A SIMULATION-BASED METHODOLOGY FOR EVALUATING THE FACTORS ON SHIP EMERGENCY EVACUATION

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SUMMARY

There are many hazards on a ship that makes an emergency evacuation process inevitable. Providing safe and effective evacuation of passengers from ships in an emergency situation becomes critical. Handling a real ship evacuation practice is often unaffordable as modelling such an environment is very expensive and may cause severe distress to participants. As an alternative, simulation models have been used to overwhelm the issue above in recent years. Therefore, this paper proposes a novel simulation-based methodology for evaluating the effect of factors including physical as well as psychological passenger characteristics and routeing systematic on emergency evacuation process for public marine transportation. A detailed questionnaire has been conducted in this work to reflect passenger characteristics on simulation model in a more realistic manner. Also, a new routeing systematic is developed to provide an efficient evacuation procedure. As another contribution, a novel grid-based approach where the meshed discretized nodes can contain more than one passenger is proposed in simulation model for the first time. Then, a statistical analysis is included within the methodology to assess the importance level of each factor on evacuation time. The proposed methodology is applied to a real life Ro-Ro ferry. A validation protocol based on IMO regulations is conducted and confirmed the effectiveness of the suggested simulation model. The simulation of different scenario types have indicated the influencing factors in a ship emergency evacuation. According to results, passenger characteristics has been identified as the most dominant factor on evacuation performance. The highest evacuation time difference has been observed for different levels of weight attribute. Moreover, it is concluded that the consideration of load utilization balancing among evacuation systems for routeing decreases evacuation time significantly. Finally, significant evacuation time difference between grid approaches have been demonstrated.

NOMENCLATURE

[Symbol]	[Definition] [(unit)]
a_{ij}	Distance order between the j^{th} MES and the i^{th} hall
AS	Set of halls that are partially or completely assigned to an MES
AUR	Average load factor of the MES
α_{lm}	Passengers' ratio for factor l and category m
β_w	Capacity ratio of MES_w
CAP_w	Total capacity of MES_w
cap_j	The capacity of the MES that is placed at the j^{th} MES
C_j:	Number of passengers who have been assigned to the j^{th} MES
d_{ij}	Distance from saloon i to the j^{th} MES
d_{oj}	Distance from seat group o to the j^{th} MES
IMO	International Maritime Organisation
IDO	Istanbul Sea Buses Industry and Trade
RGBS	Rigid Grid-Based Simulation
FBGBS	Flexible-Board Grid-Based Simulation
SIC	Safety Information Card
SDA	Shortest Distance Algorithm
SDA+EPLRBA	Shortest Distance Algorithm is integrated with Evacuation Points Load Rate Balancing Algorithm
MES	Marine Evacuation System
N	Number of evacuation points
M	Number of saloons
ESI	Smoothing index of the evacuation
ts_j	Total number of passengers directed to the j^{th} MES
LSA_j	Set of MESs that passengers can be transferred from
P	Number of seat groups
SE	Hall-MES matrix
pas_o	Total number of seats for the seat group o
$tpas_i$	Total number of seats of the i^{th} hall
SG	Seat group-evacuation point matrix
POP	Population (number of respondents) for questionnaire
PAS_{wlm}	Number of passengers with factor l and category m who are locating on the nearest seats to the MES_w
RAS_{jq}	Alternative exit point
S_{lm}	Number of passengers with factor l and category m
T_{cap}	The total number of passengers
URj	Load factor of the j^{th} MES

1. INTRODUCTION

The investigation of the National Transportation Safety Board (NTSB) revealed that 78% of all casualties happened post-impact, of 95.4% were resulted from the hazards like smoke inhalation and burns resulted from delayed and inefficient evacuations. They also mentioned that if the passengers who are survived after crash can be evacuated quickly, the survival rate would be raised by

98.3% as claimed by NTSB (Coalition for Airport and Airplane Passenger Safety, 1999). Afterwards, because of marine accidents all over the world between 2002 and 2015, 10899 fatalities has occurred, and 1982 ships were sunk or lost (European Maritime Safety Agency, 2015 and (EMSA) 2014).

Maritime safety is one of the core topics discussed in global platforms, especially to enhance design and operation of safe systems at sea (Akyuz, Akgun, and Celik 2016; Njumo, 2017; Akyuz, 2017). Every company/institution that is performing public marine transportation activities must consider the security of its passengers and crew. In case of an emergency, ensuring safe and prompt evacuation of passengers from ship is critical. Understanding how people behave during emergency within maritime transportation are vital if one is to design and develop efficient evacuation vessels and evacuation procedures (Galea *et al*. 2011). A series of tests must be conducted during ship design to meet domestic and international regulations, service permissions. The International Maritime Organization (IMO, C 105/3(a)/1) requires that the passenger ships must be provided with appropriate emergency procedures and sufficient exits to help fast and smooth evacuation within a reasonable time.

On February 2nd, 1987 the engine of the tanker O.T. Garth exploded and the ship ran aground in the Bay of Seine. The evacuation of the victims was made in debatable conditions and based on this unfortunate event, the first research paper on maritime emergency evacuation was released by Bigo *et al*. (1989). They tried to analyse the problems of coordination among crisis schemes according to SECMAR (Sauvetage maritime) directions, ministerial instructions of 1983 and the reality of operational obligations. There have been numerous accidents of passenger vessels at sea, and they have caused massive losses of human lives, so the need of improving the evacuation procedures considering guiding, directing, mustering, and controlling of passenger movements was firmly vital. The 1995 International Conference on the Safety of Life at Sea (SOLAS 1995) addressed this issue particularly by the adoption of a new regulation (SOLAS II-2/28.3), where it is declared that a proper evacuation analysis shall evaluate onboard escape routes of Ro-Ro ferries.

Simulation is a fast and cost-effective tool for modelling marine emergency evacuation in complex ship environment including different hazards such as heel/trim and fire. In this context, cell-based and, in a privileged way the grid-based simulation techniques are considered to apply. The cell-based simulation model divides the space into a uniform grid called a cell. This leads naturally to the concept of "grid-based simulation", in which simulations are performed at various points comprising a grid. In Klupfel *et al*. (2001), the importance of simulation in maritime emergency evacuation (MEE) is highlighted. They mentioned that it is possible to perform evacuation under ideal conditions if the parameters are chosen correctly. Therefore, an important part of MEE studies has employed simulation methods. A distance based passenger routeing methodology utilized by the code EVDEMON (EVacuation DEmonstration & MOdeliNg) as described by Boulougouris and Papanikolaou (Boulougouris and Papanikolaou, 2002). A crowd simulation for improving the design of the built environment and guidelines was conducted by Sagun *et al*. (Sagun, Bouchlaghem, and Anumba, 2011). The purpose of their Simulation Case Studies (SCS) was to investigate how the factors identified in the Observation Case Studies (OCS) affect evacuations using crowd modelling techniques. Thus, they defined three different scenarios based on predefined procedures and their observations. They simulated an emergency evacuation process in case of fire on board to assess the time of evacuation and number of casualties. They used EXODUS simulation program to perform different scenario types. Ha *et al*. (2012) presented a simulation of advanced evacuation analysis using a cell-based simulation model for human behaviour that consists of individual, crowd, and counter flow-avoiding behaviours, in a passenger ship. In term of validation, they compared simulation results of their proposed evacuation model with the passenger behaviour model through IMO tests and confirmed that the proposed model realizes the evacuation process with only the difference of 5%.

Roh and Ha (2013) presented an advanced ship evacuation analysis as a stochastic method in which the total evacuation time was calculated via computer-based simulations, by considering each passenger's characteristics. They tried to model the individual behaviour, the crowd reaction, the counter flow-avoiding behaviour and then tried to verify the passenger behaviour model through IMO tests on a Ro-Ro passenger ship. They compared their results with those of EVi simulation program and concluded that despite the 4% difference, the total evacuation time met the requirements. A multi-agent based congestion evacuation model incorporating panic behaviour is proposed in the paper of Wang *et al*. (2015) to simulate pedestrian evacuation in public places. In Fang *et al*. (2016), the impact of seating area and pedestrian's ''hesitation'' before leaving exits are considered on escape process of Airbus A380 to optimize the rule of exit choice. They reproduced typical characteristics of aircraft evacuation such as the movement synchronisation by simulation technique. A velocity-based egress model, which took into account different aspects of human behaviour in an emergency situation, for the evacuation analysis on passenger ships was presented by Cho *et al*. (2016). They assumed that the escape model consists of three behaviours; individual, crowd, and emergency behaviour. The personal behaviour 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 behaviour of the passengers was composed of two elements; one was a crowd behaviour, a form of collective behaviour of a vast number of interacting passengers with a common group objective, and the other was a leader following behaviour, which caused one or more passengers to follow another moving passenger who was designated as the leader. The emergency behaviour of the passengers in their work was represented by a counter flow-avoiding behaviour to evade collision with other passengers walking in the opposite direction. They conducted eleven necessary tests and two detailed examples in IMO Maritime Safety Committee/Circulation 1238 and confirmed the validity of such trials. They used EVi commercial program to simulate and compare the results.

