FLOODSTAND Integrated Flooding Control and Standard for Stability and Crises Management

FP7-RTD- 218532

FLOODSTAND-deliverable:

Report on validation and sensitivity testing of methods for assessing effectiveness of mustering process.

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SEVENTH FRAMEWORK PROGRAMME

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This deliverable describes the model for the Mustering phase of the Mustering-Abandonment and Rescue MAR process. It also describes a computer program developed to compute the expected number of fatalities during the MAR process.</td></tr>
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CONTENTS

1 EXECUTIVE SUMMARY

In case of an emergency, the master of a passenger vessel faces a crucial decision: stay onboard or abandon ship? As a wrong decision can lead to many lives being lost, it is vital to develop reliable estimates for the number of fatalities that are to be expected in a Mustering-Abandonment-Rescue (MAR) process. Within the FLOODSTAND project, this work is undertaken in work package 5.

The aim of task 5.2 is to develop a comprehensive model for the mustering process.

In addition to the description of the Mustering phase, an overview of the whole MAR process and the elements (obstacles) that describe it are presented in this deliverable. A computer program which was written to compute the expected number of casualties in a MAR process is also presented in this deliverable.

SSRC's software 'Evi' is used to simulate mustering processes and to predict the time to mustering. In particular, two ships are studied in detail, the 'Estonia' and a cruise liner. For both vessels, mustering times are computed for a range of scenarios with different times of day and heel angles.

According to the Description of Work, sensitivity testing was expected to be done within tasks 5.2 to 5.4. After evaluation of the whole process, it has been concluded that the sensitivity analysis would be more relevant during the last phase of the work package, in task 5.5. The sensitivity analysis can be found in the deliverable D5.5.

2 INTRODUCTION

In WP5, Task 5.2, 5.3 and 5.4 are closely linked as they describe the different components of the same process: the Mustering, Abandonment and Rescue (MAR) process.

During the completion of the work for these three tasks it was felt that in addition to the study of each phase separately, it was necessary to have a complete picture of the MAR process in order to estimate the expected number of fatalities.

Because no deliverable was initially planned for the whole process it was decided among the WP5 partners that the best way to present the complete work was to give an overview of the Mustering, Abandonment and Rescue (MAR) process and the different obstacles that define it as part of deliverable D5.2.

It was also decided to include with this deliverable the description of the algorithm specifically developed to estimate the expected number of fatalities during the Abandonment and Rescue phases. Its application to the abandonment and rescue process (all the obstacles combined), will be described in FLOODSTAND deliverable D5.5.

These two aspects i.e. the list of obstacles of the MAR process as well as the computer program to compute the expected number of fatalities will form the first part of this deliverable.

In the second part, the mustering process (which is the main subject of this deliverable as presented in the Description of Work) is studied in detail and the results of the assessment of the mustering phase are presented.

3 Part I: MAR process and list of obstacles

As introduced in FLOODSTAND deliverable D5.1, the human health status (HHS) was chosen as the indicator to assess the risk for passengers when abandoning the ship.
The escape and rescue process (or route) was defined as a sequence of actions that passengers (and crew) need to perform in order to evacuate from their initial location to a place of safety (shore or rescuing vessel). In doing so, they would rely on Life Saving System (LSS).

Escape and rescue routes can be split up into different phases as follows:

1. Mustering
2. Abandonment
3. Survival at sea
4. Rescue

In addition, the escape and rescue route can be defined as a series of obstacles which are characterised by the hazard they generate. These hazards can affect people directly (later referred to as Human Factor (HF) obstacle) or indirectly through the life saving appliances (later referred to as Hardware (HW) obstacles) by degrading (or not) their Health status.

So in order to define the Mustering, Abandonment and Rescue (MAR) process, the obstacles which constitute each phase needed to be identified.

Based on the findings of task 5.1 and the results of the FP6 funded project SAFECRAFTS, a first comprehensive list of obstacles for each phase of the process was produced. Then, efforts were dedicated to simplify this list and reduce it to a manageable size (for example there were 43 obstacles in the Mustering phase alone).

At the end of this process the WP5 partners agreed on the final list below:

Mustering

Id	**Obstacle**	**Type**
M1	Passengers' reaction time	N/A
M2	Passengers' location	N/A
M3	Passengers' (intrinsic) mobility	N/A
M4	Effects of heel on passengers' mobility	N/A
M5	Blocked doors	N/A
M6	Objects obstructing the passage	N/A
M7	Injuries due to the list (static)	HF
M8	Injuries due to ship motions (dynamic)	HF

Abandonment

Id	Obstacle	Type
A1	Deployment impossible	HW
A2	Davit deployment failure	HW
A3	Chute deployment failure	HW
A4	Liferaft malfunction	HW
A5	Lifeboat engine failure	HW
A6	Embarkation time	
A7	Structural failure/capsize due to premature release of the LSA	HW
A8	Structural failure due to impacts of the LSA against the hull during lowering	HW
A9	Injuries due to impacts of the LSA against the hull during lowering	HF
A10	Injuries due to slamming	HF
A11	Injuries while using the escape ladders	HF
A12	Structural failure due to impact against the hull while afloat	HW
A13	Injuries due to impact against the hull while afloat	HF
A14	Failure of the bowsing lines	HW
A15	Injuries while moving to seat	HF
A16	Failure to clear off the vessel	HW

Rescue

Id	Obstacle	Type
R1	Time to rescue passengers	N/A
R2	Impossible to transfer passengers by using the side door	HW
R3	Injuries while transferring passengers through the side door	HF
R4	Impossible to transfer passengers by using the escape ladder, pilot ladder, rope ladder	HF
R5	Injuries while transferring passengers with escape ladder, pilot ladder, rope ladder	HF
R6	Capsizing/Downflooding	HW
R7	Injuries due to LSA motions	HF
R8	Hypothermia	HF
R9	Seasickness	HF

During the assessment of the different obstacles, additional obstacles were ignored as they were found to be less significant than previously thought. For example, obstacle A4 "Liferaft malfunction" was not relevant as Passenger ships, as a regulatory requirement (SOLAS), need to carry Life Saving Appliances (generally Liferafts) in excess and the malfunction of a Liferaft should not affect the spare LSA capacity.

The ignored obstacles appear shaded in the above tables.

4 Assessing the whole process: The Casualty Calculator

As described in deliverable D5.1, each obstacle has a “degradation” matrix associated with it which changes the health status of passengers when they go through that obstacle.

Hardware (HW) obstacles affect several people simultaneously, whereas Human Factor (HF) obstacles only act on individual passengers. For example, if the Davit of a Lifeboat fails, we assume that all passengers in that particular lifeboat are lost (affected the same way), whereas if the obstacle is “Hypothermia”, for example, then people are affected independently from each other. In addition, HF obstacles affect people differently if they belong to different age groups. For the HW obstacles, people are all affected in the same way whatever their age group (please refer to FLOODSTAND deliverable D5.1 for more details).

For the whole MAR process, the obstacle matrices are combined together and used to calculate the probability of a passenger to lose his/her life during the MAR process[1].
A computer program called “CasualtyCalculator”, which is described in the next section, was developed to perform the computations.
The results of the “CasualtyCalculator” computations for the ships considered in this Work Package (Estonia and the Cruise Liner) will be presented in FLOODSTAND deliverable D5.5.

4.1 Overview over the software

The Casualty Calculator is a Windows Console application written in C++. Its purpose is to compute the probability distribution for the number of fatalities expected in a Mustering/Abandonment/Rescue process. The software is linked to a MySQL database which contains the obstacles that describe this process.

4.2 Input

The software expects the following input from the user:

- The number of passengers in each age group
- The initial health distribution in each health group
- The sea state
- The number and capacity of the primary LSA
- The number and capacity of the secondary LSA (optional)
- The sequence of obstacles encountered in the process

These details can be entered via the screen or via a comma-separated input file.

4.3 Output

The Casualty Calculator computes the expected number of fatalities and its standard deviation based on the details of the MAR process. In addition, the final health

[1] Fatalities due to the accident are not considered here. Only those who might result as a consequence of abandoning the ship are calculated.

vectors for each age group are computed, as well as the exact probability distribution for the number of fatalities (see
Figure 1 for an example of a probability distribution).
The output can be displayed on the screen or saved in text files.

