CO3.1) and the corridor 3.2 (CO3.2). At the end of each corridor on the 3rd Deck is a stairway leading upstairs to

Table 2. Clear Width of the Evacuation Facilities

Position	Serial No.	Category	Clear Width (mm)	Position	Serial No.	Category	Clear Width(mm)
3rd deck	CO3.1	Corridor	1050	Upper deck	PATH1	Weather path	1700
	CO3.2	Corridor	1050		PATH2	Weather path	1700
	SW3.1	Stairway	750		PATH3	Weather path	1700
	SW3.2	Stairway	750		CO1.1P	Corridor	700
2nd deck	CO2.1	Corridor	900		CO1.1S	Corridor	700
	CO2.2	Corridor	900		CO1.2	Corridor	700
	CO2.3	Corridor	900		CO1.3	Corridor	700
	CO2.4	Corridor	700		SW1.1	Stairway	450
	SW2.1	Stairway	450		SW1.2	Stairway	450
	SW2.2	Stairway	450		SW1.3	stairway	450
	SW2.3	Stairway	450				
	SW2.4	Stairway	450				

Source: Finished plans of MS Yu-Ying No. 2.

the 2nd deck. The 2nd deck includes the cadets' rooms (CA2.1 - CA2.12) and the mess room 2.1 (MR2.1), which has a capacity of 80 persons. There are three watertight doors (WT2.1, WT2.2 and WT2.3) on the 2nd deck. WT2.1 is located between CO2.1 and CO2.2, WT2.2 is located between CO2.2 and CO2.3, and WT2.3 is located between CO2.3 and CO2.4. At each corridor on the 2nd deck, there is a stairway leading to the upper deck. The evacuation facilities on the upper deck include three weather deck paths (Path 1, Path 2, and Path 3) and four corridors (CO1.1P, CO1.1S, CO1.2, and CO1.3). There are three stairways (SW1.1, SW1.2 and SW1.3) leading to the boat deck.

IV. SYSTEM SIMULATION MODEL BASED ON MODIFIED HYDRAULIC MODEL

1. Hydraulic Model

The flow of groups of persons is an important factor in emergency movement. The typical methods for predicting the flow of groups of persons in emergencies are based on the relationship between the movement speed and the population density of the evacuating stream of persons. These methods assume the following:

(1) All persons start evacuating at the same time.
(2) Occupant flow does not involve any interruption caused by decisions of the persons involved.
(3) All the persons involved are free of disabilities that would significantly impede their ability to keep up with the movement of a group.

The above mentioned approach is often referred to as a hydraulic model of emergency egress (Nelson and MacLennan, 1995).

Evacuation generally includes two phases: the starting phase and the evacuation phase. The hydraulic model deals only with the latter. The original hydraulic model did not take human factors into consideration. On the contrary, our modified hydraulic model has been incorporated two human factors, the number of persons moving forward or aft in corridors and the number of persons turning to the left or right at T junctions, into the emergency evacuation model. Crowd movements are quantitatively specified using three fundamental characteristics, density, speed, and flow, all of which are expressed as rates. Density is the number of persons per unit area of the walkway. This characteristic is quantified using the inverse of density, which allows a much clearer visualization of the relative quality of service (Fruin, 1970) (i.e., area per person, such as 0.4 m^2 per person). Speed is simply the distance travelled by a moving person in a unit of time (e.g., 1.2 m/s). Flow is defined by the number of people that pass some reference point per unit of time (e.g., 2 persons/s).

$$\text{Flow} = \text{speed} \times \text{density} \times \text{width}$$

When the pedestrian density is less than approximately 0.5 person/m^2, people are able to move along walkways at approximately 1.25 m/s, which is an average unrestricted walking speed. Speed decreases as density increases, and decreases very markedly at very high densities, reaching a standstill when density reaches 4 or 5 persons/m^2. The speed of movement is slightly lower on stairs. Relatively fit people can average approximately 1.1 m/s going up stairs at low density (Pauls, 1995).

2. Input Data Analysis

In order to calculate the flow, we need three fundamental values: speed, density, and width. First, the width of corridors or stairways can be measured directly. Table 2 summarizes the related information. This study uses the IMO's Clear width (Wc) instead of Pauls' Effective width. IMO defines the clear width as measured off the handrails for corridors and stairways and the actual passage width of a door in its fully open position.

Table 3. Walking speed on flat terrain (e.g., corridors).

Passengers	Walking speed on flat terrain	
	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
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
Crew	Walking speed on flat terrain	
	Minimum (m/s)	Maximum (m/s)
Crew females	0.93	1.55
Crew males	1.11	1.85

Source: Guidelines for evacuation analysis for new and existing passenger ships (MSC.1/Circ. 1238).

Table 4. Walking speed on stairs.

Passengers	Walking speed on stairs			
	Stairs down		Stairs up	
	Min. (m/s)	Max. (m/s)	Min. (m/s)	Max. (m/s)
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
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
Crew	Walking speed on flat terrain			
	Stairs down		Stairs up	
	Min. (m/s)	Max. (m/s)	Min. (m/s)	Max. (m/s)
Crew females	0.56	0.94	0.47	0.79
Crew males	0.76	1.26	0.5	0.84

Source: Guidelines for evacuation analysis for new and existing passenger ships (MSC.1/Circ. 1238).

Pauls' effective width accounts for the propensity of people to sway laterally – the width remaining once edge effects are deduced from 150 mm in from each wall boundary and 90 mm in from each handrail centerline. The walking speed along the corridor and upstairs stairway were set to 1.2 m/s and 0.79 m/s respectively, as suggested by IMO (see Tables 3 and 4).

Finally, the density can be defined as the number of people per unit of an area. While running the simulation model, we can have different values of density, depending on how many people on the specific area. The maximum density cannot exceed the value of 4 or 5 peoples/m^2 because people cannot move forward if the density is greater than 4 or 5 peoples/m^2 (Pauls, 1995).

3. Model Structure and Process

The mechanism for advancing simulation is based on moving people through a series of connected source facilities and target facilities. How to move a person from a source facility (e.g., AV3.1 in the 3rd deck or MR2.1 in the 2nd deck) to a neighboring target facility was decided based on the residual capacity of the neighboring target facility. This process can be divided into three steps. First, check if the evacuees in the source facility are ready to move into the neighboring (target) facility. Second, check if there is residual capacity in the neighboring facility, allowing evacuees to move in. Third, if the answer to the first and second questions is yes, then move evacuees into the target facility. If any answer is no, then queuing occurs (see Fig. 3).

A possible evacuation route can be modeled as a series of connected source facilities and target facilities. A current target facility becomes the source facility as people move through the evacuation route. For example, people move from the AV room (source facility) into the corridor (target facility), then move from the corridor (source facility) into the stairway (target facility), and so on. As people gradually move through the evacuation route, they eventually arrive at the destination.

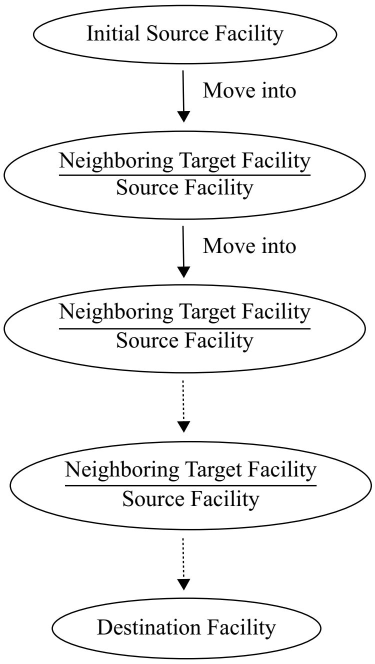

Fig. 3. Mechanism for advancing simulation.