To address the issues mentioned above, this study contributes to the relevant literature by developing a novel simulation based methodology that considers physical and psychological characteristics of passengers for emergency evacuation process in public marine transportation. Moreover, a Flexible-Board Grid-Based Simulation (FBGBS) approach in conjunction with a multi-level network representation is proposed for the first time within the methodology. In addition, three different passenger routeing algorithms are used in this work to emulate the emergency evacuation process.

The rest of this paper is organised as follows: Section 2 describes the emergency evacuation process. Section 3 explains grid-based simulation approaches. Section 4 presents different passenger routeing approaches. Section 5 introduces the proposed methodology for marine emergency evacuation. An application together with the comparative analysis, results and analyses are discussed in details in Section 6 and a brief closure is presented at the last section.

2. THE EMERGENCY EVACUATION PROCESS

In recent years, the research of crowd evacuation in emergency has greatly been enhanced more deeply (Shao and Yang, 2015). Evacuation of people can be defined as mustering, directing or taking many people away from an area under the existing or potential hazard to a relatively safe place in a planned manner. There are many hazards on a ship like fire or sinking that makes an emergency evacuation process inevitable. Structure for evacuation process in marine transportation systems is given in Figure 1.

While accruing an emergency condition on board, the ship authorities make a decision regarding the IMO regulations for commencing the evacuation or not. The process starts by striking up the alarm by the skipper and ends by evacuating the last passenger to a safe place. Through this process, all the ship passengers are following the directions coming from crew and safety information card (SIC). It should be noted that physical and psychological factors affect the movement of passengers. In the panic mode of evacuation, in which the density of walkers is relatively large, the distances between the passengers are small (Li *et al*, 2017).

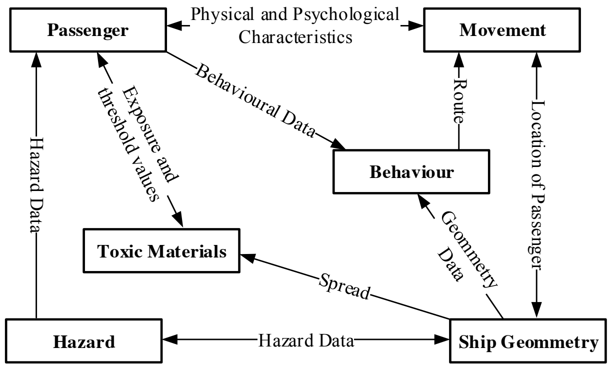

Figure 1: Marine Emergency Evacuation Process

The most realistic closed area simulators are mostly grid based. They can cover the geometry of construction by discretizing all spaces into dimensioned shapes. Consequently, grid-based marine evacuation simulation programs have the halls of a ship meshed into a set of square nodes with an identical size equal to the space occupied by a passenger in a dense crowd. Thereby, all movements of passengers are subjected to the restriction that a node can only be occupied by at most one passenger at the same time. If another passenger occupies the target node, at this moment a passenger has to wait for moving into the target node until the node is unoccupied. By this way, passengers' movement can be dramatically simplified and coded readily. (Kirchner *et al*., 2003). However, this simplified treatment will cause a “gap” between passengers in the process of moving, because a node will be in an occupied status until the occupant is completely moved out. It can be observed that the passengers are tended to stay very closely next to each other and cause different conflicts in a real emergency evacuation (Guan, Wang, and Chen, 2016).

Regarding the next dimension of our proposed evaluation, to overcome the issue above, artificial passengers are permitted to move towards their target node with small steps according to their speed of movement. Any node may contain more than one passenger at a time simultaneously, but passengers are not allowed to overlap with each other. The rules of movement for each passenger are as follows:

(1) Passengers moving along the same direction can enter the same node with no “gap” between two passengers.

(2) Passengers are supposed to move towards the targets based on the defined routeing method for each scenario type.

(3) In any time unit (i.e. the minimum simulation step), all passengers have opportunities to move. All passengers are sorted by the distance from their current positions to their target exit. Those who have a smaller distance to exit will move first within the same time unit.

3. GRID APPROACHES FOR EMERGENCY EVACUATION SIMULATION

Compared to other simulation environments, like buildings, aircraft, parks, and public squares, a passenger ship has several unique features, such as complex structure, numerous obstructions and stairs on evacuation paths, and narrow aisles. In most marine evacuation simulation models, the internal structure of a ship can be represented by a set of interconnected two-dimensional "nodes", each of which can be either empty or occupied by passenger(s).

One of the planned simulation models is RGBS model while one node can contain at most one person despite the possible space of the node to have more persons as it is illustrated in Figure 2. In order to study the evacuation process in more detail, researchers have paid more attention to finer discrete model, in which a pedestrian occupies more than one lattice site (Cao *et al*., 2015). Based on this, the need for a more flexible grid-based simulation approach seems to be inevitable.

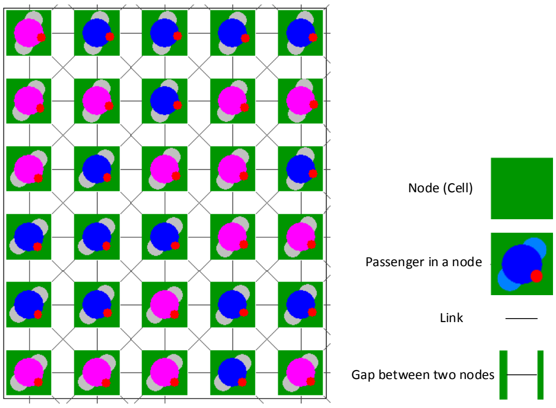

Figure 2: Illustration for Rigid Grid-Based Simulation model geometry

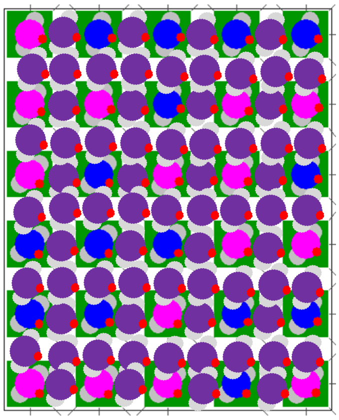

Figure 3: Illustration for Flexible-Board Grid-Based Simulation model geometry

The second grid approach is the FBGBS model providing that one node can contain more than one person at the same time if it is possible based on the size of the passenger and node. At this moment, each cell and gaps between cells can be permissible to the agents as it is illustrated in Figure 3.

4. PASSENGER ROUTEING METHODS

Although a significant amount of studies have already been performed on how to control the pedestrian outflow and to maximize the escape velocity in hazardous situations, there is no very simple but effective approach to obtain the optimal geometrical parameters of obstacles, including the optimal size of obstacle, the optimal obstacle–door gap and asymmetric offset distance of obstacle to the centre of the exit (Zhao *et al*., 2017). Therefore, the best way is to work on the passenger routeing methods for better evacuation procedures. Recently, two methods have been proposed in shape of a passenger routeing systematic that has been developed for the sake of ensuring the efficient evacuation of passengers regarding the evacuation time. As mentioned in Appendix A, the Shortest Distance Algorithm (SDA), one of the passenger routeing techniques, has been composed of first, second and third modules of the routeing systematic. The Shortest Distance Algorithm is integrated with Evacuation Points Load Rate Balancing Algorithm (Module 4) and this integration has been considered as a different routeing technique has been abbreviated as SDA+EPLRBA. The related definitions, parameters and formulations are given as follows.

Definitions

Seat group: Contiguous seats that any corridor, way or the main horizontal axis of the ship is not passing through.

Hall: Seat groups that are separated on the floor by a separator or a wall (providing the main horizontal axis of the ship passes through a hall so that the hall is considered as two independent halls).

Parameters

C_j: Number of passengers who have been assigned to the j^{th} MES
AS: Set of halls that are partially or completely assigned to an MES
N: Number of evacuation points
M: Number of saloons
P: Number of seat groups
SE: Hall-MES matrix

$$SE = \begin{bmatrix} (d_{11}, a_{11}, b_{11}) & . \; . \; . \; . \; . \; . & (d_{1N}, a_{1N}, b_{1N}) \\ . & . \; . \; . \; . \; . \; . & . \\ . & . \; . \; . \; . \; . \; . & . \\ . & . \; . \; . \; . \; . \; . & . \\ . & . \; . \; . \; . \; . \; . & . \\ (d_{M1}, a_{M1}, b_{M1}) & . \; . \; . \; . \; . \; . & (d_{MN}, a_{MN}, b_{MN}) \end{bmatrix} \quad (1)$$

In this matrix, each cell consists of three components (d_{ij}, a_{ij}, b_{ij}).

d_{ij}: Distance from saloon i to the j^{th} MES; i=1… M, j=1… N.

$$d_{ij} = \frac{\sum_{i \in T_i} d_{oj} \times pas_o}{tpas_i} \quad (2)$$

d_{oj}: Distance from seat group o to the j^{th} MES; o= 1… P, j= 1… N.

pas_o: Total number of seats for the seat group o; o= 1… P.