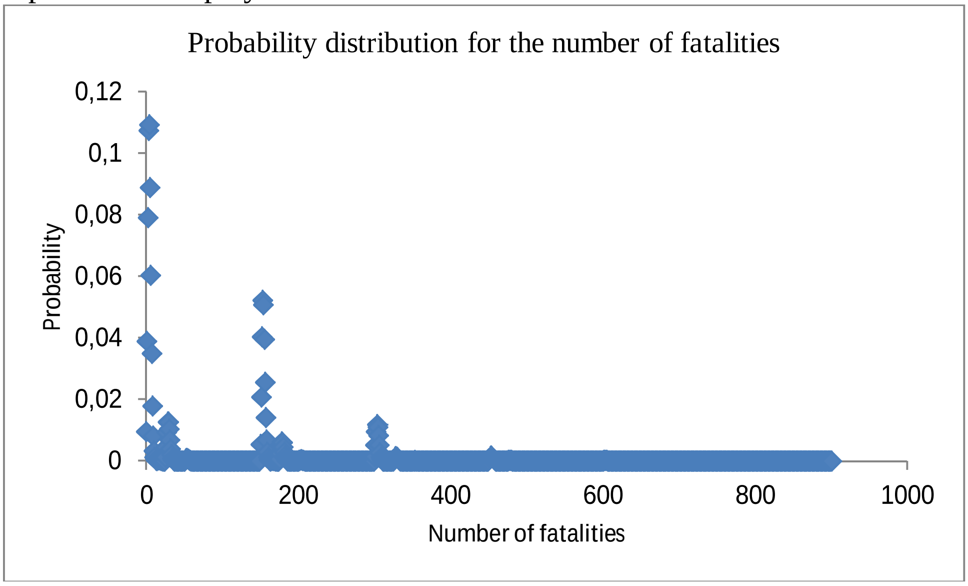


Figure 1: Plot of probability distribution for the number of fatalities as computed by the Casualty Calculator

4.4 Computation

The software uses the matrix model for obstacles as described in deliverable D5.1. Expectation values and standard deviations are computed algebraically (as the output is simply a linear combination of random variables). The probability distribution is calculated using binomial distributions.

For further details on the software, please refer to Appendix A.

5 Part II: the Mustering phase

The mustering phase differs from the Rescue and Abandonment phases of the MAR process in that it was assessed differently. Although the term “obstacle” was used for the mustering phase, no matrices are involved in the assessment. The term “obstacle” was used for uniformity reasons.
The main output of the assessment of this phase is the time it takes people on board to muster under different conditions. This time will then be used to estimate the probability of failure of the mustering process under certain damage conditions.

The mustering process in its very nature is a very complex process. In order to assess it the Evacuability Index software Evi, which is a simulation tool developed at SSRC, was used.

The most relevant parameters of this phase of the MAR process were identified as being:

1. Passengers’ reaction time (obstacle M1):

Once the general alarm is sounded and people are instructed to go to muster stations, there is a time delay before they proceed as people may not realise that it is a real emergency and others may want to retrieve personnel belongings or look for other members of their group or family.

2. Passengers’ location (obstacle M2):

It is the space location of people on board at the time of the accident. Depending on the time of day, they can be either in their cabins (at night) or in different areas of the ship to which they have access.

3. Passengers’ (intrinsic) mobility (obstacle M3)

These are the individual characteristics of the people onboard: age, gender and walking speed that will influence the movement of the people.

4. Effects of heel on passengers’ mobility (obstacle M4)

Due to the fact that the ship is subject to different motions people might experience difficulties in moving which will reduce their walking speed.

5. Blocked doors (obstacle M5)

If doors are blocked, passengers might need to find alternative ways to reach the muster stations. For the scenarios considered in this task, it was assumed that only the watertight doors at lower levels of the ship would be closed. Those in the other parts of the ship could be used by the passengers when evacuating.

In Evi the reaction time, passenger location and mobility are input to the software in the form of probability distributions.
The effect of heel on the passenger mobility is accounted for during the simulation by reducing the walking speed according to the heel angle.
If needed during the simulation doors in the model can be blocked.

5.1 EVI description

Evi (**Ev**acuability **I**ndex) is a passenger evacuation simulation tool based on multi agent modelling techniques (people on board are modelled as intelligent agents able to perceive, decide and act), which combines macroscopic (high level: path planning for example) and microscopic (low level: human behaviour) models. Evi is termed a *mesoscopic* model. Details of the mathematical modelling of the software are given in Appendix B.

5.2 Software overview

The Evi suite is a software package containing Eve, the Evacuation Editor and Evi the simulation tool.

The evacuation editor Eve

Eve is the editor tool which generates the database (ship model) to be used in the simulation.

First the General Arrangement (GA) of the ship is imported into Eve in DXF format. The ship model is then "built" according to the GA, where the different spaces are modelled using either simple rectangles or convex polygons.

Spaces are connected with doors (virtual or actual). Figure 2 below shows an example of a deck being modelled in Eve. The different colours represent different space types, for example, cabins are yellow and corridors are blue.

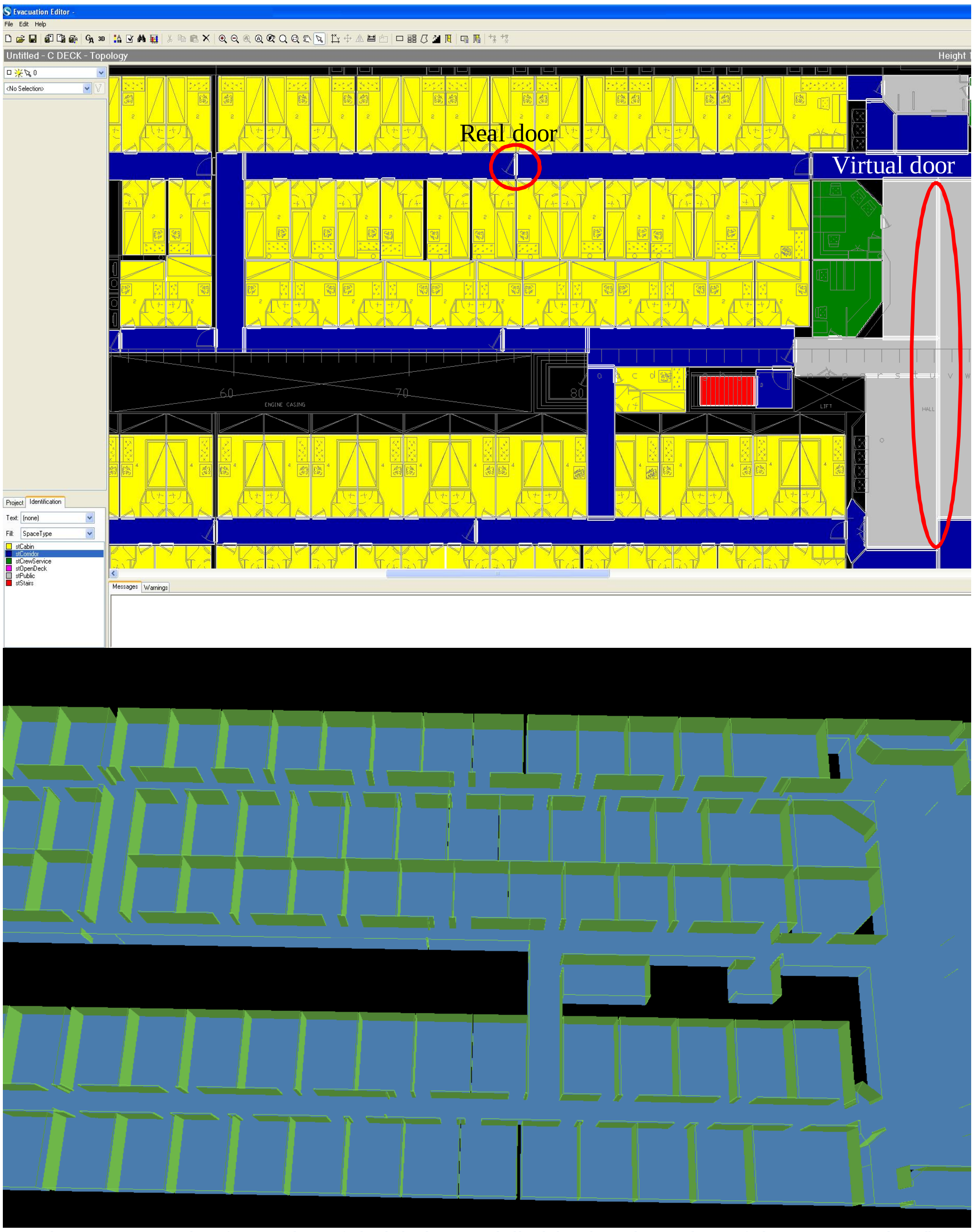
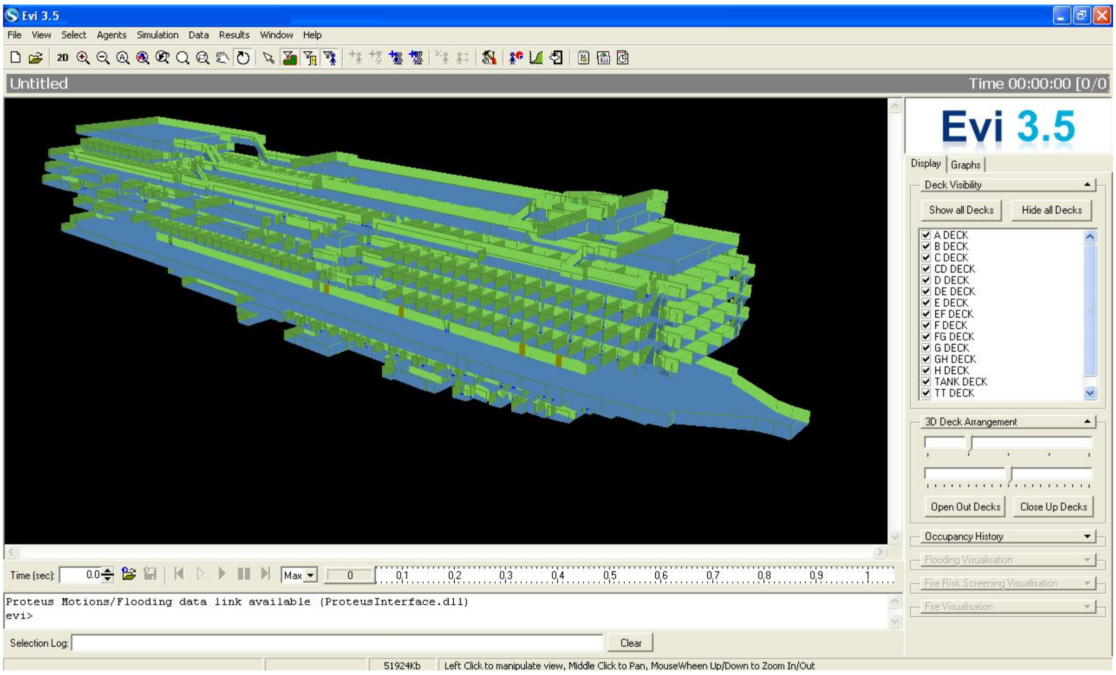


Figure 2: Example of a portion of deck being modelled (top) and 3 D view of the same portion (bottom)

Information about the different space types, fire zones, muster stations, main evacuation routes and other attributes are included in the model at the modelling stage.