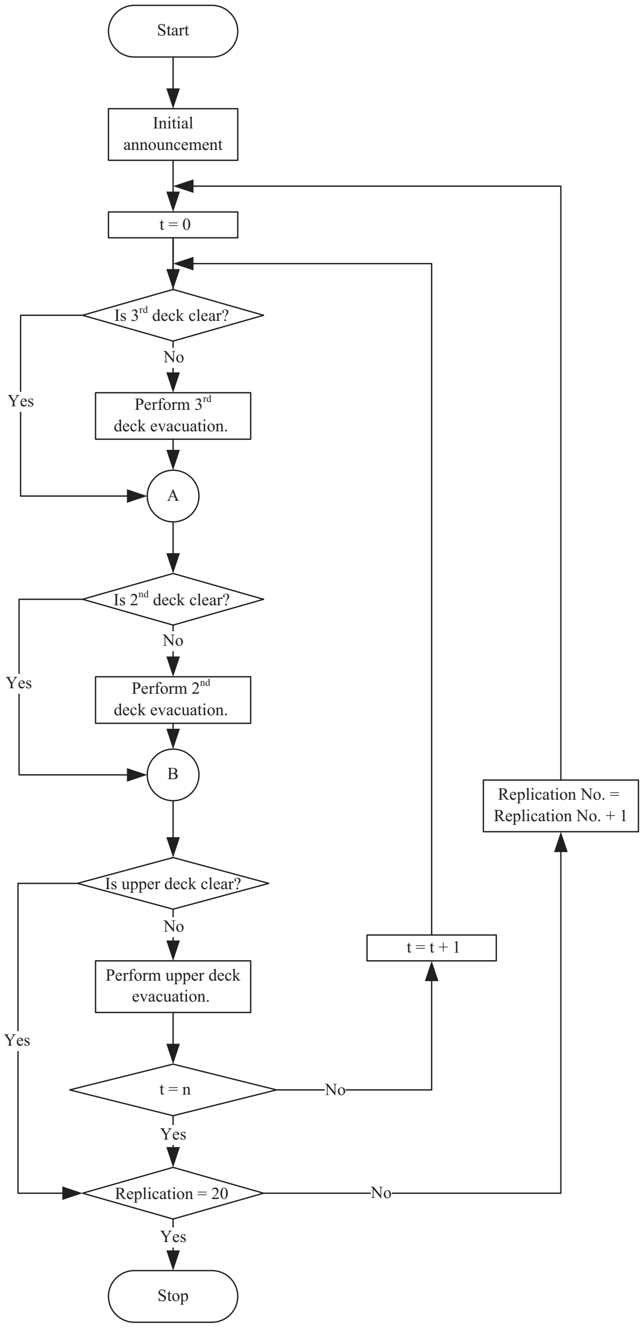

Fig. 4. Simulation flow diagrams.

Fig. 4 depicts the main flow process of this study. All initial parameters are declared at the beginning of the flow diagram. Unlike land building evacuation, maritime evacuation equipments (the life boats and survival crafts) are stored on top of the ship. Thus, the direction of evacuation is upward. The check of clearness of people is from the lowest deck to the upper deck. This flow diagram, at the same time t, checks all decks including the 3rd deck, the 2nd deck, and the upper deck. This program uses three switch values to denote the clearness of people on the 3rd deck, 2nd deck, and upper deck, respectively. If a certain deck is clear (the switch value equals 1), the program stops scanning that deck and jumps to the connection node A or B and then proceeds to next deck directly. In the flow diagram, we run the program with 20 repetitions by setting the same scenarios and the same portion of evacuees. In calculating the mean evacuation times, we searched these means with a minimum evacuation time to decide the correspondence to the optimal evacuation route.

Fig. 5 shows a detailed flow diagram of the 3rd deck. From Fig. 2, we know that people escaping from AV3.1 will move into CO3.2. After entering CO3.2, people can move either forward (through CO3.1 to SW3.1) or aft (through DR3.1 to SW3.2). The flow diagram in Fig. 5 can be divided into two parts by the red dash line. The flow diagram above the dash line represents the detailed coding logic of people moving aft and the flow diagram under the dash line stands for the detailed coding logic of people moving forward.

Because there are so many possible scenarios of evacuation in Fig. 5, we just demonstrate one possible scenario for explanation purpose. Starting at the top of the flow diagram, the program checks if there are more than two cadets in AV3.1 to enter CO3.2 and there is enough residual capacity left in CO3.2 at time t (blue diamonds). If both answers are yes, our program will allow two cadets to enter CO3.2 at time t + 1 and update the number of cadets in both AV3.1and CO3.2 as well as the residual capacity and density of CO3.2 (blue rectangle).

The clear width of SW3.2 is only 750mm allowing only one person to pass at a time. The program checks if there is a cadet in CO3.2 to enter SW3.2 and there is enough residual capacity left in SW3.2 (orange diamonds). If both answers are yes, our program will allow one cadet to enter SW3.2 at time t + 1 and update the number of cadets in CO3.2 and

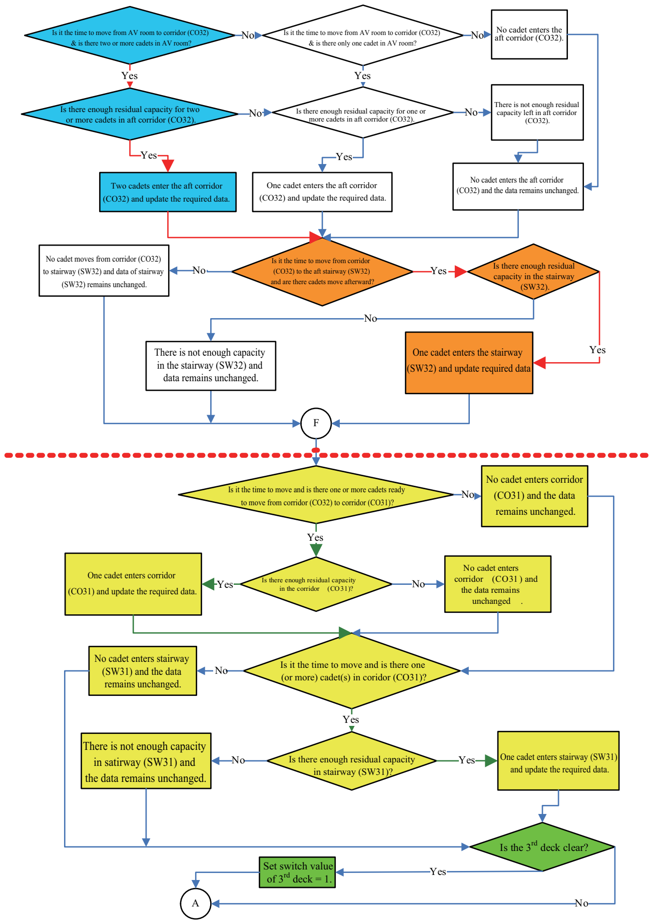

Fig. 5. Flow chart of the 3rd deck evacuation.

SW3.2 as well as the residual capacity and density of SW3.2 (orange rectangle).

With similar reasoning, we have the detailed coding logic of people moving forward (the flow diagram under the red dash line). The green diamond is used to check whether the 3rd deck has been clear or not. If the answer is yes, then, set switch value of the 3rd deck equals one. When the switch value is equal to one, the program will stop scanning this deck and go directly to scan the 2nd deck.

It is more complicated to evacuate from the 2nd deck and the upper deck. Whether cadets to escape from the nearest stairway or to change the route to go to the farther stairway due to crowd, there are many detailed flow diagrams like Fig. 5 for explanation. Due to the length limit of the manuscript, we could not demo all flow diagrams. If readers have interesting about these diagrams, they are available upon request.

4. Model Verification and Validation

Verification is concerned with determining if the simulation computer program is working as intended, and the initial verification efforts included following:

(1) The model was coded and debugged in steps.
(2) Model output results were checked for reasonableness.
(3) Model summary statistics for the values generated from the input probability distribution were compared to historical data summary statistics (Law and Kelton, 2000).

The FORTRAN language was used to write the simulation model. We did not find any program errors after running the FORTRAN program. Furthermore, checking input parameters revealed that the output results of the model were reasonable. Thus, model verification was achieved. If input data parameters and logical structure of the model are correctly represented in the computer, verification has been completed (Banks et al., 2005).

Since accurate records on the actual system do not exist, then it may be impossible to validate the model. In this case, concentrate on the verification and use the best judgment of individuals who are the most familiar with the system's capability. We had the simulation results reviewed by the captain of the training ship for reasonableness. Captain agreed that the simulation results are consistent with perceived system behavior, so our model is said to have face validity (Kelton et al., 2008).

V. SIMULATION RESULT

As pointed out by Galea et al. (2002), the simulation must address a number of aspects:

(1) Configurational: the physical layout and arrangement of the vessel with dimensions of rooms, corridors and stairways.
(2) Environmental: factors that affect people under the evacuation, such as ship listing, ship motion, presence of debris, heat, smoke, toxic substances, etc.
(3) Procedural: basic rules for the phases in the evacuation process, for example, rules related to the guidance of passengers by the crew, the organization at mustering stations, etc.
(4) Behavioral: characteristics of how individuals behave and perform. The group of people on board should reflect a realistic composition in terms of sex, age, walking speed and ability to respond adequately. Some of these attributes may be dynamic and change values during the evacuation.