$tpas_i$: Total number of seats of the i^{th} hall; i= 1… M.

a_{ij}: Distance order between the j^{th} MES and the i^{th} hall (the closest=1, and the furthest=N); i= 1… M, j= 1… N.

b_{ij}: 1, On condition that the j^{th} MES is in (or in the borders of) the i^{th} hall; 2, Provided that the j^{th} MES and the i^{th} hall are on the same floor; ,. As long as the i^{th} hall is on an upper floor than the j^{th} MES; 4, Providing the i^{th} hall is on a lower floor than the j^{th} MES; i=1… M, j=1… N.

SG= Seat group-evacuation point matrix.

$$SG = \begin{bmatrix} (d_{11}, a_{11}, b_{11}) & \cdots & (d_{1N}, a_{1N}, b_{1N}) \\ \vdots & \ddots & \vdots \\ (d_{P1}, a_{P1}, b_{P1}) & \cdots & (d_{PN}, a_{PN}, b_{PN}) \end{bmatrix} \quad (3)$$

The three components (d_{oj}, a_{oj}, b_{oj}) are indicated in this matrix as well as SE matrix.

d_{oj}: Distance from seat group o to the j^{th} MES; o= 1… P, j= 1… N.

a_{oj}: Distance order between the j^{th} MES and the i^{th} hall (the closest=1, the furthest=N); i= 1…M j= 1…N.

b_{ij}: 1. On condition that the seat group o is in (or in the borders of) the j^{th} MES; 2. Provided that the seat group o and the j^{th} MES are on the same floor; 3. As long as the seat group o is on an upper floor than the j^{th} MES; 4. Providing the seat group o is on a lower floor than the j^{th} MES.

RAS_{jq}: Alternative exit point that passengers have been transferred during an emergency q, where the j^{th} MES is unavailable; J= 1… N, q= sinking, fire, sinking+fire.

ESI: Smoothing index of the evacuation

$$ESI = \sum_{j=1}^{N} \left| UR_j - AUR \right| \quad (4)$$

URj: Load factor of the j^{th} MES; j: 1…N.

$$UR_j = \frac{ts_j}{cap_j} \quad (5)$$

ts_j: Total number of passengers directed to the j^{th} MES; j= 1…N.

cap_j: The capacity of the MES that is placed at the j^{th} MES

LSA_j: Set of MESs that passengers can be transferred from the j^{th} MES (while using occupancy rate balancing of the MESs module); j=1… N.

AUR: Average load factor of the MES

$$AUR = \frac{\sum_{j=1}^{N} UR_j}{N} \quad (6)$$

The developed routeing systematic is presented in Appendix A. Within the first module, parameters for the evacuation points, halls and seat groups are determined. Then, passenger halls (Module 2) and seat groups (Module 3) are assigned to evacuation points with the aim of matching them with MESs with respect to “closest distance” principle so that partial or complete assignment of each hall is possible under the MES capacity restrictions. Consecutively, a balancing algorithm has been presented in the fourth module that decreases the evacuation time by balancing the density difference between evacuation points (Appendix B). The algorithm performs calculations through capacity load factor as the capacities of evacuation systems at the several points differ from each other. Based on load factor balancing algorithm for evacuation points, transfers from the evacuation points with a higher load factor (more than average) to the ones that have a lower load factor (less than average) under the capacity and flow restrictions. Finally, the fifth module determines the other available evacuation exits, in the presence of any unavailable MES related to the emergency scenarios.

5. THE PROPOSED EVACUATION METHODOLOGY

Recently, some attention was drawn upon the fact that a full description and analysis of aspects involved in an evacuation process. This issue needs to consider the disposition of the individuals as internal states which may influence the reactions of the pedestrians and, ultimately, their motions (Dossetti, Bouzat, and Kuperman, 2017). Aiming this, the steps of experimental research are going to be fulfilled via the proposed methodology which includes five phases, namely survey, experimental design, simulation, validation and statistical analysis (Figure 4). A reliable research methodology should be designed and performed based on a well-defined research question to obtain desired results. Therefore, the methodology starts with defining the research question(s) that is a liable inquiry into a particular matter or subject.

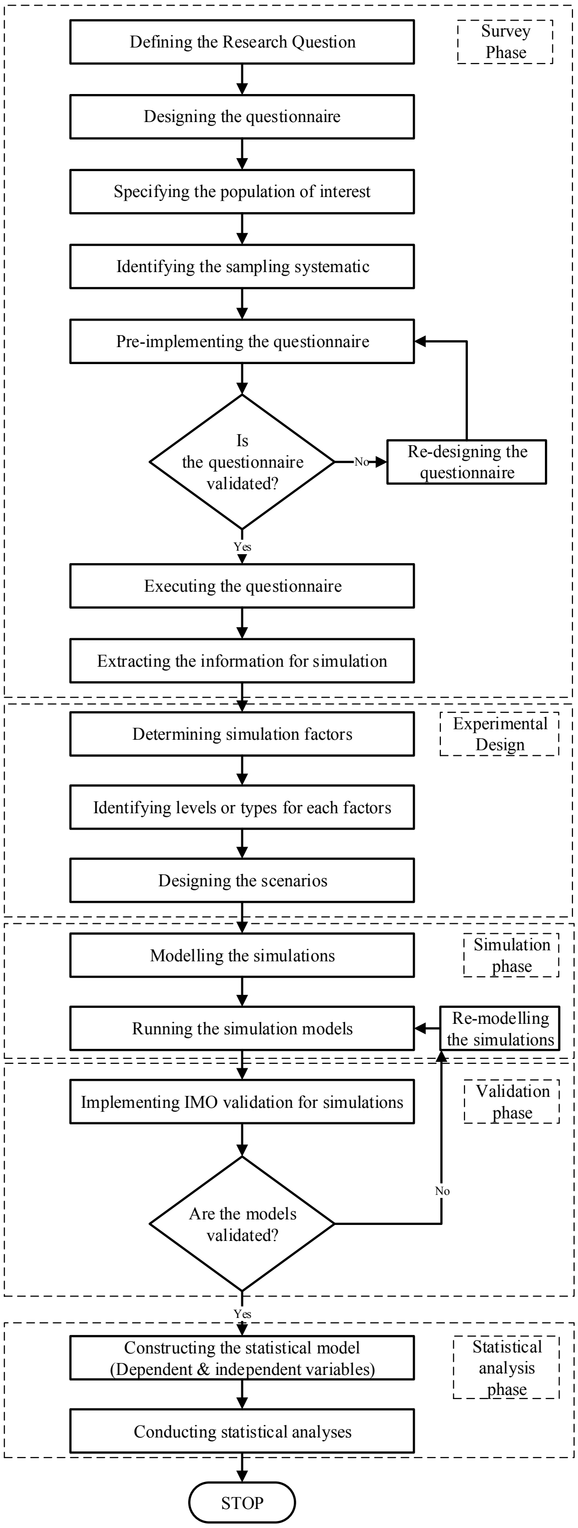

Figure 4: Research methodology

After defining research question(s), a comprehensive questionnaire must be designed to obtain the characteristics of passengers. Then an appropriate sampling technique for the specified population of interest should be determined so as to provide effectiveness in conducting the questionnaire. Survey phase ends with compiling the data about passenger characteristics which will be used for simulation.

The experimental design phase is a crucial stage to catch required factors for simulation models with respect to reliability and reality. Through this phase, demographic (e.g. gender and age) and physical characteristics (height and weight) of passengers and also behaviour types of passengers (panic levels while emergency) are gathered. The factors mentioned above need to be categorised into sub-factors and levels to catch the precise specifications of the passengers by the simulation program. Generally, the categorisation process for human demographic and characteristics have been based on "Height and Weight Charts" (2017). After categorisation of the passenger factors, the simulation scenarios are designed taking passenger routeing and grid approaches into account. This stage combines the physical-psychological characteristics of the passengers with routeing and grid approaches to model various scenario types for examining the effects of different factors on evacuation time.

An emergency evacuation simulator handles the designed scenarios at the simulation phase. As the developed simulation models are unique, their results from the fulfilling of the simulations are meant to be validated regarding verification. Thus, a systematic verification is still essential to evaluate the simulation results. The next phase of the proposed methodology is to verify the simulation results comparing based on the International Maritime Organization-IMO, MSC/Circ.1033 (Galea *et al.*, 2012) validation formula and guidelines.

After collecting the characteristic data of passengers and the evacuation data resulted from performing the simulations, statistical analysis has to be conducted to capture the significant relations between the evacuation factors. A statistical analysis technique that assesses potential differences has been adopted.