Once the model is completed it is then imported into Evi.

The simulation (Evi)



Before an evacuation simulation for the environment defined in Eve (the ship model), can be performed, a scenario needs to be defined as follows:

1- the population and its characteristics (age, gender, awareness time, speed etc),
2- the initial spatial distribution of the population
3- the list of tasks to be performed by the agents

In Evi, the agents' tasks are modelled by "Objectives".

Agents representing passengers are mainly controlled with two objectives:

1- The *Evacuate* objective (default objective) is used to assign an assembly station to an agent and control the route it takes to get there.

2- The *Lost* objective is applied to passenger agents when they are modelled as lost as part of the initial conditions of the scenario. Lost agents will select exit doors randomly. This behaviour continues until route information is found from the environment or a crewmember.

Agents representing Crew have a wider range of objectives:

1- The *Control* objective is used to model crew procedural activities such as Stairway Guiding. The objective has the effect that passengers near the controlling agent crew increase their speed and any lost agents are directed to an assembly station.

2- The *Search* objective is used to model crew travelling around the environment making passenger agents aware of the evacuation. This behaviour reduces passenger's awareness (reaction) time.

3- The Inspect Clear objective is similar to the Search objective except that the crew agent will wait until all passenger agents have left the space before proceeding to the next to be searched.

4- The Re Route objective is used to direct passenger agents to alternative routes.

In addition to the objectives, a messaging system exists which provides a way for agents to communicate between them.

Through messaging, crew agents can directly affect the behaviour of passenger agents.
For example a passenger agent will receive information about the location of the muster station from crewmembers or about alternative routes to use.
Passenger agents can also send messages to other passenger agent informing them of the presence of a blocked door.

Two forms of messages are supported:

1- Local verbal messages are broadcast at the location of the sending agent and travel for only a short distance controlled by the range distribution for passengers and crew separately.

2- System wide messages are broadcast at the centre of all spaces and have an unlimited range of travel (represents PA system for example).

Once the scenario is constructed, both the ship model and the scenario are loaded into Evi and the simulation can be started.

Evi output

In addition to the total mustering time, several other outputs are produced by Evi, ranging from crossing rates for doors, space occupancy, congestion time history, etc.

6 CASE STUDY

In this section the results of the simulations of the mustering phase for the two ships selected to be studied in FLOODSTAND project are presented: the Estonia and a Cruise Liner.

As explained in section 5.2 of this document, to perform an evacuation simulation, first the ship model needs to be built, then attributes (demographics) of the people on board needs to be defined. Finally the spatial location of the people on board is defined and any specific tasks either for passenger or crew agents are set.
This procedure will be followed for the two ships considered in the case study.
In addition the following assumptions are made:

- Crew members know the emergency procedures
- Passengers will follow signage and crew instructions
- No panic

6.1 The Estonia

The ship

The Estonia had a length between perpendiculars of 137.40 m (length, over all 155.40 m) and a moulded breadth of 24.20 m and could accommodate up to 2,000 passengers. The Estonia was compliant with the rules and regulations in place at the time of the accident.

There were 10 decks (see Appendix C for detailed deck plans).

The main deck, deck 2 (A-Deck) was the vehicle deck. Below on deck 1 (tween-deck) economy class cabins for 358 passengers were arranged. The sauna and pool area were on deck 0 (tank-deck). The main passenger accommodation areas were on decks:

- 4 (C-deck) containing 98 cabins with beds for 204 passengers and 81 cabins with beds for 200 passengers,
- 5 (D-deck) containing 102 cabins and 212 beds and
- 6 (E-deck) with 103 cabins and 212 beds.

The accommodations extended from side to side without any open-air passage or other open-air spaces except the aft decks.

The crew accommodation was on decks 7 (F-deck) with three cabin departments (forward 25 cabins, amidships 25 cabins and aft 29 cabins) and 8 (G-deck) and the navigation bridge was on deck 9 (H-deck).

The centre casing on the car deck contained staircases. Six sets of stairs led from the lower passenger spaces to a common passageway inside the casing. Four sets of stairs led from this passageway to deck 4 and six sets led upwards to higher decks.
Stairs were also arranged at the aft open-air deck spaces from deck 4 upwards to deck 8.

The rescue stations and the embarkation area for lifeboats were on the open deck of deck 7. Passengers accessed the deck via two main staircases and staircases between the aft open-air decks.

Also on deck 7 were cradles for liferafts and bins for lifejackets for passengers and crew. Additional liferafts and lifeboat davits were on deck 8. Deck 8 was accessible to passengers only via external stairs from deck 7.

Figure 3 presents the Evi model of the Estonia.

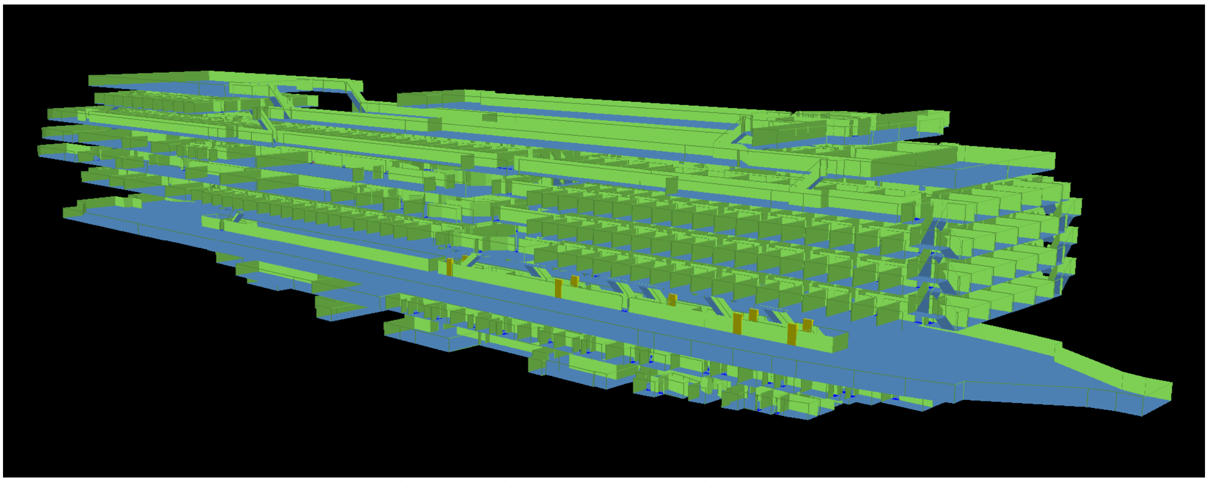


Figure 3: Evi model of the Estonia

People on board

Some information about the demographics of the people on board the Estonia as well as their spatial location prior to the accident was available from the final accident report [2]. This information was used for the simulation and it is presented hereafter.

There were 989 people on board: 803 passengers and 186 crew members.

Passengers and crew demographics

According to [2], the gender distribution of the passengers and crew is as follows:

	Passengers		Crew	
Gender	Number	Percentage	Number	Percentage
Female	385	48	100	54
Male	418	52	86	46
Total	803	100	186	100

Table 1: Gender distribution of the people on board the Estonia

The age distribution for passengers and crew is as shown in the table below:

#	Age	Male	%	Female	%	Total	%
1	<15	9	2	6	1	15	2
2	15–19	20	4	20	4	40	4
3	20–24	60	12	40	8	100	10
4	25–34	85	17	77	16	162	16
5	35–44	98	19	85	18	183	18
6	45–54	82	16	106	22	188	19
7	55–64	61	12	73	15	134	14

8	65–74	76	15	69	14	145	15
9	>75	13	3	9	2	22	2
	Total	**504**	**100**	**485**	**100**	**989**	**100**

Table 2: Age distribution of people on board the Estonia

Data from IMO circular [1] was used for the walking speed.

In the IMO circular, the walking speed is defined according to age groups.
Crew and passengers are considered separately.