Following Galea's suggestion, this study introduces the configuration in Section 3 and assumes the environment is calm weather with no listing or effect of fire. As to the procedural aspect, this study assumes that cadets follow the guidance of crew and move forward the mustering station. The behavioral characteristics of an evacuee can be reflected by gender, age and moving capacity. All these characteristics can be quantified by walking speed as shown in Tables 3 and 4.

To find the optimal evacuation plan, it is necessary to find the route with the minimum evacuation time. In our simulation model, evacuation time can be expressed as a function of three variables: walking speed, the number of cadets turning to the left or right at T junctions and the number of cadets moving forward or aft in the corridors. In the program, we set walking speed 1.2 m/s which is suggested by IMO. The remaining two

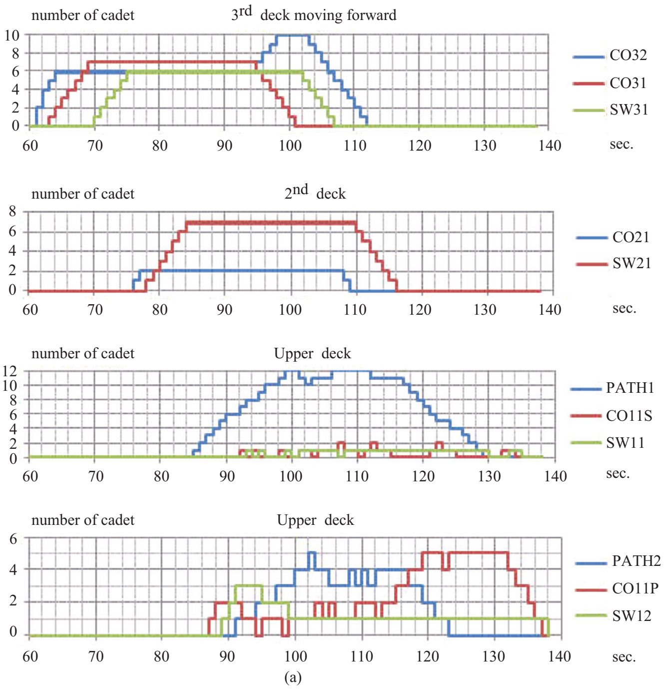

Fig. 6a The number of cadets and elapsed time at different facilities (Initial Pavy = 32, RN > = 0.7).

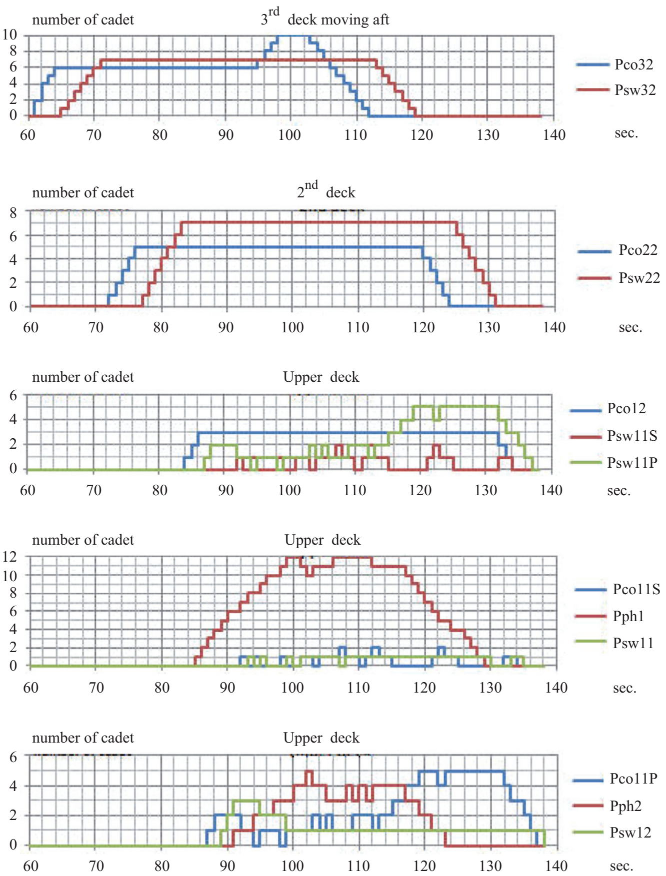

Fig. 6b The number of cadets and the elapsed time at different facilities (Initial Pavx = 48, RN > = 0.7).

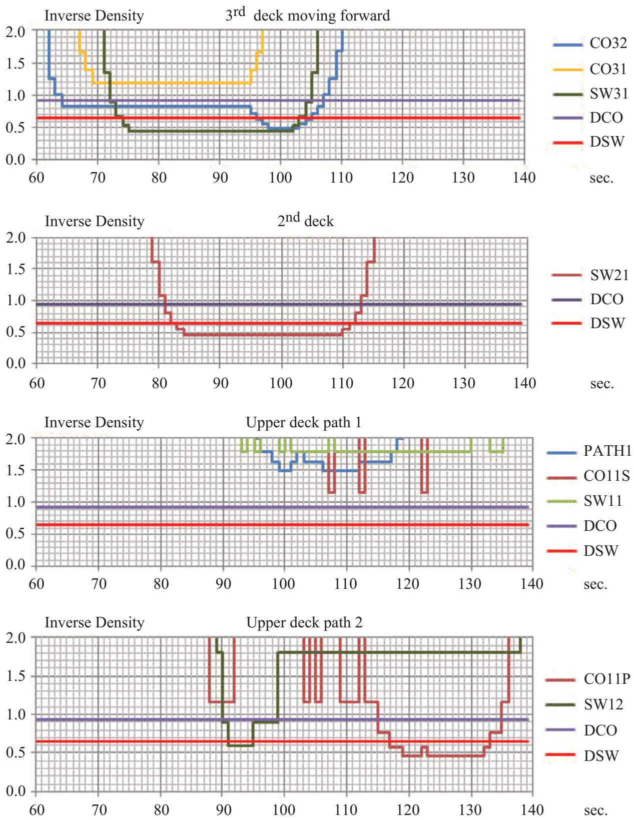

Fig. 6c Inverse Density at different facilities.

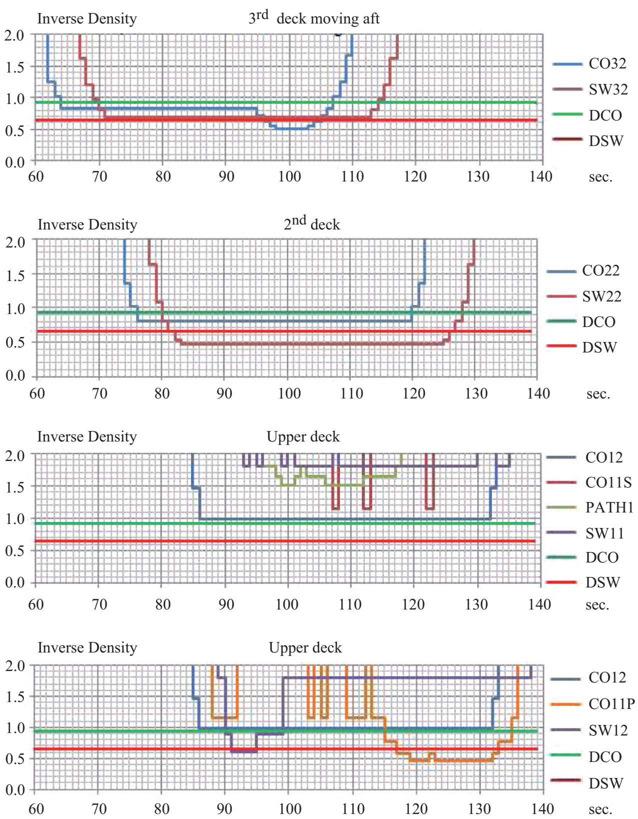

Fig. 6d Inverse Density at different facilities.

Table 5. One way ANOVA of the mean evacuation time.