6. APPLICATION

The logical approach is based on three research questions which have been listed as below;

1. Is there any effect of locating a particular group of the passengers with certain characteristics nearer to the exits during an emergency on the evacuation time?
2. Does the FBGBS approach yield a significant difference on the evacuation time compared to the RGBS approach for emergency evacuation simulation?

3. Is there any difference among passenger routeing methods regarding emergency evacuation time.

In this section, to apply the proposed evaluation methodology, we focus on an application that is involving a real Ro-Ro ferryboat. Therefore, the fleet of Istanbul Sea Buses Industry and Trade (IDO) has been considered to apply each methodological step. Hereby, Osman Gazi ferry commuting between Istanbul (Yenikapi) and Bursa (the ship carried 1.154.088 passengers in 2016) is selected as the case. The ferry has the capacity of 1184 passengers and 225 cars. This feature makes the ship the highest passenger capacitated vessel among the other ships in the fleet of IDO. Besides, there are six marine evacuation systems (MES) on the ferry which are designed to evacuate, in the event of an emergency, passengers from high freeboard fast ferries directly into inflatable liferafts. The slide/liferaft units are installed in or adjacent to the passenger accommodation area, from where direct access is gained. The link liferaft units are located adjacent to each MES and are linked to the associated MES by permanently rigged lines so that the effective capacity of each MES is doubled or tripled depending on the number of link rafts associated with the MES in question. The inflation cycle of the slide and liferaft takes approximately sixty seconds (Liferaft Systems Australia, 2006).

Information about the capacity and location of each MES is presented in Table 1, and technical drawing of Osman Gazi 1 ferry is given in Appendix C.

Table 1: The location and capacity information for MESs

MES	**Location**	Capacity
1	Mezzanine Deck-Starboard	200
2	Mezzanine Deck-Port	200
3	Upper Deck-Starboard	250
4	Upper Deck-Port	300
5	Main Deck-Starboard	200
6	Main Deck-Port	200

The principles and the methodology suggested by (Sekaran, 1992) were taken into account for designing of the questionnaire. Categorical scaling was used in the response parts due to its consistency with the current survey questions. The survey designed is illustrated in Appendix D. In addition to passenger characteristics, the survey obtained the information like passengers' travel frequencies, the status of their accompaniment, passenger's experiences in any emergency case or practice, their knowledge levels about ship layout and emergency assemblies or evacuation points during emergencies.

Systematic sampling technique was used as the sampling method. Within the scope of the method, the participant selection process was conducted in order with eight seats intervals. If someone sitting on the determined place rejected to answer or was unavailable to fill a survey, or the place was free, then the next seat was focused. Before executing the survey on board the pre-testing of the questionnaire, the survey was conducted for a group of 30 persons as a pilot practice, and then it was modified to the final version. The questionnaire was addressed to 1563 passengers during the survey, and 594 individuals responded (participation rate: 38%); therefore, the sample size was 594. Based on the survey results, we categorised the factors based on the classification of "Height and Weight Charts" (2017). In addition, we considered the first and second quartile of passengers' age as young, the third quartile as middle age and the fourth quartile as old. In order to catch the effects of locating a certain group of passengers with predefined physical and panic level categories we need to have the passengers groups located on the nearest seats to the MESs. Therefore, the exact numbers of passengers to be located near each MES are calculated through the formulation (9).

T_{cap} = The total number of passengers

α_{lm} = Passengers' ratio for factor l and category m

R_{lm} = Number of passengers for factor l and category m

POP = Population (number of respondents) for questionnaire

$$\alpha_{lm} = \frac{R_{lm}}{POP}$$

S_{lm} = Number of passengers with factor l and category m

β_w = Capacity ratio of MES_w

CAP_w = Total capacity of MES_w

PAS_{wlm} = Number of passengers with factor l and category m who are locating on the nearest seats to the MES_w

$$S_{lm} = T_{cap} \times \alpha_{lm} \tag{7}$$

$$\beta_w = \frac{CAP_w}{\sum_w CAP_w} \tag{8}$$

$$PAS_{wlm} = \beta_w \times S_{lm} \tag{9}$$

Table 2 illustrates the factors and their levels, the categorisation orders and the calculation steps of the number of passengers to be located near the MESs.

Table 2: Survey results and the table of simulation factors

	Factor (l)	Level	Frq.	Category (m)	α_{lm}	S_{lm}	PAS_{1lm}	PAS_{2lm}	PAS_{3lm}	PAS_{4lm}	PAS_{5lm}	PAS_{6lm}
Physical Characteristics	**Age**	-17	0.04	Young	0.26	334	49	49	62	75	49	49
		18-25	0.22									
		26-35	0.235	Middle Age	0.62	796	117	117	148	175	117	117
		36-45	0.23									
		46-55	0.155									
		56+	0.12	Old	0.12	154	23	23	28	41	23	23
	Gender	-	0.52	Male	0.52	666	99	99	123	152	99	99
		-	0.48	Female	0.48	618	91	91	114	140	91	91
	Weight	-50	0.03	Lightweight	0.06	79	12	12	15	20	12	12
		51-60	0.03									
		61-70	0.265	Moderate	0.82	1051	156	156	194	236	156	156
		71-80	0.29									
		81-90	0.265									
		91-100	0.105	Heavyweight	0.12	154	23	23	28	36	23	23
		101+	0.015									
	Height	-150	0.04	Short	0.175	225	33	33	42	52	33	33
		151-160	0.135									
		161-170	0.305	Moderate	0.655	841	124	124	156	190	124	124
		171-180	0.35									
		181-190	0.15	Tall	0.17	218	32	32	40	51	32	32
		191+	0.02									
Psychological Characteristics	**Panic**	I would follow the warning signs to the nearest evacuation point.	0.15	Low	0.2	256	38	38	47	59	38	38
		I would wait for the crew directions.	0.05									
		I would orient to the point I entered.	0.35	Moderate	0.5	642	95	95	119	145	95	95
		I would orient to the evacuation point that I know.	0.15									
		I would follow the crowd.	0.17									
		I would jump into the water at the first opportunity.	0.13	High	0.13	166	25	25	31	39	25	25
	Grid			RGBS FBGBS								
	Routeing			MER SDA SDA+EPLRBA								