The age groups for passengers (for both males and females) as well as their percentage of the population (According to IMO) are given in the table below:

#	Population	Percentage (%)
1	Younger than 30 years	7
2	Between 30-50 years old	7
3	Older than 50 years	16
4	Older than 50, mobility impaired (1)	10
5	Older than 50, mobility impaired (2)	10

Table 3: Age groups as defined in IMO Circular [1]

The mobility impaired (1) and (2) for both females and males have different walking speeds.

To have the same age groups as the IMO circular, the data from Table 2 was grouped based on the following assumptions:

- All People under 24 (line 1-3) are passengers: 89 males and 66 females.
- All people older than 45 (lines 6-9 from) are passengers: 232 males and 257 females.
- The remaining people (lines 4 and 5) are passengers and crew members for a total of 183 males and 162 females.
- We assume that all crew members are aged between 25 and 44 years old. So the total number of passengers in this age category is 97 males and 62 females.

The tables below summarize the passengers' distribution:

#	Population	Male	(%)	Female	(%)
1	Younger than 24 years	89	11	66	8
2	Between 25-44 years old	97	12	62	8
3	Older than 45 years	232	29	257	32
	Total	**418**	**52**	**385**	**48**

Table 4: Estonia. Passengers' age distribution grouped to reflect IMO age groups

For the “Older than 45 years” group, we further distribute the passengers as follows:

#	Population	Male	(%)	Female	(%)
1	Older than 45 years	102	13	113	14
2	Older than 45 years, mobility impaired (1)	65	8	72	9
3	Older than 45 years, mobility impaired (2)	65	8	72	9
	Total	**232**	**29**	**257**	**32**

Table 5: Estonia. Passengers' age distribution for the “Older than 45 years” group

Spatial location of passengers and crew

<u>Passengers:</u>

In the IMO Circular [1], the spatial distribution of people on board as well as their reaction time is different whether the evacuation takes place during the day or during the night.
In the night case all passengers are considered to be in their cabins as well as most of the crew members. The rest of the crew are either in service spaces, their emergency stations or in the muster stations.

For the day case, all passengers and a third of the crew are in public spaces. Another third of the crew is in cabins and the rest in service spaces, emergency stations and muster stations.

For the Estonia and according to [2] from the 134 surviving passengers and crew testimonies we have the following distribution:

Deck #	Survivors	Number of people in addition to survivors*	Total
1	22	0	22
4	32	4	36
5	31	26 to 62	57 to 93
6	16	2	18
7	26	1	27
8	4	3	7
9	0	3	3

Table 6: Spatial location of people on board the Estonia according to accident report

*: in some cases additional information about the initial number of people was given in the report.

There were between 60 and 96 passengers in public spaces (casino, Pub, lounge etc).
We will assume that 96 (≈12% of the passengers) is the total number of passengers in public areas.
The rest i.e. 707 passengers were assumed to be in their cabins and distributed as follows:

- All cabins on Deck 1 were occupied (economy cabins) for a total of 358 passengers.
- Because deck 4 has a capacity of almost twice the capacity of deck 5 or 6, the remaining 349 passengers are distributed as follows: 50% on deck 4, 25% on deck 5 and 25% on deck 6.

Reaction time

The passengers who were in the public spaces apart from those in the lounge on deck 5 all have a "day time" reaction time as they were awake at the time of the accident.

The crew:

Between 30 and 60 people were in the Pub Admiral. We assume that 7 of them were crew members.
19 Crew members were in either public spaces such as information desk or bars, attending to passengers and crew spaces such as mess, engine control room etc, which makes a total of 26 crew members in either public spaces or service spaces.

The rest i.e. 160 are assumed to have been in their cabins.

Reaction time

The crew members who were not in their cabins at the time of the accident have a "day time" reaction time.

The crew and passengers distribution, as explained above, will be used to simulate an evacuation during night.

The day case

Passengers and crew demographics:

The same demographics as explained in the previous section were used to simulate an evacuation scenario for the day case.

The response (reaction) time is adjusted to reflect the day time as defined in the IMO guidelines.

Spatial distribution:

Passengers and crew were distributed according to the day distribution as defined in the IMO guidelines i.e. all passengers with one third of the crew located in public spaces, one third of the crew distributed in the crew cabins; and the remaining 1/3 distributed in service spaces, emergency stations and in muster stations.

In addition, two variations of the cases have been considered:
- Passengers and crew in public spaces inside the ship,

- Passengers and crew in public spaces as well as in open decks.

THE RESULTS

To account for the variability of the different parameters of the simulations, a specific scenario is run a number of times. For the night case 50 runs are usually statistically significant. For the day case because there is more variation in the initial spatial location of agents (in contrast with the night case where all passengers are in their cabins), the scenarios are run 100 times.

In addition scenarios with different heel angles were also simulated.

The results of the different mustering times (in seconds) for the Estonia are shown in Table 7(for the day case), and Table 8 (for the night case) below:

Heel (°)	Min.	Max.	95th percentile	Average.	Standard deviation
0	864.5	1285	1210	1023.115	89.82896
16	1012	1403.5	1238	1131.19	62.72732
18	1027.5	1255	1236	1130.435	49.47296
20	1046.5	1345	1293	1142.55	61.03301
22	1121	1428.5	1350	1233.805	57.3117
24	1290	1695.5	1509.5	1401.315	70.00987
26	1502	2192.5	1872	1682.6	99.65496
28	1943.5	2513	2393	2151.94	113.9839
30	2763	3283	3170	2967.005	108.0613
32	4584	6966.5	5854	5065.96	389.7009

Table 7: Mustering times for different heel angles for the Day scenario of the Estonia

Heel (°)	Min	Max	95th percentile	Average	Standard deviation
0	1142.5	1418	1313	1221.06	51.21908
16	1374	1717	1661	1469.82	76.40813
18	1369.5	1776	1653.5	1483.31	88.8735
20	1413	1824.5	1659.5	1483.96	79.61757
22	1527.5	1890	1805	1638.28	78.28005
24	1714.5	2227	2149.5	1868.32	143.6204
26	1962.5	2512	2342.5	2110.74	115.805
28	2385	3217	3003	2650.62	184.6825
30	3197	5149.5	4139.5	3524.95	327.3436
32*	5051	7030.5	6770	5737.125	619.0882

Table 8: Mustering times for different heel angles for the Night scenario of the Estonia

* for 32° heel only 32 runs were performed.

The cumulative probability distributions for the time to muster in different heel angles for the Estonia for the day and night case are shown in Figure 4 and Figure 5 respectively.

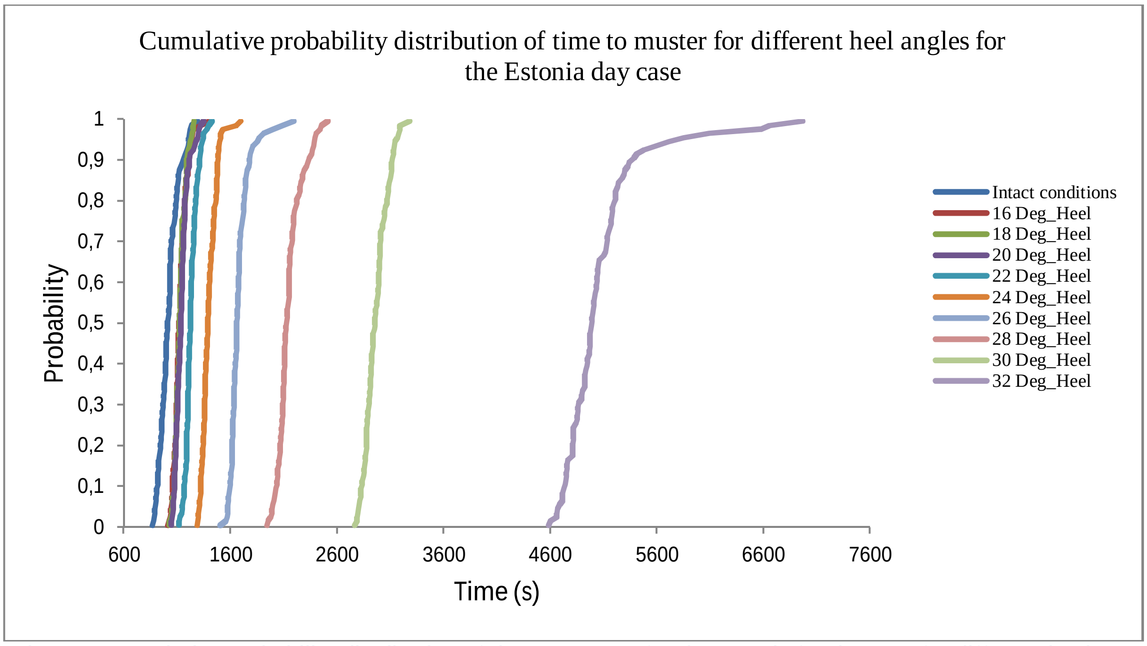


Figure 4: Cumulative probability distribution of time to muster for the Estonia for day case for different heel angles