		RN > = 0.0 (all turn right) Abstract			RN > = 0.1 Abstract			RN > = 0.2 Abstract		
Component	Number	SUM	MEAN	VAR	SUM	MEAN	VAR	SUM	MEAN	VAR
0%	20	3620	181.0	0.000	3453	172.7	6.345	3338	166.9	2.200
10%	20	3460	173.0	0.000	3315	165.8	3.776	3177	158.9	2.871
20%	20	3300	165.0	0.000	3188	159.4	7.200	3079	154.0	7.103
30%	20	3140	157.0	0.000	3061	153.1	5.524	2973	148.7	15.082
40%	20	2980	149.0	0.000	2916	145.8	6.484	2875	143.8	4.303
50%	20	2820	141.0	0.000	2844	142.2	1.116	2842	142.1	5.358
60%	20	2780	139.0	0.000	2861	143.1	10.682	2845	142.3	8.303
70%	20	2940	147.0	0.000	2933	146.7	5.503	2899	145.0	1.734
80%	20	3100	155.0	0.000	3053	152.7	1.187	3040	152.0	0.000
90%	20	3260	163.0	0.000	3203	160.2	0.239	3200	160.0	0.000
100%	20	3420	171.0	0.000	3361	168.1	0.050	3360	168.0	0.000
		F	P-value	Critical	F	P-value	Critical	F	P-value	Critical
		65535	0.000	1.876	508.478	9.76E-141	1.876	424.870	6E-133	1.876

		RN > = 0.3 Abstract			RN > = 0.4 Abstract			RN > = 0.5 Abstract		
Component	Number	SUM	MEAN	VAR	SUM	MEAN	VAR	SUM	MEAN	VAR
0%	20	3320	166.0	0.000	3320	166.0	0.000	3320	166.0	0.000
10%	20	3163	158.2	0.450	3160	158.0	0.000	3160	158.0	0.000
20%	20	3004	150.2	0.484	3000	150.0	0.000	3000	150.0	0.000
30%	20	2899	145.0	11.629	2857	142.9	3.082	2846	142.3	0.853
40%	20	2836	141.8	5.221	2837	141.9	7.503	2830	141.5	11.842
50%	20	2849	142.5	7.945	2829	141.5	10.997	2803	140.2	10.029
60%	20	2844	142.2	9.011	2835	141.8	10.829	2819	141.0	9.524
70%	20	2883	144.2	0.239	2881	144.1	0.050	2880	144.0	0.000
80%	20	3040	152.0	0.000	3040	152.0	0.000	3040	152.0	0.000
90%	20	3200	160.0	0.000	3200	160.0	0.000	3200	160.0	0.000
100%	20	3360	168.0	0.000	3360	168.0	0.000	3360	168.0	0.000
		F	P-value	Critical	F	P-value	Critical	F	P-value	Critical
		603.332	3.31E-148	1.876	690.613	3.87E-154	1.876	736.351	5.80E-157	1.876

		RN > = 0.6 Abstract			**RN > = 0.7 Abstract**			RN > = 0.8 Abstract		
Component	Number	SUM	MEAN	VAR	**SUM**	**MEAN**	**VAR**	SUM	MEAN	VAR
0%	20	3320	166.0	0.000	**3320**	**166.0**	**0.000**	3338	166.9	2.200
10%	20	3160	158.0	0.000	**3160**	**158.0**	**0.000**	3177	158.9	2.871
20%	20	3000	150.0	0.000	**3000**	**150.0**	**0.000**	3079	154.0	7.103
30%	20	2857	142.9	3.082	**2879**	**144.0**	**4.997**	2973	148.7	15.082
40%	20	2837	141.9	7.503	**2856**	**142.8**	**11.958**	2875	143.8	4.303
50%	20	2829	141.5	10.997	**2778**	**138.9**	**9.042**	2842	142.1	5.358
60%	20	2835	141.8	10.829	**2759**	**138.0**	**4.155**	2845	142.3	8.303
70%	20	2881	144.1	0.050	**2882**	**144.1**	**0.200**	2899	145.0	1.734
80%	20	3040	152.0	0.000	**3040**	**152.0**	**0.000**	3040	152.0	0.000
90%	20	3200	160.0	0.000	**3200**	**160.0**	**0.000**	3200	160.0	0.000
100%	20	3360	168.0	0.000	**3360**	**168.0**	**0.000**	3360	168.0	0.000
		F	P-value	Critical	**F**	**P-value**	**Critical**	F	P-value	Critical
		690.613	3.8735E-154	1.876	**817.024**	**1.49E-161**	**1.876**	424.870	6E-133	1.876

		RN > = 0.9 Abstract			RN > = 1.0 (all turn left) Abstract		
Component	Number	SUM	MEAN	VAR	SUM	MEAN	VAR
0%	20	3454	172.7	6.221	3600	180.0	0.000
10%	20	3315	165.8	3.776	3440	172.0	0.000
20%	20	3188	159.4	7.200	3280	164.0	0.000
30%	20	3061	153.1	5.524	3120	156.0	0.000
40%	20	2916	145.8	6.484	2960	148.0	0.000
50%	20	2844	142.2	1.116	2800	140.0	0.000
60%	20	2861	143.1	10.682	2780	139.0	0.000
70%	20	2933	146.7	5.503	2940	147.0	0.000
80%	20	3053	152.7	1.187	3100	155.0	0.000
90%	20	3203	160.2	0.239	3260	163.0	0.000
100%	20	3361	168.1	0.050	3420	171.0	0.000
		F	P-value	Critical	F	P-value	Critical
		510.580	6.457E-141	1.876	65535	0.000	1.876

variables affecting the evacuating time can be controlled and varied by the random number and the loop in the FORTRAN program, respectively.

By setting variables affecting evacuation time and executing the FORTRAN program, we can obtain the detail information of the cadet in different facilities at a different time easily. Tables A.1 and A.2 (Appendix) show information of the fastest case. Based on the data of Tables A.1 and A.2, we can plot the Figs. 6a and 6b. By converting data into pictures, it is easier to visualize the number of cadets at different facilities at any time and the elapses time of each facility. The elapsed time of each facility is defined as from the first cadet coming into the facility to the last cadet going out the facility.

Tables A.3 and A.4 in appendix summarize the work of Fruin (1970), the level of service standards for walkways and stairways. Based on service level E, the critical values of congestion occurred at corridors and stairways are 0.93 and 0.65, respectively. Congestion can be defined by an inverse density smaller than 0.93 for corridors and inverse density smaller than 0.65 for stairways. As long as the inverse density is less than the critical value, congestion occurs at the facility. Using the data of Tables A.1 and A.2, we first calculated the inverse density of each facility and presented in Tables A.5 and A.6, and then we draw the Figs. 6c and 6d. The horizontal lines DCO and DSW represent the critical values of congestion occurred at corridor and stairway based on the service level E. By looking at the Figs. 6c and 6d, we can find the congestion facilities easily as long as the inverse density is below DCO and DSW. The main congestions occur on the 3rd deck CO3.2, SW3.1 and the 2nd deck CO2.2, SW2.1, SW2.2, and the upper deck CO1.1.P, SW1.2. This is because the walking speed from the corridor (walking speed = 1.2 m/s) to the stairway (walking speed = 0.79 m/s) decreases 0.41 m/s, causing some waiting. Another reason is when cadets made route choice, most cadets turned left, causing congestion in that target facility.

By varying two variables, the number of cadets moving forward or aft in the corridors and the number of cadets turning to the left or right at T junctions, we executed the program 121 times, each with 20 iterations. After running the program, we acquired the data and performed one way ANOVA (Table 5). In Table 5, RN stands for random number used to determine the probability of cadets turning left at T junctions in the escape route. (RN > = 0 represents all cadets turn right, RN >= 1 represents all cadets turn left). The Component column means the proportion of cadets going aft. Because there were eighty cadets in the experiment, 10% means eight cadets going aft. The Number column denotes the iteration number of each simulation. The SUM, MEAN and VAR columns represent the total evacuation time of twenty iterations, mean evacuation time and standard deviation, respectively. By looking at Table 5 carefully, we can find the minimum evacuation time is 138 seconds and the probability of turning left is equal 0.7 (RN >= 0.7).