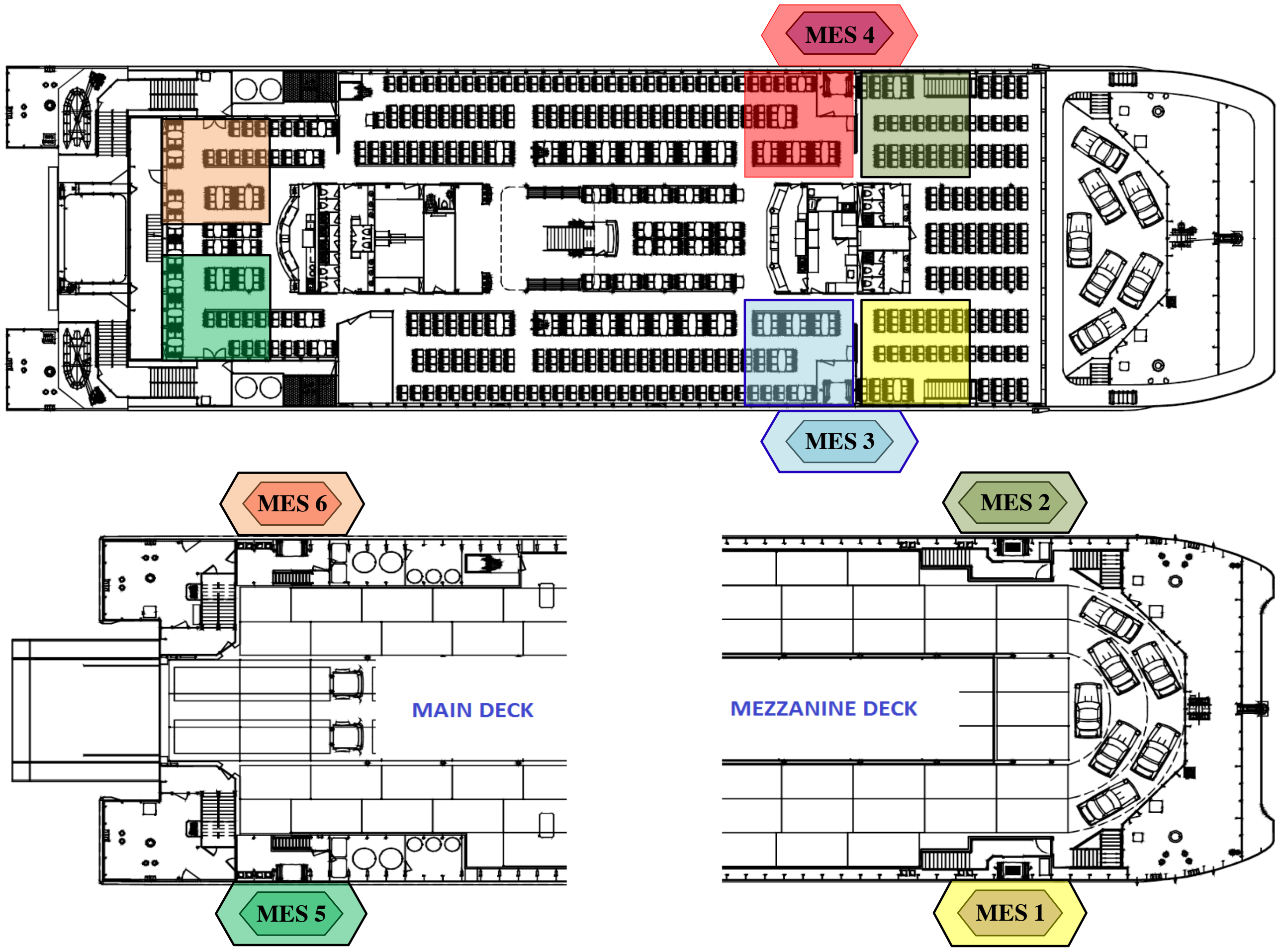

Figure 5: The closest seats to MESs

Table 3: Scenario generation table

Passenger characteristics					Grid	Routeing
Age	**Gender**	**Weight**	**Height**	**Panic Level**		
Young_closest	Male_closest	Lightweight_closest	Short_closest	Low level_closest	RGBS	MER
Middle age_closest	Female_closest	Moderate weight_closest	Moderate_closest	Moderate_closest	FBGBS	SDA
Old_closest		Heavyweight_closest	Tall_closest	Highlevel_closest		SDA+EPLRBA

Based on the calculation of distances between seat groups and MESs, the nearer seats are illustrated in Figure 5.

As for FBGBS aspect, the pseudocodes for each grid approach is given in Appendix E. One of the passenger routeing methods considered in this paper is the grid-based simulation software, named MER (Maritime EXODUS Routeing), is an autonomous passenger routeing. The others are SDA and SDA+EPLRBA which are thoroughly described in Section 4.

In the light of the information above and based on Table 3, eighty-four different combinations of scenarios (fourteen levels of passenger characteristics (three for age, two for gender, three for weight, three for height and three for the panic level)× two different grid approaches× three different routeing methods) occur. It should be noted that, "category m_closest" indicates that PAS_{wlm} passengers (in category m for factor l) located on the nearest seats to MES_w.

Scenarios for emergency evacuation were simulated via Maritime EXODUS V5.1. Simulation of each scenario was run for 250 times in an interior environment of the simulator and the average evacuation time was recorded. Figures 6 and 7 illustrate the visualisations of the simulations while running.

Figure 6: A cross section of halls using Maritime EXODUS V5.1

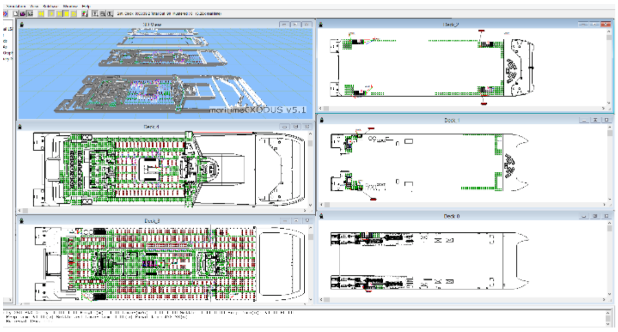

Figure 7: Simultaneous display of evacuation simulation on different layers

The simulator tests all scenario types while each one contains one of the two distinct conditions. The first condition is when one node can contain at most one person despite the possible space of the node to have more agents (RGBS), and the other test condition is when one node can include more than one person simultaneously if it is possible based on the size of the agent and the node (FBGBS). The second simulation state is possible if the modifications are installed with producing a command file as Script Control File to control basic simulation program's functionality. The changes in the script provide the expert user higher and easier control over the setting up of a model as well as the conditions present during the simulation.

The validity of the simulations was examined based on the guideline of International Maritime Organization-IMO with number MSC/Circ.1033 (IMO, 2002). In this guideline, the evacuation time for the ship was computed by the formulation using door-to-hallway dimensions, the number of passengers on the floor and passenger movement parameters.

Based on the simulation results, the average evacuation time in an emergency for the considered ship is 947 seconds. This value deviated almost 3.3% from the IMO validation result that is 917 seconds for the mentioned ship. Considering this research's results, the average egress time while each node contains more than one person is 922 seconds and it is more realistic and very close to the IMO validation results with 0.5% error.

After the simulation of the generated scenarios, Analysis of Variance (ANOVA) is conducted via SPSS 23.0 software to analyse the effects of the independent variables of physical characteristics of travellers, grid approaches, and routeing methods on the dependent variables of total evacuation time. The significance level was set to be 5%.

The effects of passenger characteristics, grid approach and routeing method are all found to be statistically significant (Table 4). What's more, the effect of two-way and three-way interactions are not significant.

Table 4. Test between-subject effects.

Source	**F**	**Sig. (*p*)**	**Partial Eta Squared**
Passenger Characteristics	65.407	0.000*	0.970
Grid Approach	11.152	0.003*	0.300
Routeing Method	6.615	0.005*	0.337
Passenger Characteristics *Grid Approach	1.665	0.130	0.454
Grid Approach *Routeing Method	0.507	0.608	0.038
Passenger Characteristics *Routeing Method	1.212	0.314	0.548
R Squared = 0.973 (Adjusted R Squared = 0.913)			
(*) significant at 0.05 level.			

Table 5. Mean evacuation time for factor

Factor	**Level**	**Mean Evacuation Time (sec.)**
Gender	Female	980.167
	Male	949.457
Weight	Heavy	1028.667
	Moderate	880.833
	Light	810.000
Height	Tall	980.467
	Moderate	965.247
	Short	960.112
Age	Young	881.716
	Middle Age	963.839
	Old	1008.660
Panic Level	Low	874.646
	Moderate	981.063
	High	1057.136
Grid Approach	RGBS	980.500
	FBGBS	882.310
Routeing Method	MER	936.002
	SDA	912.860
	SDA+EPLRBA	843.329

According to Table 5, evacuation time differs among factors and their levels. Mean evacuation time for men is observed to be less than that of women. Similarly, mean evacuation time for heavy weighted and old passengers are proportionally high. As an important finding, average evacuation time dramatically increases with increasing level of panic factor. The results clearly present the effects of FBGBS and SDA+EPLRBA routeing method on the average evacuation time.