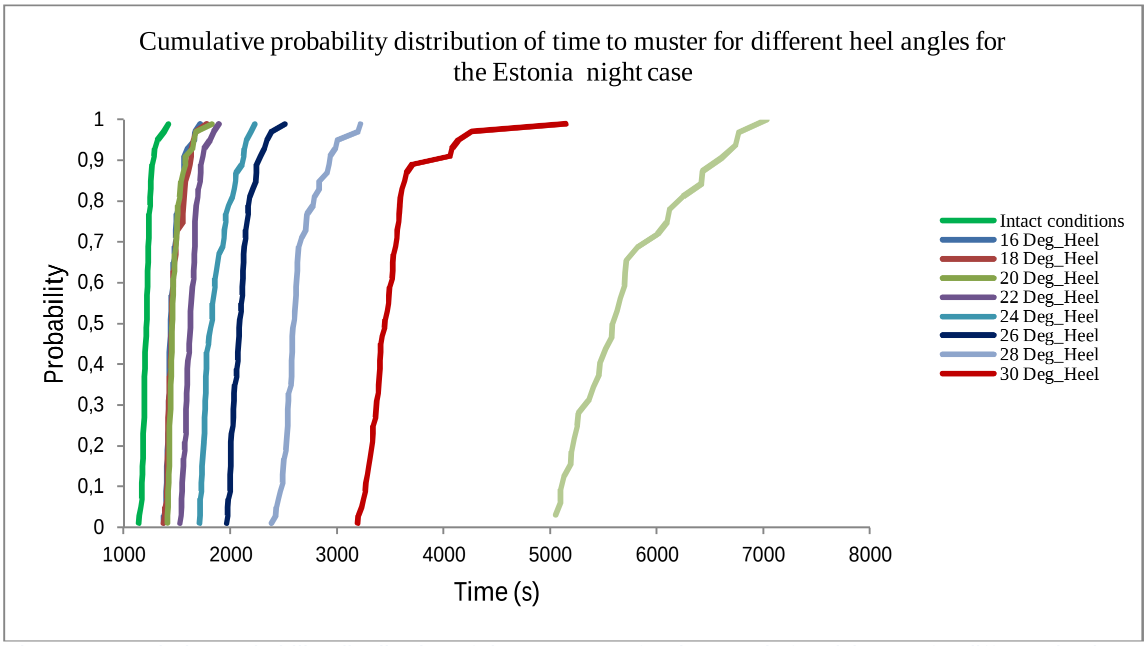


Figure 5: Cumulative probability distribution of time to muster for the Estonia for night case for different heel angles

In the figures below, average time to muster vs. different heel angles along with the upper and lower 99% confidence interval bounds for the average are shown for both the day (Figure 6) and night (Figure 7) case.

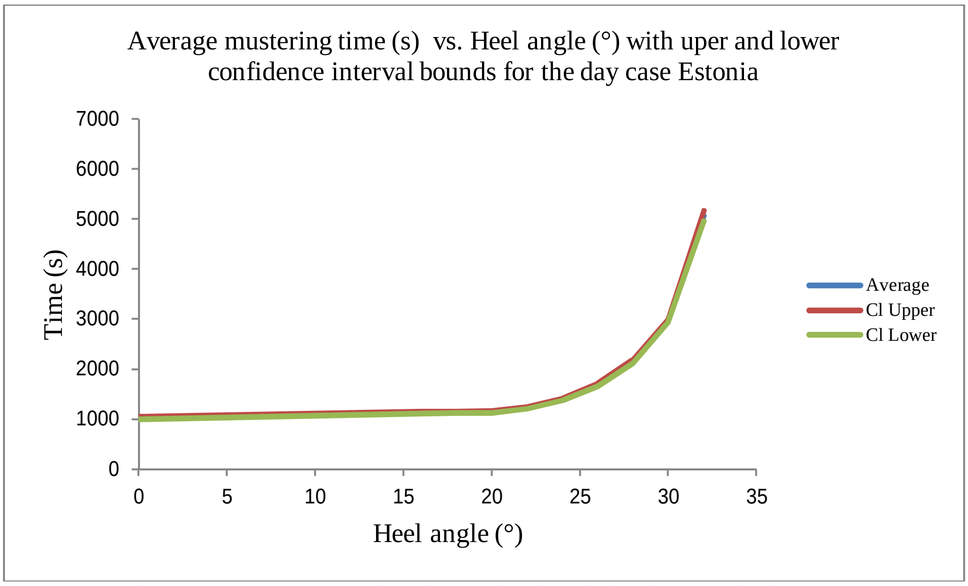


Figure 6 : Average mustering time vs. heel angle for the Estonia day case

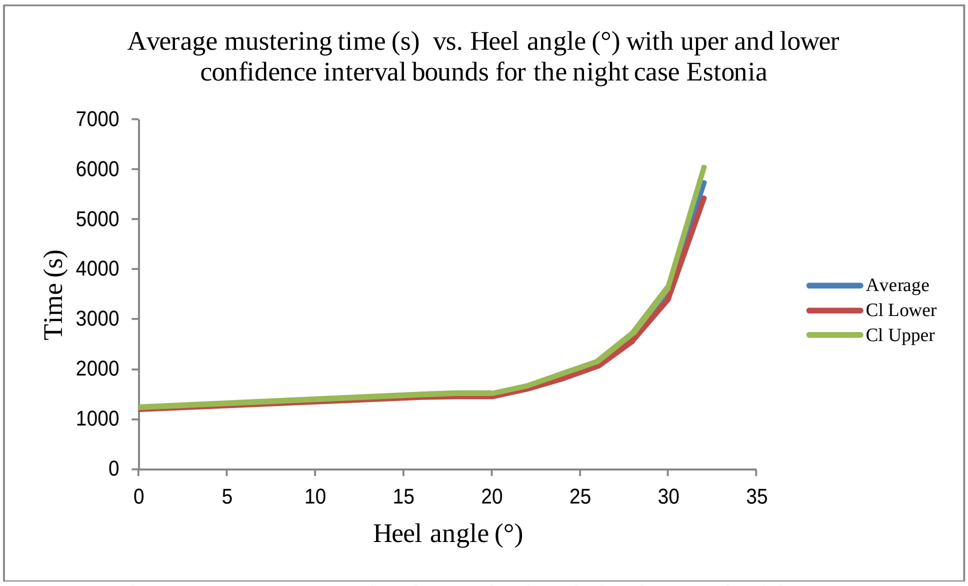


Figure 7: Average mustering time vs. heel angle for the Estonia night case

6.2 Cruise Liner

The ship

The Cruise Liner has a length of 268.33 m and a breadth of 32.20 m and could accommodate up to 2,766 passengers. The cruise liner is still in operations today and its design complies with all relevant IMO rules and regulations.

There are 15 decks numbered from 0 to 14 (deck plans cannot be provided for confidentially reasons).

On Deck 0 there is the engine room, the crew cabins, the laundry, the photo lab as well as the printing office.
On deck 1 there are more crew cabins as well as the provision area.

Passengers' accommodations are located on deck 2 to 10. The main dining area is on deck 3 as well as the Centrum a seven storey atrium. A second dining area is located on deck 4.
The casino, shops, music lounge and a coffee shop are all located on deck 5.
On deck 7, there are conference rooms as well as a lounge which is also the location of two muster stations. The other assembly stations (and embarkation stations) are located outside on deck 7.
Another big lounge is located on deck 8.
A beauty salon as well as a Spa and fitness centre can be found on deck 9.
Aft of deck 10 is a children's area and fore is the bridge.
Swimming pool, sport deck, restaurant, bar and cafe could all be found on Deck 11. On deck 12 there are open areas as well as a lounge. Deck 13 is the panorama deck and on deck 14 is a lounge.
The main stairway connects all the decks from 1 to 12.

Below is a picture of the Evi model for the Cruise Liner.

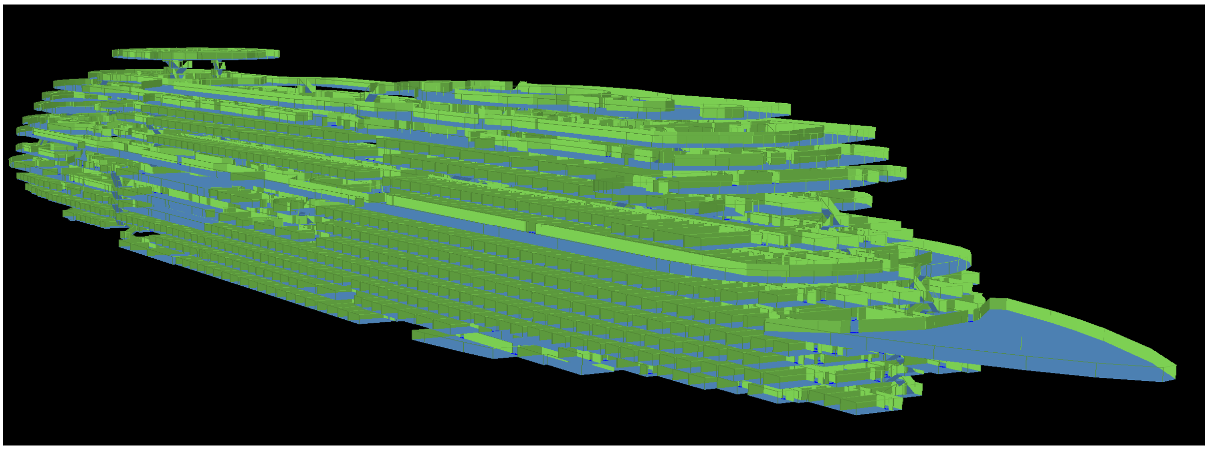


Figure 8: Evi model of the Cruise Liner

People on board

For the purpose of this study we consider 2557 passengers and 831 crew members on board.