Actually, in practice, it is hard to control human behavior. Some measures must be taken in order to achieve minimum

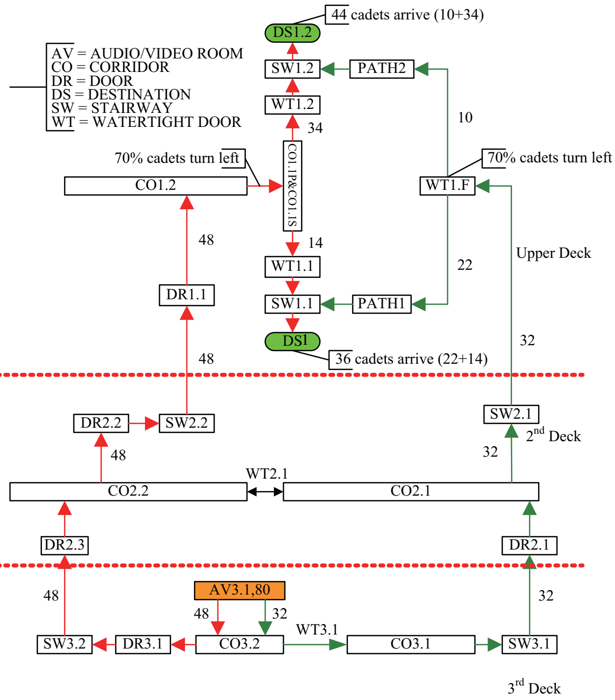

Fig. 7. Fastest evacuation route.

evacuation time. A muster drill must be conducted to familiarize crew and passengers with escape routes. Some flat screen TVs installed on the wall of corridors show detailed evacuation routes of the simulation. A commander and guide crew on site must help the passengers to follow and find optimum evacuation routes.

In fact, most people use their right hands. When walking in a dark circumstance or a dangerous condition, most people turn left at T junctions naturally. This is the reason why that the stronger right side protects the weaker left side, giving people a sense of security in turning left. Helbing et al. (2000) showed the absolute difference in the numbers of persons leaving through the left exit or right exit as a function of the panic parameters. Our study assumes that 70% of cadets turn left when making a route choice. Thus, 138.0 seconds is the simulated evacuation time for 48 cadets going aft and 32 cadets going forward (see Table 5, RN > = 0.7, Component = 60%, MEAN = 138.0). Under this condition, cadet's evacuation goes through two routes. One is going aft through CO3.2, SW3.2, CO2.2, SW2.2, CO1.2, and then turning right through CO1.1S, SW1.1 to arrive at destination DS1.1 or turning left through CO1.1P, SW1.2 to arrive at destination DS1.2 (Fig. 7, the red arrow route). The other is going forward through CO3.1, SW3.1, CO2.1, SW2.1, and then turning left through the PATH1, SW1.1 to arrive at destination DS1.1 or to turn right through PATH2, SW1.2 to arrive at destination DS1.2 (Fig. 7, the green arrow route). These routes and the number of cadets represent the evacuation plan on a training ship by minimizing the total evacuation time.

In a small training ship, one may obtain some of the shortest paths between sources nodes and destination nodes by observation. These shortest paths happen to provide routes with minimum evacuation time. However, how many cadets must be assign to routes is another question. To answer this question must use a computer simulation like our study. In fact, before cadets reach their destination, they would meet many T junctions. Each T junction is a decision point, turn right or left. Besides, if they found too many persons in the facility (corridor or stairway), they may change the route using an alternative exit. By computer simulation, we can find congestion points, avoid bottlenecks and evacuate at minimum time.

VI. CONCLUSIONS

A ship at sea is like an isolating island; if an accident occurs, it often results in loss of human life. To prevent this type of tragedy, the emergency evacuation of a ship is an important issue in case of an accident. Although the IMO regulations allow simplified analyses carried out by hand, advanced evacuation simulations using ship evacuation software and computer for calculations are considered to be a time saving and cost effective option. This study presents a simple and efficient system simulation model to identify the cadet evacuation route to increase safety of life at sea. The proposed model modifies a hydraulic model and considers human factors. To the best of our knowledge, this scenario has not been considered in the literature.

The proposed model offers greater programming controllability, cheaper cost and a shorter model execution time. With a small modification and changing the input parameters, it is possible to find the fastest evacuation route of any type of ship easily. The inclusion of human factors, such as left/right turns is novel in a ship evacuation model. Hence, this model can be an alternative method for planning training or passenger ship evacuation. As for further research, other human factors, such as group effects and kin behavior, can be incorporated into our model. Use of such model is thus believed to be the preferable choice for executing evacuation analyses in the future. Furthermore, an animation of our model can be built to provide more insights into the evacuation procedures.

APPENDIX

Table A .1 The number of cadets in each facility at different times (corresponding to red arrow route in Fig. 7).

Facility / t	Pco32	Psw32	Pco22	Psw22	Pco12	Pco11S	Pph1	Psw11	Pds11	Pco11P	Pph2	Psw12	Pds12
60	0	0	0	0	0	0	0	0	0	0	0	0	0
61	2	0	0	0	0	0	0	0	0	0	0	0	0
62	4	0	0	0	0	0	0	0	0	0	0	0	0
63	5	0	0	0	0	0	0	0	0	0	0	0	0
64	6	0	0	0	0	0	0	0	0	0	0	0	0
65	6	1	0	0	0	0	0	0	0	0	0	0	0
66	6	2	0	0	0	0	0	0	0	0	0	0	0
67	6	3	0	0	0	0	0	0	0	0	0	0	0
68	6	4	0	0	0	0	0	0	0	0	0	0	0
69	6	5	0	0	0	0	0	0	0	0	0	0	0
70	6	6	0	0	0	0	0	0	0	0	0	0	0
71	6	7	0	0	0	0	0	0	0	0	0	0	0
72	6	7	1	0	0	0	0	0	0	0	0	0	0
73	6	7	2	0	0	0	0	0	0	0	0	0	0
74	6	7	3	0	0	0	0	0	0	0	0	0	0
75	6	7	4	0	0	0	0	0	0	0	0	0	0
76	6	7	5	0	0	0	0	0	0	0	0	0	0
77	6	7	5	1	0	0	0	0	0	0	0	0	0
78	6	7	5	2	0	0	0	0	0	0	0	0	0
79	6	7	5	3	0	0	0	0	0	0	0	0	0
80	6	7	5	4	0	0	0	0	0	0	0	0	0
81	6	7	5	5	0	0	0	0	0	0	0	0	0
82	6	7	5	6	0	0	0	0	0	0	0	0	0
83	6	7	5	7	0	0	0	0	0	0	0	0	0
84	6	7	5	7	1	0	0	0	0	0	0	0	0
85	6	7	5	7	2	0	1	0	0	0	0	0	0
86	6	7	5	7	3	0	2	0	0	0	0	0	0
87	6	7	5	7	3	0	3	0	0	1	0	0	0
88	6	7	5	7	3	0	4	0	0	2	0	0	0

Table A .1 (Continued)