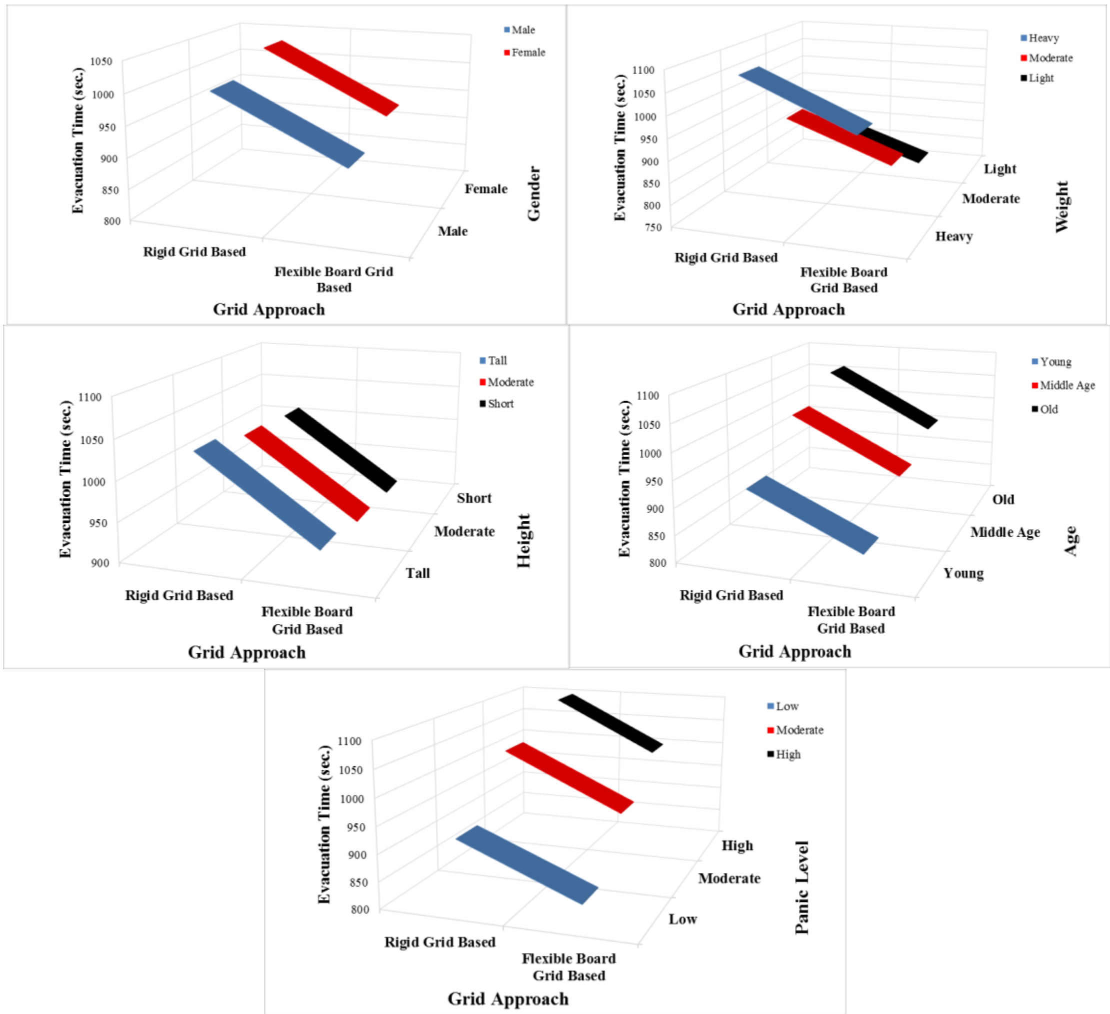

Figure 8: The effect of passenger physical-psychological characteristics with different grid approaches

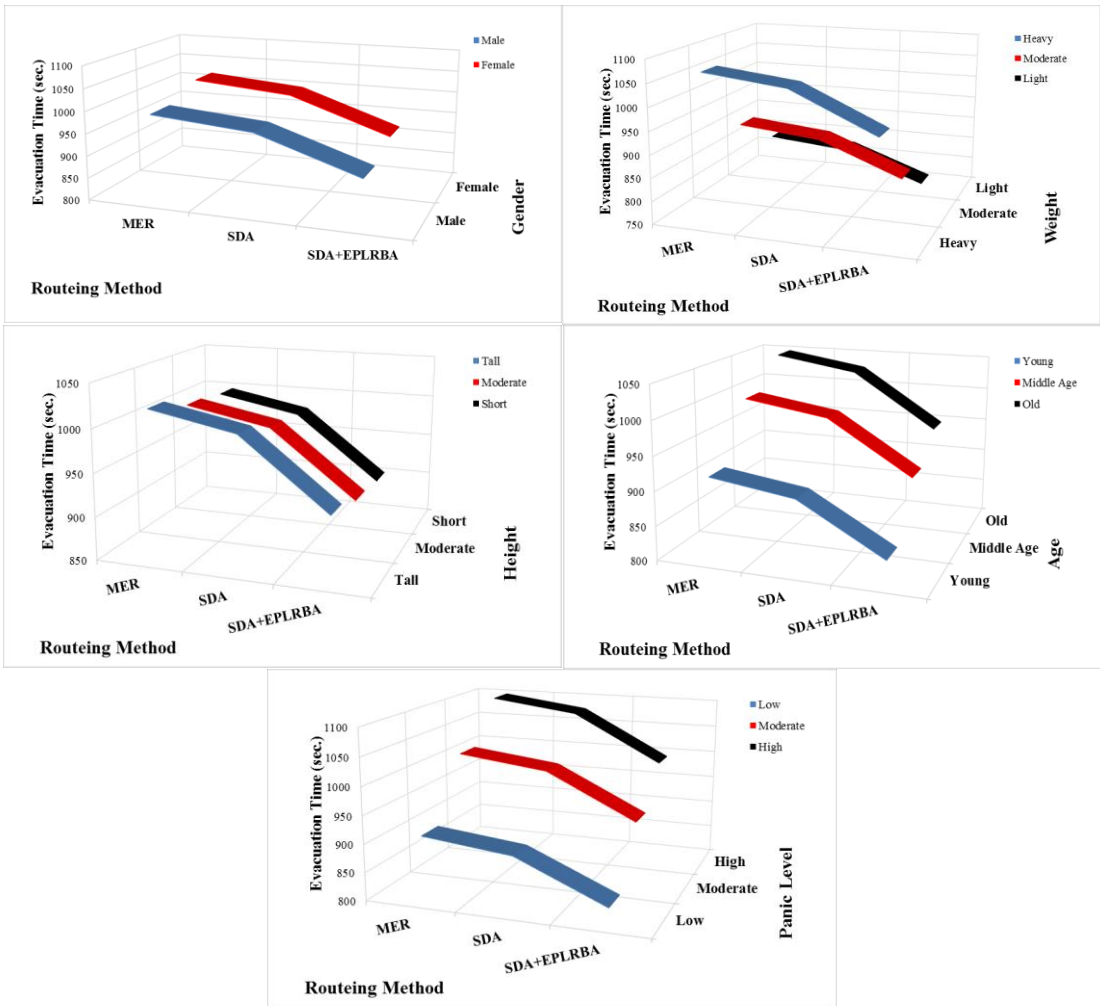

Figure 9: The effect of passenger physical-psychological characteristics with different routeing methods

7. CONCLUSIONS

Issues regarding the marine evacuation of passengers have received increasing attention due to significant losses caused by major maritime disasters and the boost in the number of large capacity cruise ships. Therefore, we propose a methodology for maritime emergency evacuation which contributes to the relevant literature which considers different passenger characteristics by developing a novel routeing systematic and a flexible-board grid-based approach for the first time.

The methodology was applied to a real life ferry-boat and the results from the constructed simulation model match well with the IMO regulation based validations. Besides, a series of elaborations and adjustments is scripted into the coded background of the default commercial simulation program to subdivide the ship's grid spaces into the nodes with the capability to take more than one person in case of possibility. Therefore, the limitation that each node could be only occupied by one passenger has been overcome in the new model to make the simulation closer to the reality.

The paper is believed to improve planning and control capability of administrators who are related to evacuation management. Moreover, results and conclusions, achieved by this article, could provide guidelines for ship design and on-line check-in systems. Consequently, it should also be emphasized that the proposed methodology is expandable to other passenger ships.

It will be meaningful to state some insights which are inferred from obtained results.

- Significant effect of routeing on evacuation has been demonstrated in this study. Evacuation convenience of ships should be addressed especially since design phase and should be supported by training during their operating.
- Keeping load utilization balance among evacuation systems decreases evacuation time significantly due to the fact that smoothness among evacuation systems leads to less waiting time for passengers. This issue may also be adapted to on-line check-in systems in such a way that seat assignment/suggestion may be performed with respect to real time utilization rate of evacuation systems.

- In an emergency scenario, the physical characteristics of a passenger, like body weight, gender, age yield a significant impact on evacuation time performance. This point can be considered in online check-in systems. For instance, when information about such attributes is obtained, some seats may be suggested for the passenger.
- Determining the number and position of guiding crew appropriately is thought to increase evacuation performance. As for position aspect, stairways and large halls are critical crew positions.
- Because of complex nature of ship structure, the level of passenger knowledge about layout has a vital importance on MEE with respect to panic level of passengers. Therefore, this aspect should be improved via instructor monitors, guidance arrows on floors, visual lightening.
- Having the knowledge about the exact location of passengers is a critical point for emergency evacuation. That being the case, passenger traceability can be enhanced using technological applications (RFID, Augmented reality, sensors, embedded systems, etc.).

However, there are several research directions to be pursued for future work. First, sensitivity analysis can be performed for specifying the dimensions of the nodes respecting to more accurate evacuation time for commercial simulation programs. What is more, the time effect of group behaviour which makes evacuation behaviours more complicated may be analysed.