Passengers and crew demographics

No information is available regarding the demographics of people on board Cruise Liner so the IMO demographics [1] are used for both the day and night case.

Spatial location of passengers and crew:

The passengers and crew will be distributed according to the IMO circular.

For the night case most passengers were located in cabins as far as possible from the muster stations. So we assume that the berthing capacity of:

- decks 2, 3, 4 and 5 is used at 100%.
- deck 6 is used at 90%.

- deck 7 is used at 77%.
- deck 8 is used at 85% and
- deck 9 and 10 at 80% and 73% respectively.

THE RESULTS

As for the Estonia 50 runs were performed for the night case and 100 runs for the day case.
Different heel angles were also considered for the cruise liner. The results are presented in the tables below:

Day

Heel (°)	Min	Max	95th percentile	Average	Standard deviation
0	1887	3780	2408.5	2088.99	224.2067
16	1897.5	3846.5	3347	2498.73	802.146
18	1778	3984	3012	2271.54	377.8364
20	1843.5	2955.5	2677	2264.175	210.4921
22	1855	4398	3319	2426.15	411.7198
24	2252.5	4869	3285	2691.895	355.189
26	2843	5115	4321	3388.22	439.9845
28*	3560	7222	7132	4707.052	1121.767
30**	4966.5	8129.5	7147	6335.2	951.0054

Table 9: Mustering time of the Cruise liner for the day case

* 29 runs
**10 runs

Night

Heel (°)	Min	Max	95th percentile	Average	Standard deviation
0	2836	2997	2995.5	2912.76	50.20562
16	3620.5	4805.5	4393.5	4005.03	239.7427
18	3629	4655.5	4476	3991.52	238.8622
20	3541.5	4873	4434	3963.6	282.7068
22	3880.5	5264	4793.5	4351.84	254.8141
24	4268	5511.5	5485.5	4906.52	299.8303
26	5106	6734	6430.5	5817.32	378.3172
28*	6347	7158	7047	6811.538	217.2948

Table 10: Mustering time of the Cruise liner for the night case

*13 runs

The cumulative probability distributions for the time to muster in different heel angles for the cruise liner for the day and night case are shown in Figure 9 and Figure 10 respectively.

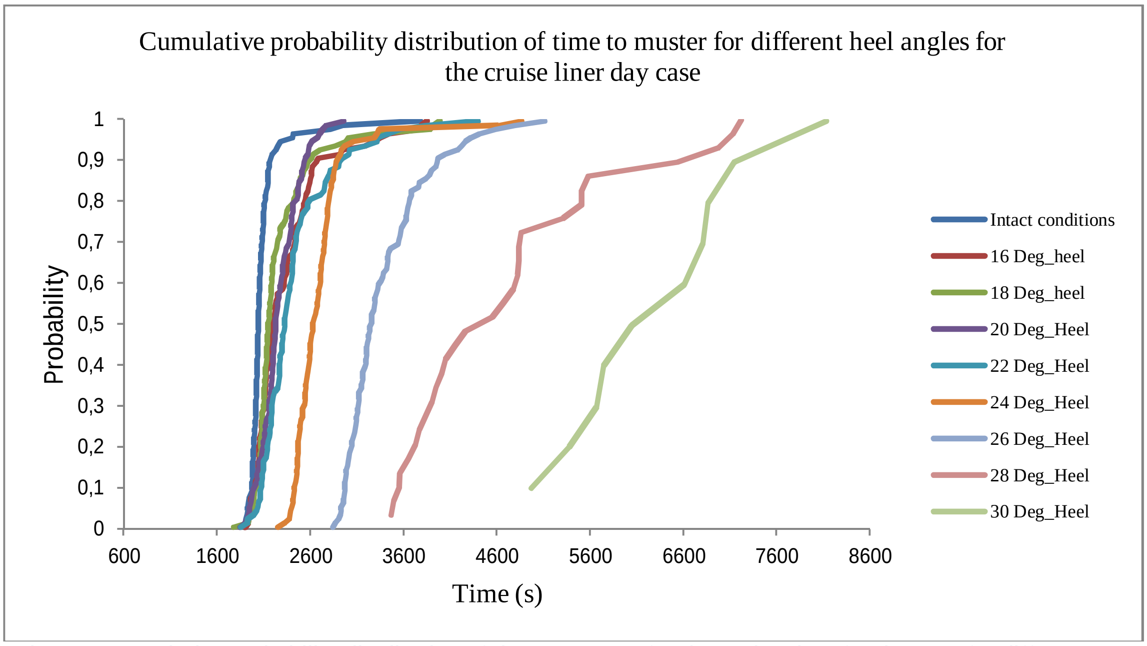


Figure 9: Cumulative probability distribution of time to muster for the Cruise Liner for day case for different heel angles

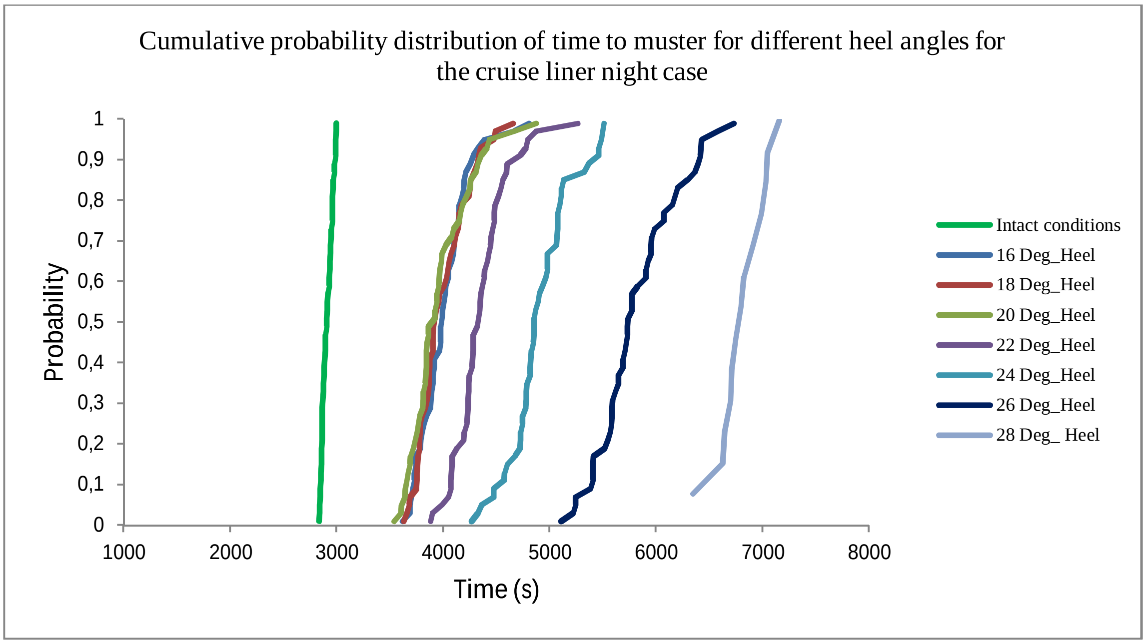


Figure 10: Cumulative probability distribution of time to muster for the Cruise Liner for night case for different heel angles

The average time to muster vs. different heel angles along with the upper and lower 99% confidence interval bounds for the average are shown below for both the day and night case in Figure 11 and Figure 12 respectively.

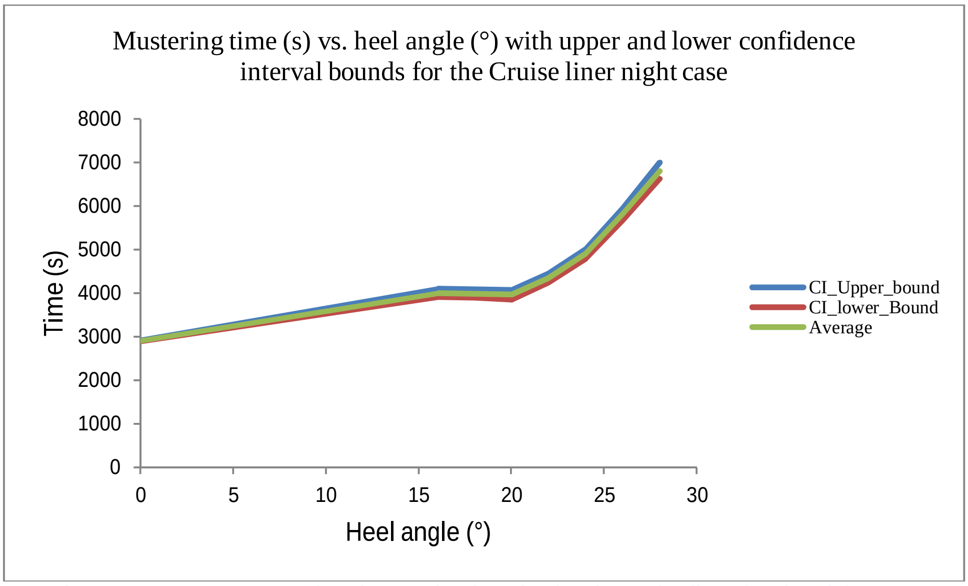


Figure 11: Average mustering time vs. heel angles for the cruise liner for the night case