Facility / t	Pco32	Psw32	Pco22	Psw22	Pco12	Pco11S	Pph1	Psw11	Pds11	Pco11P	Pph2	Psw12	Pds12
89	6	7	5	7	3	0	5	0	0	2	0	1	0
90	6	7	5	7	3	0	6	0	0	2	0	2	0
91	6	7	5	7	3	0	6	0	0	2	1	3	0
92	6	7	5	7	3	1	7	0	0	1	1	3	1
93	6	7	5	7	3	0	8	1	0	1	1	3	2
94	6	7	5	7	3	1	8	0	1	0	2	3	3
95	7	7	5	7	3	0	9	1	1	1	2	2	4
96	8	7	5	7	3	0	10	0	2	1	2	2	5
97	9	7	5	7	3	0	10	0	2	1	3	2	6
98	10	7	5	7	3	1	11	0	2	0	3	2	7
99	10	7	5	7	3	0	12	1	2	1	3	1	8
100	10	7	5	7	3	0	12	0	3	1	4	1	9
101	10	7	5	7	3	1	11	1	3	1	4	1	10
102	10	7	5	7	3	1	10	1	4	1	5	1	11
103	9	7	5	7	3	0	11	1	5	2	4	1	12
104	8	7	5	7	3	1	11	1	6	1	4	1	13
105	7	7	5	7	3	1	11	1	7	2	3	1	14
106	6	7	5	7	3	1	12	1	8	1	3	1	15
107	5	7	5	7	3	2	12	0	9	1	3	1	16
108	4	7	5	7	3	1	12	1	9	1	4	1	17
109	3	7	5	7	3	1	12	1	10	2	3	1	18
110	2	7	5	7	3	0	12	1	11	2	4	1	19
111	1	7	5	7	3	1	12	1	12	2	3	1	20
112	0	7	5	7	3	2	11	1	13	1	4	1	21
113	0	6	5	7	3	1	11	1	14	2	4	1	22
114	0	5	5	7	3	1	11	1	15	2	4	1	23
115	0	4	5	7	3	0	11	1	16	3	4	1	24
116	0	3	5	7	3	0	11	1	17	3	4	1	25
117	0	2	5	7	3	0	10	1	18	4	3	1	26
118	0	1	5	7	3	0	9	1	19	4	3	1	27
119	0	0	5	7	3	0	8	1	20	5	2	1	28
120	0	0	4	7	3	0	7	1	21	5	2	1	29
121	0	0	3	7	3	1	6	1	22	5	1	1	30
122	0	0	2	7	3	2	5	1	23	4	1	1	31
123	0	0	1	7	3	1	5	1	24	5	0	1	32
124	0	0	0	7	3	1	4	1	25	5	0	1	33
125	0	0	0	6	3	0	4	1	26	5	0	1	34
126	0	0	0	5	3	0	3	1	27	5	0	1	35
127	0	0	0	4	3	0	2	1	28	5	0	1	36
128	0	0	0	3	3	0	1	1	29	5	0	1	37
129	0	0	0	2	3	0	0	1	30	5	0	1	38
130	0	0	0	1	3	0	0	0	31	5	0	1	39
131	0	0	0	0	3	0	0	0	31	5	0	1	40
132	0	0	0	0	2	1	0	0	31	4	0	1	41
133	0	0	0	0	1	1	0	1	31	3	0	1	42
134	0	0	0	0	0	0	0	1	32	3	0	1	43
135	0	0	0	0	0	0	0	0	33	2	0	1	44
136	0	0	0	0	0	0	0	0	33	1	0	1	45
137	0	0	0	0	0	0	0	0	33	0	0	1	46
138	0	0	0	0	0	0	0	0	33	0	0	0	47

RN > = 0.7, Pavx = 48, Pavy = 32

Table A.2 The number of cadets in each facility at different times (corresponding to green arrow route in Fig. 7).

t \ Facility	Pco32	Pco31	Psw31	Pco21	Psw21	Pph1	Pco11S	Psw11	Pds11	Pph2	Pco11P	Psw12	Pds12
60	0	0	0	0	0	0	0	0	0	0	0	0	0
61	2	0	0	0	0	0	0	0	0	0	0	0	0
62	4	0	0	0	0	0	0	0	0	0	0	0	0
63	5	1	0	0	0	0	0	0	0	0	0	0	0
64	6	2	0	0	0	0	0	0	0	0	0	0	0
65	6	3	0	0	0	0	0	0	0	0	0	0	0
66	6	4	0	0	0	0	0	0	0	0	0	0	0
67	6	5	0	0	0	0	0	0	0	0	0	0	0
68	6	6	0	0	0	0	0	0	0	0	0	0	0
69	6	7	0	0	0	0	0	0	0	0	0	0	0
70	6	7	1	0	0	0	0	0	0	0	0	0	0
71	6	7	2	0	0	0	0	0	0	0	0	0	0
72	6	7	3	0	0	0	0	0	0	0	0	0	0
73	6	7	4	0	0	0	0	0	0	0	0	0	0
74	6	7	5	0	0	0	0	0	0	0	0	0	0
75	6	7	6	0	0	0	0	0	0	0	0	0	0
76	6	7	6	1	0	0	0	0	0	0	0	0	0
77	6	7	6	2	0	0	0	0	0	0	0	0	0
78	6	7	6	2	1	0	0	0	0	0	0	0	0
79	6	7	6	2	2	0	0	0	0	0	0	0	0
80	6	7	6	2	3	0	0	0	0	0	0	0	0
81	6	7	6	2	4	0	0	0	0	0	0	0	0
82	6	7	6	2	5	0	0	0	0	0	0	0	0
83	6	7	6	2	6	0	0	0	0	0	0	0	0
84	6	7	6	2	7	0	0	0	0	0	0	0	0
85	6	7	6	2	7	1	0	0	0	0	0	0	0
86	6	7	6	2	7	2	0	0	0	0	0	0	0
87	6	7	6	2	7	3	0	0	0	0	1	0	0
88	6	7	6	2	7	4	0	0	0	0	2	0	0
89	6	7	6	2	7	5	0	0	0	0	2	1	0
90	6	7	6	2	7	6	0	0	0	0	2	2	0
91	6	7	6	2	7	6	0	0	0	1	2	3	0
92	6	7	6	2	7	7	1	0	0	1	1	3	1
93	6	7	6	2	7	8	0	1	0	1	1	3	2
94	6	7	6	2	7	8	1	0	1	2	0	3	3
95	7	6	6	2	7	9	0	1	1	2	1	2	4
96	8	5	6	2	7	10	0	0	2	2	1	2	5
97	9	4	6	2	7	10	0	0	2	3	1	2	6
98	10	3	6	2	7	11	1	0	2	3	0	2	7
99	10	2	6	2	7	12	0	1	2	3	1	1	8
100	10	1	6	2	7	12	0	0	3	4	1	1	9
101	10	0	6	2	7	11	1	1	3	4	1	1	10
102	10	0	5	2	7	10	1	1	4	5	1	1	11
103	9	0	4	2	7	11	0	1	5	4	2	1	12
104	8	0	3	2	7	11	1	1	6	4	1	1	13
105	7	0	2	2	7	11	1	1	7	3	2	1	14
106	6	0	1	2	7	12	1	1	8	3	1	1	15
107	5	0	0	2	7	12	2	0	9	3	1	1	16
108	4	0	0	1	7	12	1	1	9	4	1	1	17
109	3	0	0	0	7	12	1	1	10	3	2	1	18
110	2	0	0	0	6	12	0	1	11	4	2	1	19
111	1	0	0	0	5	12	1	1	12	3	2	1	20
112	0	0	0	0	4	11	2	1	13	4	1	1	21
113	0	0	0	0	3	11	1	1	14	4	2	1	22

Table A.2 (Continued)

Facility / t	Pco32	Pco31	Psw31	Pco21	Psw21	Pph1	Pco11S	Psw11	Pds11	Pph2	Pco11P	Psw12	Pds12
114	0	0	0	0	2	11	1	1	15	4	2	1	23
115	0	0	0	0	1	11	0	1	16	4	3	1	24
116	0	0	0	0	0	11	0	1	17	4	3	1	25
117	0	0	0	0	0	10	0	1	18	3	4	1	26
118	0	0	0	0	0	9	0	1	19	3	4	1	27
119	0	0	0	0	0	8	0	1	20	2	5	1	28
120	0	0	0	0	0	7	0	1	21	2	5	1	29
121	0	0	0	0	0	6	1	1	22	1	5	1	30
122	0	0	0	0	0	5	2	1	23	1	4	1	31
123	0	0	0	0	0	5	1	1	24	0	5	1	32
124	0	0	0	0	0	4	1	1	25	0	5	1	33
125	0	0	0	0	0	4	0	1	26	0	5	1	34
126	0	0	0	0	0	3	0	1	27	0	5	1	35
127	0	0	0	0	0	2	0	1	28	0	5	1	36
128	0	0	0	0	0	1	0	1	29	0	5	1	37
129	0	0	0	0	0	0	0	1	30	0	5	1	38
130	0	0	0	0	0	0	0	0	31	0	5	1	39
131	0	0	0	0	0	0	0	0	31	0	5	1	40
132	0	0	0	0	0	0	1	0	31	0	4	1	41
133	0	0	0	0	0	0	1	1	31	0	3	1	42
134	0	0	0	0	0	0	0	1	32	0	3	1	43
135	0	0	0	0	0	0	0	0	33	0	2	1	44
136	0	0	0	0	0	0	0	0	33	0	1	1	45
137	0	0	0	0	0	0	0	0	33	0	0	1	46
138	0	0	0	0	0	0	0	0	33	0	0	0	47

RN > = 0.7, Pavx = 48, Pavy = 32

Table A.3 Summary of level of service standards for walkways.

Level of Service	Average Area Module (Square Meter)	Normal Walking Speed	Reverse Flow	Cross Flow
A	> 3.25	Free	Free	Free
B	2.32 - 3.25	Free	Free	Restricted
C	1.39 - 2.32	Free	Restricted	Restricted
D	0.93 - 1.39	Restricted	Restricted	Severely Restricted
E	0.46 - 0.93	Restricted	Severely Restricted	Severely Restricted
F	< 0.46	Severely Restricted	Severely Restricted	Severely Restricted

Source: Fruin (1970).