8. ACKNOWLEDGMENTS

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9. FUNDING

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APPENDIX A: The Developed Routeing Systematic

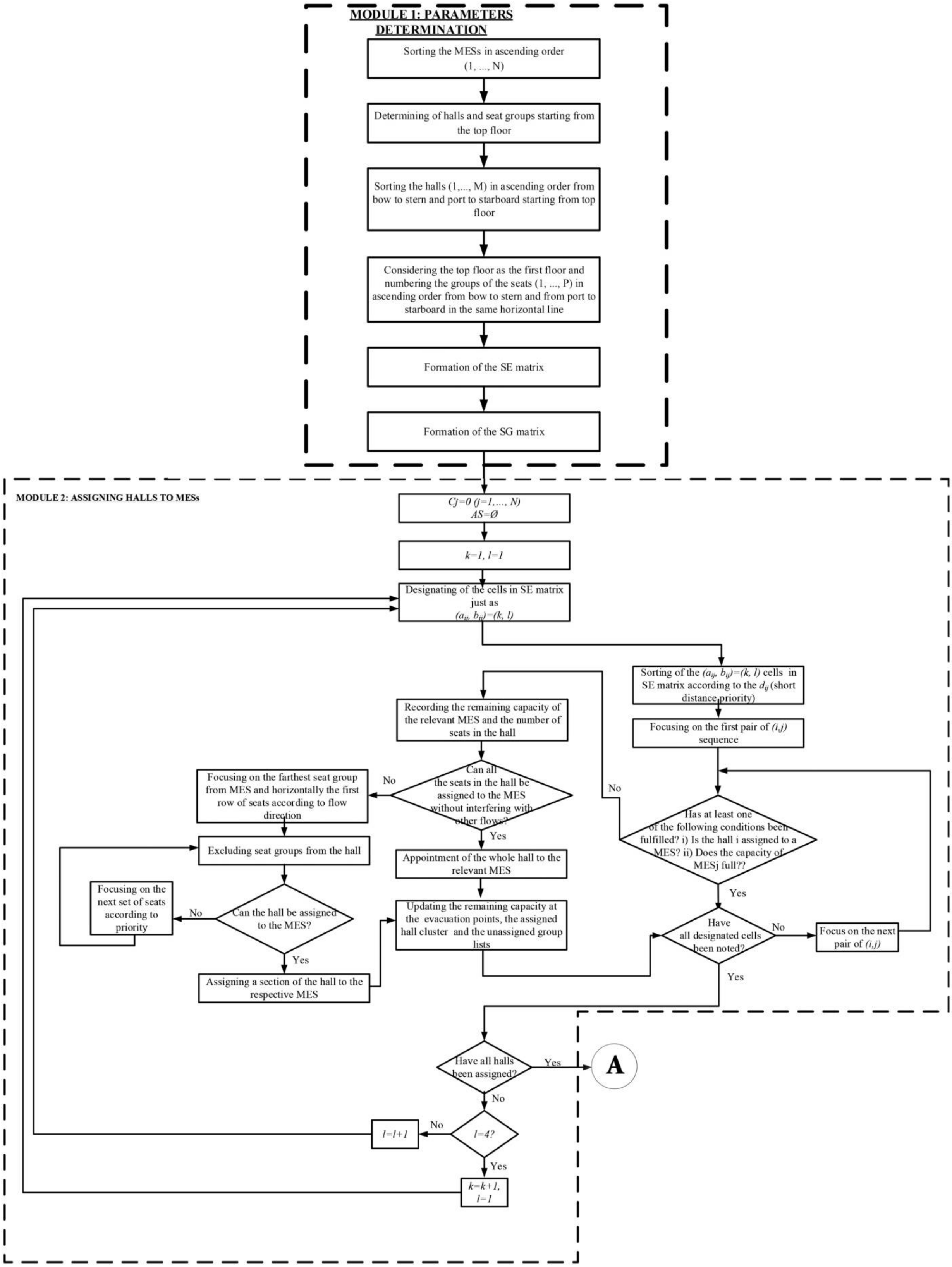

Figure. A1. Flowchart of the proposed systematic illustrating the routeing modules

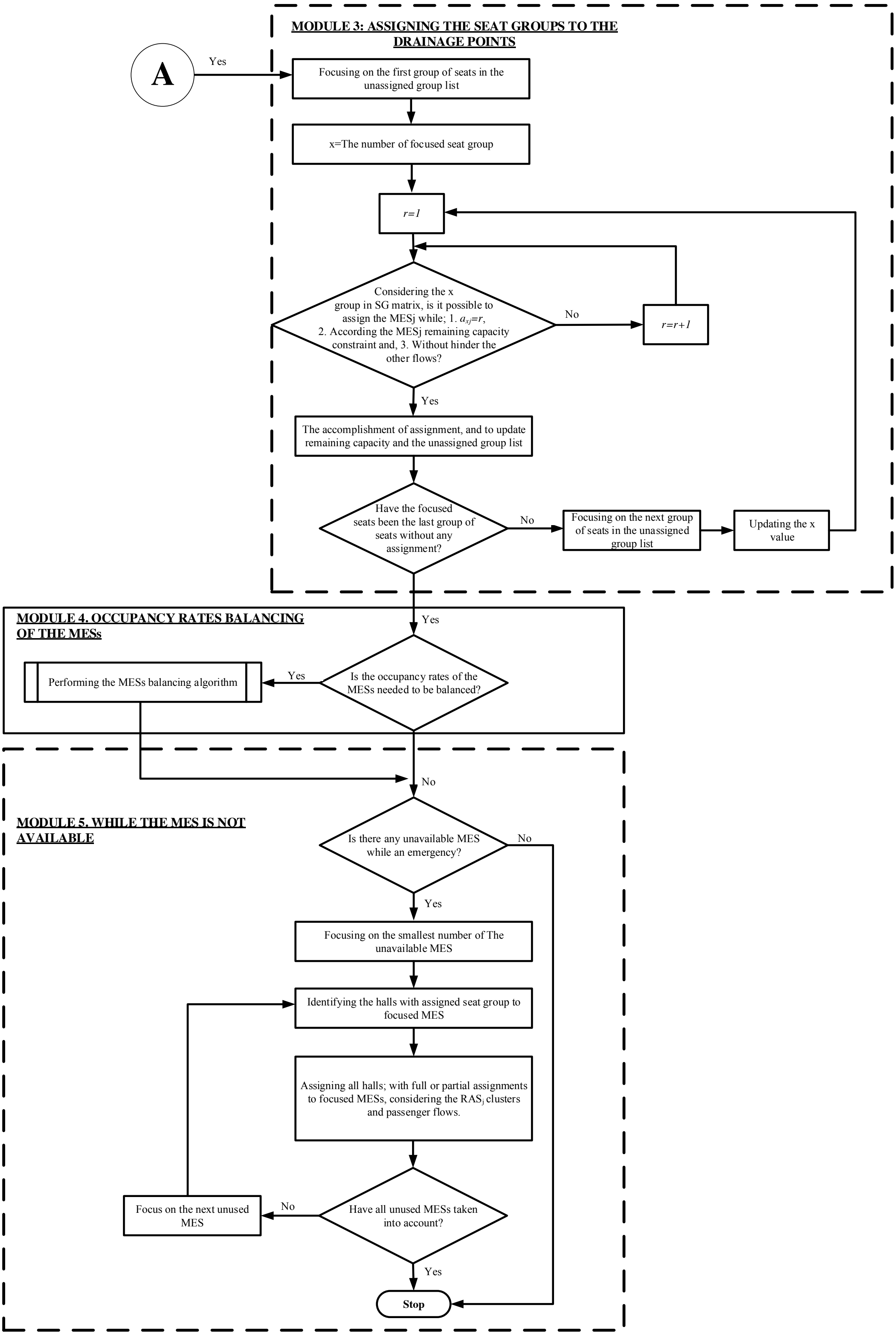

Figure. A1. Flowchart of the proposed systematic illustrating the routeing modules (Continued).