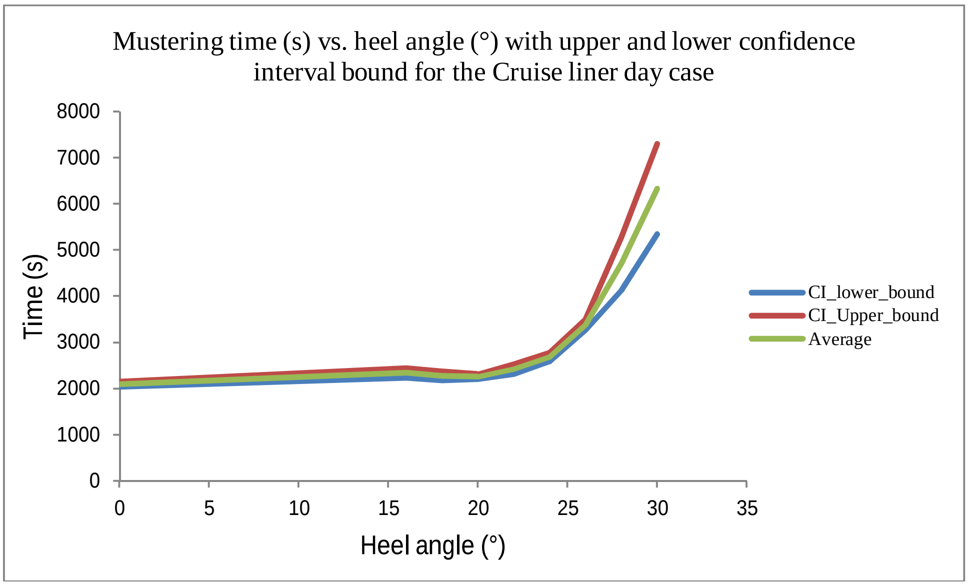


Figure 12: Average mustering time vs. heel angles for the Cruise Liner for the day case

Discussion

In Table 10, the mustering time for 16 degrees heel is bigger than the one for 18 degrees which is not what one would expect. The reason is that for less than 20 degrees heel there is no speed reduction (see appendix B for details of speed reduction function). The only effect is the handrail effect in stairs (see appendix B).
And because the speed is a random distribution, it might happen that the values assigned in the runs for 16 degrees were much higher than those of the 18 degrees runs and that the handrail effect was not enough to compensate for the difference.
After 20 degrees this phenomenon is not observed anymore as the speed starts to reduce with the heel.

6.3 Probability of number of fatalities: time to capsize vs. mustering time

In this section the probability distribution of loss of a specific number of people for a specific damage scenario is estimated.
In order to do that, the evacuation time is used in conjunction with the analytical model of time to capsize.

The analytical model of time to capsize, described in details in FLOODSTAND deliverable D4.2, is defined as follows:

$$F_{caps}(t_c|Hs) = 1 - \left[1 - \Phi\left(\frac{Hs - H_{crit}}{0.039.H_{crit} + 0.049}\right)\right]^{\frac{t_c}{t_0}}$$

$$H_{crit} = 4\left(\frac{GZ_{Max}}{0.25}.\frac{Range}{25}\right)$$

Where *Hs* is the significant wave height and H_{crit} is the critical sea state calculated using the GZ curve particulars of a specific damage scenario.

The probability distribution of loss of life can be then computed using:

$$pr_N(N|damage) = f_{caps}\left(t_{fail}(N)\right).\left|\partial t_{fail}(N)\right|$$

Where:

$$f_{caps} = \frac{\partial F_{caps}}{\partial t}$$
$$\partial t_{fail}(N) = t_{fail}(N) - t_{fail}(N-1)$$
$$t_{fail}(N) = N^{-1}(t)$$
$$N_{fail}(t) = N_{max} - N_{evac}(t)$$

and,
N_{max} is the total number of people onboard and $N_{evac}(t)$ is the number of passengers evacuated within time t. More details about this method can be found in FP6, SAFEDOR project deliverable [3].

Based on the model of time to capsize, we can estimate the probability of failure of the evacuation of the ship (the probability that not enough time will be available for people to leave the ship) in different sea conditions (different Hs).

To illustrate this, for a specific damage scenario, the probability of failure of the evacuation (mustering time + abandonment time) for the Estonia was estimated. Two heel angles were considered for the evacuation time for both the day and night scenarios. The results for the average evacuation times are given in the table below:

	Day		Night	
HS (m)	0° heel	20° heel	0° heel	20° heel
0.3	0.00046	0.00048	0.00048	0.000513
0.4	0.03899	0.04028	0.04077	0.04335
0.5	0.47599	0.48736	0.49156	0.51334
0.6	0.96606	0.96974	0.97101	0.97695
0.7	0.99994	0.99995	0.99996	0.99998
0.8	1	1	1	1
0.9	1	1	1	1
1	1	1	1	1
1.1	1	1	1	1

Table 11: probability of failure of the Mustering process for a given damage and diffrent Hs

For very low Hs the probability of failure is quite small but for Hs bigger than 0.6m the probability of failure is almost certain. This is explained by the fact that for higher Hs and according to the analytical model, the ship would capsize rapidly as can been seen in Figure 13 below which shows the cumulative probability of time to capsize for different HS.

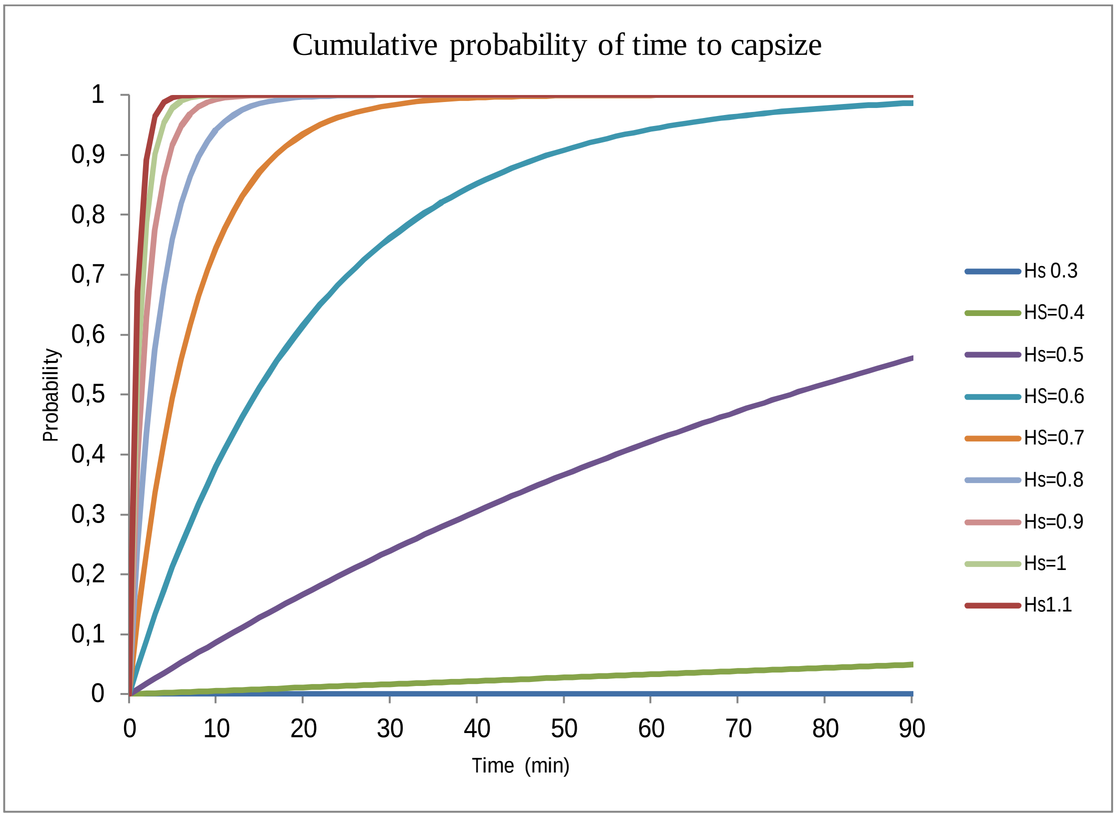


Figure 13: Cumulative probability of time to capsize for a specific damage in different Hs

7 CONCLUSION

In this deliverable, an overview over the obstacles in the Mustering, Abandonment and Rescue process was presented. In addition, a computer program which computes the expected number of fatalities for the MAR process (mainly the Abandonment and Rescue phase) was introduced. Its use is demonstrated in FLOODSTAND deliverable D5.5.

The mustering phase of the MAR process, which is the main subject of this deliverable, was assessed using evacuation simulation tools and results for the two selected ships under different conditions were presented.

The method to estimate the probability distribution of loss of a specific number of people during the mustering phase for a specific damage (collision) scenario was presented and illustrated for a particular damage case for the Estonia.