Table A.4 Summary of level of service standards for stairway.

Level of Service	Average Area Module (Square Meter)	Normal Stair Locomotion Speed	Reverse Flow
A	> 1.86	Free	Free
B	1.39 - 1.86	Free	Free
C	0.93 - 1.39	Free	Restricted
D	0.65 - 0.93	Restricted	Restricted
E	0.37 - 0.65	Restricted	Severely Restricted
F	< 0.37	Severely Restricted	Severely Restricted

Source: Fruin (1970).

Table A.5 The inverse density of each facility at different times (corresponding to red arrow route in Fig. 7).

t \ Facility	Dco32	Dco31	Dsw31	Dco21	Dsw21	Dph1	Dco11s	Dsw11	Dph2	Dco11P	Dsw12
60	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
61	2.520	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
62	1.260	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
63	1.008	8.350	∞	∞	∞	∞	∞	∞	∞	∞	∞
64	0.840	4.175	∞	∞	∞	∞	∞	∞	∞	∞	∞
65	0.840	2.783	∞	∞	∞	∞	∞	∞	∞	∞	∞
66	0.840	2.088	∞	∞	∞	∞	∞	∞	∞	∞	∞
67	0.840	1.670	∞	∞	∞	∞	∞	∞	∞	∞	∞
68	0.840	1.392	∞	∞	∞	∞	∞	∞	∞	∞	∞
69	0.840	1.193	∞	∞	∞	∞	∞	∞	∞	∞	∞
70	0.840	1.193	2.700	∞	∞	∞	∞	∞	∞	∞	∞
71	0.840	1.193	1.350	∞	∞	∞	∞	∞	∞	∞	∞
72	0.840	1.193	0.900	∞	∞	∞	∞	∞	∞	∞	∞
73	0.840	1.193	0.675	∞	∞	∞	∞	∞	∞	∞	∞
74	0.840	1.193	0.540	∞	∞	∞	∞	∞	∞	∞	∞
75	0.840	1.193	0.450	∞	∞	∞	∞	∞	∞	∞	∞
76	0.840	1.193	0.450	4.320	∞	∞	∞	∞	∞	∞	∞
77	0.840	1.193	0.450	2.160	∞	∞	∞	∞	∞	∞	∞
78	0.840	1.193	0.450	2.160	3.240	∞	∞	∞	∞	∞	∞
79	0.840	1.193	0.450	2.160	1.620	∞	∞	∞	∞	∞	∞
80	0.840	1.193	0.450	2.160	1.080	∞	∞	∞	∞	∞	∞
81	0.840	1.193	0.450	2.160	0.810	∞	∞	∞	∞	∞	∞
82	0.840	1.193	0.450	2.160	0.648	∞	∞	∞	∞	∞	∞
83	0.840	1.193	0.450	2.160	0.540	∞	∞	∞	∞	∞	∞
84	0.840	1.193	0.450	2.160	0.463	∞	∞	∞	∞	∞	∞
85	0.840	1.193	0.450	2.160	0.463	18.000	∞	∞	∞	∞	∞
86	0.840	1.193	0.450	2.160	0.463	9.000	∞	∞	∞	∞	∞
87	0.840	1.193	0.450	2.160	0.463	6.000	∞	∞	∞	2.310	∞
88	0.840	1.193	0.450	2.160	0.463	4.500	∞	∞	∞	1.155	∞
89	0.840	1.193	0.450	2.160	0.463	3.600	∞	∞	∞	1.155	1.800
90	0.840	1.193	0.450	2.160	0.463	3.000	∞	∞	∞	1.155	0.900
91	0.840	1.193	0.450	2.160	0.463	3.000	∞	∞	20.000	1.155	0.600
92	0.840	1.193	0.450	2.160	0.463	2.571	2.310	∞	20.000	2.310	0.600
93	0.840	1.193	0.450	2.160	0.463	2.250	∞	1.800	20.000	2.310	0.600
94	0.840	1.193	0.450	2.160	0.463	2.250	2.310	∞	10.000	∞	0.600
95	0.720	1.392	0.450	2.160	0.463	2.000	∞	1.800	10.000	2.310	0.900
96	0.630	1.670	0.450	2.160	0.463	1.800	∞	∞	10.000	2.310	0.900
97	0.560	2.088	0.450	2.160	0.463	1.800	∞	∞	6.667	2.310	0.900
98	0.504	2.783	0.450	2.160	0.463	1.636	2.310	∞	6.667	∞	0.900
99	0.504	4.175	0.450	2.160	0.463	1.500	∞	1.800	6.667	2.310	1.800
100	0.504	8.350	0.450	2.160	0.463	1.500	∞	∞	5.000	2.310	1.800
101	0.504	∞	0.450	2.160	0.463	1.636	2.310	1.800	5.000	2.310	1.800
102	0.504	∞	0.540	2.160	0.463	1.800	2.310	1.800	4.000	2.310	1.800
103	0.560	∞	0.675	2.160	0.463	1.636	∞	1.800	5.000	1.155	1.800
104	0.630	∞	0.900	2.160	0.463	1.636	2.310	1.800	5.000	2.310	1.800
105	0.720	∞	1.350	2.160	0.463	1.636	2.310	1.800	6.667	1.155	1.800
106	0.840	∞	2.700	2.160	0.463	1.500	2.310	1.800	6.667	2.310	1.800
107	1.008	∞	∞	2.160	0.463	1.500	1.155	∞	6.667	2.310	1.800
108	1.260	∞	∞	4.320	0.463	1.500	2.310	1.800	5.000	2.310	1.800
109	1.680	∞	∞	∞	0.463	1.500	2.310	1.800	6.667	1.155	1.800
110	2.520	∞	∞	∞	0.540	1.500	∞	1.800	5.000	1.155	1.800
111	5.040	∞	∞	∞	0.648	1.500	2.310	1.800	6.667	1.155	1.800
112	∞	∞	∞	∞	0.810	1.636	1.155	1.800	5.000	2.310	1.800
113	∞	∞	∞	∞	1.080	1.636	2.310	1.800	5.000	1.155	1.800
114	∞	∞	∞	∞	1.620	1.636	2.310	1.800	5.000	1.155	1.800

Table A.5 (Continued)

Facility / t	Dco32	Dco31	Dsw31	Dco21	Dsw21	Dph1	Dco11s	Dsw11	Dph2	Dco11P	Dsw12
115	∞	∞	∞	∞	3.240	1.636	∞	1.800	5.000	0.770	1.800
116	∞	∞	∞	∞	∞	1.636	∞	1.800	5.000	0.770	1.800
117	∞	∞	∞	∞	∞	1.800	∞	1.800	6.667	0.578	1.800
118	∞	∞	∞	∞	∞	2.000	∞	1.800	6.667	0.578	1.800
119	∞	∞	∞	∞	∞	2.250	∞	1.800	10.000	0.462	1.800
120	∞	∞	∞	∞	∞	2.571	∞	1.800	10.000	0.462	1.800
121	∞	∞	∞	∞	∞	3.000	2.310	1.800	20.000	0.462	1.800
122	∞	∞	∞	∞	∞	3.600	1.155	1.800	20.000	0.578	1.800
123	∞	∞	∞	∞	∞	3.600	2.310	1.800	∞	0.462	1.800
124	∞	∞	∞	∞	∞	4.500	2.310	1.800	∞	0.462	1.800
125	∞	∞	∞	∞	∞	4.500	∞	1.800	∞	0.462	1.800
126	∞	∞	∞	∞	∞	6.000	∞	1.800	∞	0.462	1.800
127	∞	∞	∞	∞	∞	9.000	∞	1.800	∞	0.462	1.800
128	∞	∞	∞	∞	∞	18.000	∞	1.800	∞	0.462	1.800
129	∞	∞	∞	∞	∞	∞	∞	1.800	∞	0.462	1.800
130	∞	∞	∞	∞	∞	∞	∞	∞	∞	0.462	1.800
131	∞	∞	∞	∞	∞	∞	∞	∞	∞	0.462	1.800
132	∞	∞	∞	∞	∞	∞	2.310	∞	∞	0.578	1.800
133	∞	∞	∞	∞	∞	∞	2.310	1.800	∞	0.770	1.800
134	∞	∞	∞	∞	∞	∞	∞	1.800	∞	0.770	1.800
135	∞	∞	∞	∞	∞	∞	∞	∞	∞	1.155	1.800
136	∞	∞	∞	∞	∞	∞	∞	∞	∞	2.310	1.800
137	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	1.800
138	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

RN > = 0.7, Pavx = 48, Pavy = 32

Table A.6 The inverse density of each facility at different times (corresponding to green arrow route in Fig. 7).