APPENDIX B: The Balancing Algorithm for the Proposed Routeing Systematic

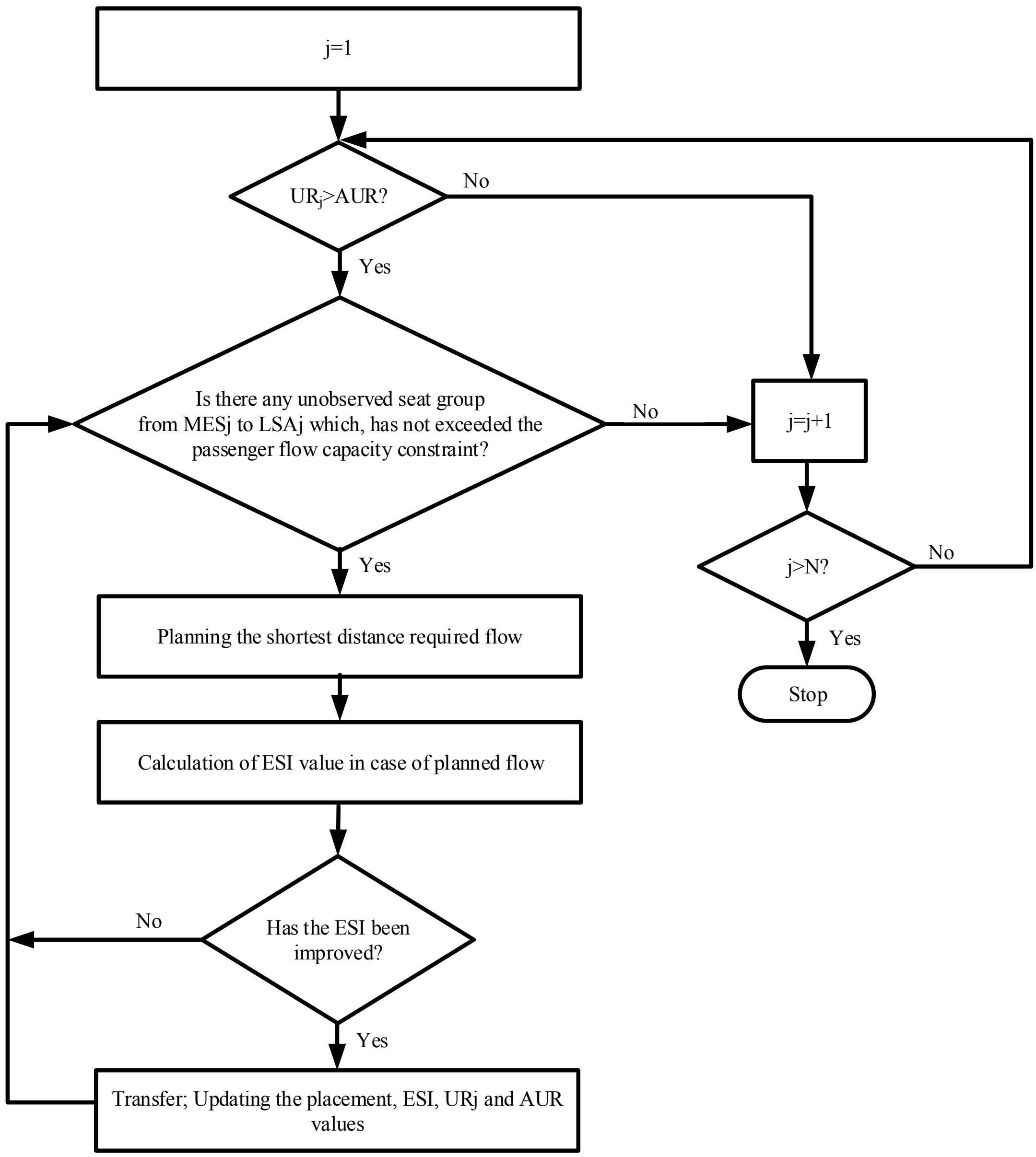

Figure. B1. Flowchart of the balancing algorithm

APPENDIX C:

Ship Layout

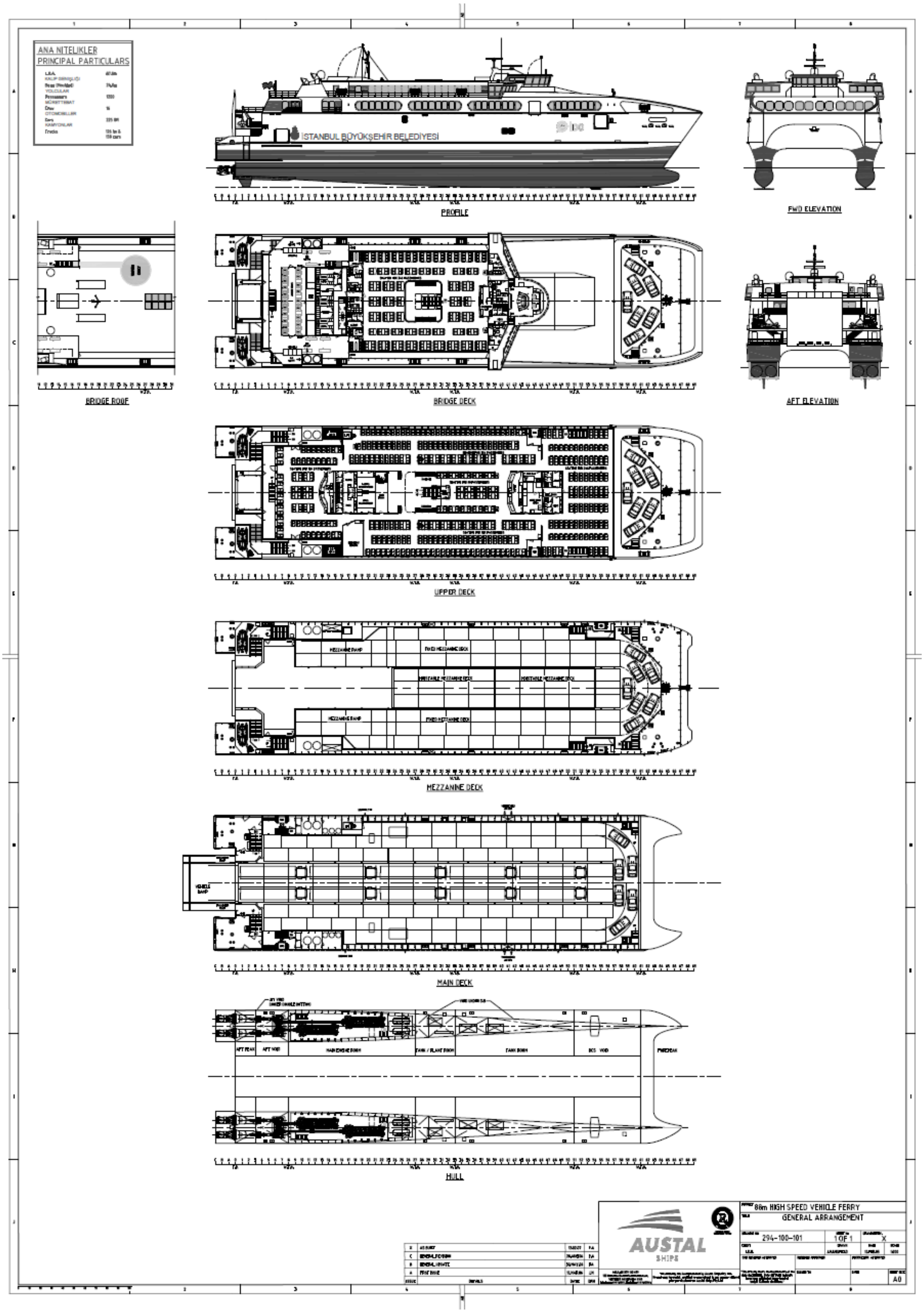

Figure. C1. Layout of the Focused Ship

APPENDIX D:

Questionnaire

PERSONAL INFORMATION

Gender:
Female ☐ Male ☐

Age
☐under 18 years old ☐18-25 ☐26-35 ☐ 36-45 ☐46-55 ☐Over 56 years

Education Status
☐Primary school ☐Middle School ☐ High school ☐ Associate Degree ☐4 years Degree ☐ Post graduate

PHYSICAL PROPERTIES AND SWIMMING

Length
☐Under 150 cm ☐151-160 cm ☐161-170 cm ☐ 171-180 cm ☐181-190 cm ☐Over 190 cm
Weight
☐Under 50 kg ☐51-60 kg ☐61-70 kg ☐71-80 kg ☐81-90 kg ☐91-100 kg ☐Over 100 kg
Do you have any disability?
☐Yes ☐No (Please specify if your answer is Yes)
Do you know swimming?
☐Yes ☐No

COMMUTING and ACCOMPANIMENT STATUS

Please specify your frequency use of the current/ prospect sea journey
☐One or two times per day
☐Every 2-3 days
☐Once a week
☐Every 2-3 weeks9
☐Once a month
☐Every 2-3 months
☐Once a year
☐Less than once a year

Are there any passengers you are currently escorting?
☐Yes ☐No (Please specify if your answer is Yes)

Are there any companions at the moment?
☐Yes ☐No

BEHAVIOUR WHILE EMERGENCIES

Do you have any emergency condition or practice experience on the sea journey?
☐Yes ☐No

Please indicate your level of knowledge regarding the ship layout and evacuation assemblies/exits.
☐None ☐Low ☐ intermediate ☐High ☐Very high

Indicate the behaviour you will show when you encounter an emergency in a sea voyage.
☐I would orient to the point I entered.
☐I would follow the warning signs to the nearest evacuation point.
☐I would orient to the evacuation point that I know
☐I would follow the crowd
☐I would wait for the crew directions
☐I would jump into the water at the first opportunity.
☐Other (Please specify)

OTHER OPINIONS AND COMMENTS ABOUT THE SURVEY:

APPENDIX E:

Pseudocodes for FBGBS and Simulation Iterations

```
# Load geometry
LoadGeom Durum1_Exodus.exo
# instructions
LoadGeomFlexibleNods.exo
LoadPopPermisedAgents.epb
IOLocation C:\TubitakProject\SettingsFile
# Additional commands appended below
# Redirect people in Node1 and Node1
# Identify previously created zone
AssignNode Node1
AssignAgent Agent1
AssignAgent Agent2
# Delete existingBoundary
ClearItinerary
AssignZone Zone1
# Delete Population itineraries
ClearItinerary
# Assign Populationto Zone 1 population
ContinueSimulation
# Load geometry
LoadGeom Durum1_Exodus.exo
# Link data with existing zones
AutoLinkHazards
# Load scenario file setting behavioural response
LoadESO PassengerBehaviour.eso
# Run simulation for 250 times
RunSimulation 250
# Save each iteration
SaveSimulationResultsAndReturn
ContinueSimulation
Shutdown
```