Facility / t	Dco32	Dsw32	Dco22	Dsw22	Dco12	Dco11S	Dph1	Dsw11	Dco11P	Dph2	Dsw12
60	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
61	2.520	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
62	1.260	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
63	1.008	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
64	0.840	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
65	0.840	4.860	∞	∞	∞	∞	∞	∞	∞	∞	∞
66	0.840	2.430	∞	∞	∞	∞	∞	∞	∞	∞	∞
67	0.840	1.620	∞	∞	∞	∞	∞	∞	∞	∞	∞
68	0.840	1.215	∞	∞	∞	∞	∞	∞	∞	∞	∞
69	0.840	0.972	∞	∞	∞	∞	∞	∞	∞	∞	∞
70	0.840	0.810	∞	∞	∞	∞	∞	∞	∞	∞	∞
71	0.840	0.694	∞	∞	∞	∞	∞	∞	∞	∞	∞
72	0.840	0.694	4.050	∞	∞	∞	∞	∞	∞	∞	∞
73	0.840	0.694	2.025	∞	∞	∞	∞	∞	∞	∞	∞
74	0.840	0.694	1.350	∞	∞	∞	∞	∞	∞	∞	∞
75	0.840	0.694	1.013	∞	∞	∞	∞	∞	∞	∞	∞
76	0.840	0.694	0.810	∞	∞	∞	∞	∞	∞	∞	∞
77	0.840	0.694	0.810	3.240	∞	∞	∞	∞	∞	∞	∞
78	0.840	0.694	0.810	1.620	∞	∞	∞	∞	∞	∞	∞
79	0.840	0.694	0.810	1.080	∞	∞	∞	∞	∞	∞	∞
80	0.840	0.694	0.810	0.810	∞	∞	∞	∞	∞	∞	∞
81	0.840	0.694	0.810	0.648	∞	∞	∞	∞	∞	∞	∞
82	0.840	0.694	0.810	0.540	∞	∞	∞	∞	∞	∞	∞

Table A.6 (Continued)

t \ Facility	Dco32	Dsw32	Dco22	Dsw22	Dco12	Dco11S	Dph1	Dsw11	Dco11P	Dph2	Dsw12
83	0.840	0.694	0.810	0.463	∞	∞	∞	∞	∞	∞	∞
84	0.840	0.694	0.810	0.463	2.940	∞	∞	∞	∞	∞	∞
85	0.840	0.694	0.810	0.463	1.470	∞	18.000	∞	∞	∞	∞
86	0.840	0.694	0.810	0.463	0.980	∞	9.000	∞	∞	∞	∞
87	0.840	0.694	0.810	0.463	0.980	∞	6.000	∞	2.310	∞	∞
88	0.840	0.694	0.810	0.463	0.980	∞	4.500	∞	1.155	∞	∞
89	0.840	0.694	0.810	0.463	0.980	∞	3.600	∞	1.155	∞	1.800
90	0.840	0.694	0.810	0.463	0.980	∞	3.000	∞	1.155	∞	0.900
91	0.840	0.694	0.810	0.463	0.980	∞	3.000	∞	1.155	20.000	0.600
92	0.840	0.694	0.810	0.463	0.980	2.310	2.571	∞	2.310	20.000	0.600
93	0.840	0.694	0.810	0.463	0.980	∞	2.250	1.800	2.310	20.000	0.600
94	0.840	0.694	0.810	0.463	0.980	2.310	2.250	∞	∞	10.000	0.600
95	0.720	0.694	0.810	0.463	0.980	∞	2.000	1.800	2.310	10.000	0.900
96	0.630	0.694	0.810	0.463	0.980	∞	1.800	∞	2.310	10.000	0.900
97	0.560	0.694	0.810	0.463	0.980	∞	1.800	∞	2.310	6.667	0.900
98	0.504	0.694	0.810	0.463	0.980	2.310	1.636	∞	∞	6.667	0.900
99	0.504	0.694	0.810	0.463	0.980	∞	1.500	1.800	2.310	6.667	1.800
100	0.504	0.694	0.810	0.463	0.980	∞	1.500	∞	2.310	5.000	1.800
101	0.504	0.694	0.810	0.463	0.980	2.310	1.636	1.800	2.310	5.000	1.800
102	0.504	0.694	0.810	0.463	0.980	2.310	1.800	1.800	2.310	4.000	1.800
103	0.560	0.694	0.810	0.463	0.980	∞	1.636	1.800	1.155	5.000	1.800
104	0.630	0.694	0.810	0.463	0.980	2.310	1.636	1.800	2.310	5.000	1.800
105	0.720	0.694	0.810	0.463	0.980	2.310	1.636	1.800	1.155	6.667	1.800
106	0.840	0.694	0.810	0.463	0.980	2.310	1.500	1.800	2.310	6.667	1.800
107	1.008	0.694	0.810	0.463	0.980	1.155	1.500	∞	2.310	6.667	1.800
108	1.260	0.694	0.810	0.463	0.980	2.310	1.500	1.800	2.310	5.000	1.800
109	1.680	0.694	0.810	0.463	0.980	2.310	1.500	1.800	1.155	6.667	1.800
110	2.520	0.694	0.810	0.463	0.980	∞	1.500	1.800	1.155	5.000	1.800
111	5.040	0.694	0.810	0.463	0.980	2.310	1.500	1.800	1.155	6.667	1.800
112	∞	0.694	0.810	0.463	0.980	1.155	1.636	1.800	2.310	5.000	1.800
113	∞	0.810	0.810	0.463	0.980	2.310	1.636	1.800	1.155	5.000	1.800
114	∞	0.972	0.810	0.463	0.980	2.310	1.636	1.800	1.155	5.000	1.800
115	∞	1.215	0.810	0.463	0.980	∞	1.636	1.800	0.770	5.000	1.800
116	∞	1.620	0.810	0.463	0.980	∞	1.636	1.800	0.770	5.000	1.800
117	∞	2.430	0.810	0.463	0.980	∞	1.800	1.800	0.578	6.667	1.800
118	∞	4.860	0.810	0.463	0.980	∞	2.000	1.800	0.578	6.667	1.800
119	∞	∞	0.810	0.463	0.980	∞	2.250	1.800	0.462	10.000	1.800
120	∞	∞	1.013	0.463	0.980	∞	2.571	1.800	0.462	10.000	1.800
121	∞	∞	1.350	0.463	0.980	2.310	3.000	1.800	0.462	20.000	1.800
122	∞	∞	2.025	0.463	0.980	1.155	3.600	1.800	0.578	20.000	1.800
123	∞	∞	4.050	0.463	0.980	2.310	3.600	1.800	0.462	∞	1.800
124	∞	∞	∞	0.463	0.980	2.310	4.500	1.800	0.462	∞	1.800
125	∞	∞	∞	0.540	0.980	∞	4.500	1.800	0.462	∞	1.800
126	∞	∞	∞	0.648	0.980	∞	6.000	1.800	0.462	∞	1.800
127	∞	∞	∞	0.810	0.980	∞	9.000	1.800	0.462	∞	1.800
128	∞	∞	∞	1.080	0.980	∞	18.000	1.800	0.462	∞	1.800
129	∞	∞	∞	1.620	0.980	∞	∞	1.800	0.462	∞	1.800
130	∞	∞	∞	3.240	0.980	∞	∞	∞	0.462	∞	1.800
131	∞	∞	∞	∞	0.980	∞	∞	∞	0.462	∞	1.800
132	∞	∞	∞	∞	1.470	2.310	∞	∞	0.578	∞	1.800
133	∞	∞	∞	∞	2.940	2.310	∞	1.800	0.770	∞	1.800
134	∞	∞	∞	∞	∞	∞	∞	1.800	0.770	∞	1.800
135	∞	∞	∞	∞	∞	∞	∞	∞	1.155	∞	1.800
136	∞	∞	∞	∞	∞	∞	∞	∞	2.310	∞	1.800
137	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	1.800
138	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

RN > = 0.7, Pavx = 48, Pavy = 32

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