8 REFERENCES

1. “*Guidelines for evacuation analysis for new and existing passenger ships*”, IMO MSC.1/Circ 1238 2007.
2. The Joint Accident Investigation Commission of Estonia, Finland and Sweden “Final report on the capsizing on 28 September 1994 in the Baltic sea of the ro-ro passenger vessel MV Estonia”, 1997
3. “Fast and accurate flooding prediction validation study”. SAFEDOR D 2.1.4. November 2007.

Appendix A: Detailed description of the Casualty Calculator**.**

1. Database

As explained in FLOODSTAND deliverable D5.1, the details of the MAR process are described by obstacle matrices. In the software implementation, these matrices are saved in a MySQL database which is accessed by the Casualty Calculator.

The database contains six tables: for each of the three sea states (3, 5 and 6) there are two tables, one containing the expectation values of the matrices and the other the variances.
Each table contains a unique obstacle code, a brief description of the obstacle and the numerical values for the three matrices (one for each age group). Each matrix is described by six entries (in case of the expectation values) or ten entries (in case of the variance).

The below screenshot (Figure 14) shows the structure of one of the tables (mean values for sea state 3). The entries of the matrices are named according to their age group – e.g. AGY_12 is the second entry in the first column of the matrix for the 'young' age group.

```
C:\Program Files\MySQL\MySQL Server 5.1\bin\mysql.exe
Enter password: *********
Welcome to the MySQL monitor.  Commands end with ; or \g.
Your MySQL connection id is 73
Server version: 5.1.52-community MySQL Community Server (GPL)

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This software comes with ABSOLUTELY NO WARRANTY. This is free software,
and you are welcome to modify and redistribute it under the GPL v2 license

Type 'help;' or '\h' for help. Type '\c' to clear the current input statement.

mysql> use obstacles;
Database changed
mysql> show tables;
+----------------------+
| Tables_in_obstacles  |
+----------------------+
| meansss3             |
| meansss5             |
| meansss6             |
| variancess3          |
| variancess5          |
| variancess6          |
+----------------------+
6 rows in set (0.00 sec)

mysql>
mysql>
mysql> explain meansss3;
+--------------+--------------+------+-----+---------+----------------+
| Field        | Type         | Null | Key | Default | Extra          |
+--------------+--------------+------+-----+---------+----------------+
| id           | int(11)      | NO   | PRI | NULL    | auto_increment |
| obstacleName | varchar(100) | NO   |     | NULL    |                |
| obstacleCode | varchar(30)  | NO   | UNI | NULL    |                |
| AGY_12       | double       | YES  |     | NULL    |                |
| AGY_13       | double       | YES  |     | NULL    |                |
| AGY_14       | double       | YES  |     | NULL    |                |
| AGY_23       | double       | YES  |     | NULL    |                |
| AGY_24       | double       | YES  |     | NULL    |                |
| AGY_34       | double       | YES  |     | NULL    |                |
| AGM_12       | double       | YES  |     | NULL    |                |
| AGM_13       | double       | YES  |     | NULL    |                |
| AGM_14       | double       | YES  |     | NULL    |                |
| AGM_23       | double       | YES  |     | NULL    |                |
| AGM_24       | double       | YES  |     | NULL    |                |
| AGM_34       | double       | YES  |     | NULL    |                |
| AGO_12       | double       | YES  |     | NULL    |                |
| AGO_13       | double       | YES  |     | NULL    |                |
| AGO_14       | double       | YES  |     | NULL    |                |
| AGO_23       | double       | YES  |     | NULL    |                |
| AGO_24       | double       | YES  |     | NULL    |                |
| AGO_34       | double       | YES  |     | NULL    |                |
+--------------+--------------+------+-----+---------+----------------+
21 rows in set (0.01 sec)
```

Figure 14: Table of obstacles

2. Input

The software expects the following input from the user.

Variable	Allowed values
Sea state	3, 5, 6
Initial health vector ('young' group)	Four real numbers between 0 and 1; numbers must add up to 1
Initial health vector ('middle' group)	As above
Initial health vector ('old' group)	As above
Total passengers in 'young' group	Zero or positive integer
Total passengers in 'middle' group	As above
Total passengers in 'old' group	As above
Number of primary LSA	Positive integer
Number of people in each primary LSA	As above
Number of people in secondary LSA (optional)	As above
Obstacles for primary LSA	Comma separated string of obstacle codes
Obstacles for secondary LSA (if required)	As above

The above values can be entered by hand or by using an **input file**. This file contains the input values in a semicolon-separated string in the following order:

GHY; MIY; SIY; DY; GHM; MIM; SIM; DM; GHO; MIO; SIO; DO; Total young passengers; Total middle passengers; Total old passengers; Sea state; Number of primary LSA; Passengers per primary LSA; Passengers per secondary LSA (only required if not enough primary LSA); Obstacles for primary LSA (comma-separated string of obstacle codes); Obstacles for secondary LSA (only required if not enough primary LSA)

Here "GHY" stands for "good health, young age group" and similarly for the other entries. Note that this data needs to be on the same line without line breaks.
The input file can be used to run **multiple scenarios** by simply adding more lines of input. The output of all scenarios will be written to the same files (refer to the Output section below).

3. Computation

Expectation values

The output health vectors are computed by simply multiplying the (expectation values of the) obstacle matrices with the input health vector for each age group:

$$v_{out}^{young} = A_1^{young} \cdots A_n^{young} \cdot v_{in}^{young}$$

Here v stands for the health vectors, and A_i denotes the obstacle matrices. Note that the obstacles are entered in the 'natural' order in which they are encountered by passengers, and not the order in which they are multiplied. I.e. an input of “A, B” means “passengers pass obstacle A first, then obstacle B”. In the computation they are multiplied as $B \cdot A$.

Standard deviation

The “error” of the output health vectors is calculated algebraically from the means and variances of the obstacle matrices. We use the following formula.

<u>Claim:</u>
Let A and B be two $n \times n$ matrices whose entries are independent random variables. We denote by $\langle A \rangle$ and $var(A)$ the expectation value and variance of A, respectively. Define $\tilde{A}$ to be the matrix containing the squared entries of $\langle A \rangle$ (and equivalently for B). The variance of the product of the two matrices is given by

$$var(A \cdot B) = \tilde{A} \cdot var(B) + var(A) \cdot \tilde{B} + var(A) \cdot var(B)$$

<u>Proof:</u>
Denote the entries of A and B by a_{ij} and b_{ij}, respectively. Using the well-known relations

$$var(x + y) = var(x) + var(y)$$
$$var(x \cdot y) = \langle x \rangle^2 var(y) + \langle y \rangle^2 var(x) + var(x) var(y)$$

for independent real-valued random variables x and y, we find for the product matrix:

$$\begin{aligned}
\big(var(AB)\big)_{ij} &= var\big((AB)_{ij}\big) \\
&= var\left(\sum_{k=1}^{n} a_{ik} b_{kj}\right) \\
&= \sum_{k=1}^{n} var\big(a_{ik} b_{kj}\big) \\
&= \sum_{k=1}^{n} \Big(\langle a_{ik} \rangle^2 \cdot var\big(b_{kj}\big) + \langle b_{kj} \rangle^2 \cdot var(a_{ik}) + var(a_{ik}) \cdot var\big(b_{kj}\big)\Big) \\
&= \Big(\tilde{A} \cdot var(B) + var(A) \cdot \tilde{B} + var(A) \cdot var(B)\Big)_{ij}
\end{aligned}$$

□

For a product of more than two matrices, the above equation is applied repeatedly.

Using this formula, it is straightforward to compute the variance of the output health vector. In particular, the variance of the expected death rate (D) is given by

$$var(D) = GH_{in}^2 \cdot var(M_{41}) + MI_{in}^2 \cdot var(M_{42}) + SI_{in}^2 \cdot var(M_{43}) \quad ,$$

where GH_{in} etc. denote the input health coefficients (which are known exactly and hence have variance zero) and M is the product of all relevant obstacle matrices.

Probability distribution

Let us first consider the case in which the deaths of passengers are independent events (as is the case if only human factor obstacles are taken into account). Then the probability to have k fatalities is simply given by the binomial distribution:

$$P(k) = \binom{n}{k} \cdot p_f^k \cdot \left(1 - p_f\right)^{n-k}$$

Here p_f is the probability to have one fatality, and n is the total number of passengers on the ship.

In reality, however, we need to take into account the fact that there are three age groups with three different values for p_f. Hence the above equation holds only for an individual age group, and the probability distribution for the whole ship is computed using combinatorics. For example, the probability to have three fatalities is made up of the probabilities to have one casualty in each age group, or three casualties in one age group and none in the others etc. In total, there are ten different scenarios to consider. In general, the number of probabilities that need to be computed grows with n^3.

If we also take into account LSA-type obstacles (e.g. lifeboats capsizing), then the events of passengers' deaths are no longer independent as all people in the same LSA are equally affected. We will discuss this case in more detail below.

4. Output

The software displays the output health vectors for each age group (for primary and/or secondary LSA) on the screen, as well as the expected number of fatalities (Figure 15).

The standard deviations of all values are given. The input and output data can be exported to a text file if the user so chooses. In addition, the probability distribution of the number of fatalities can be written to a comma-separated file (it is not displayed on the screen for reasons of legibility).

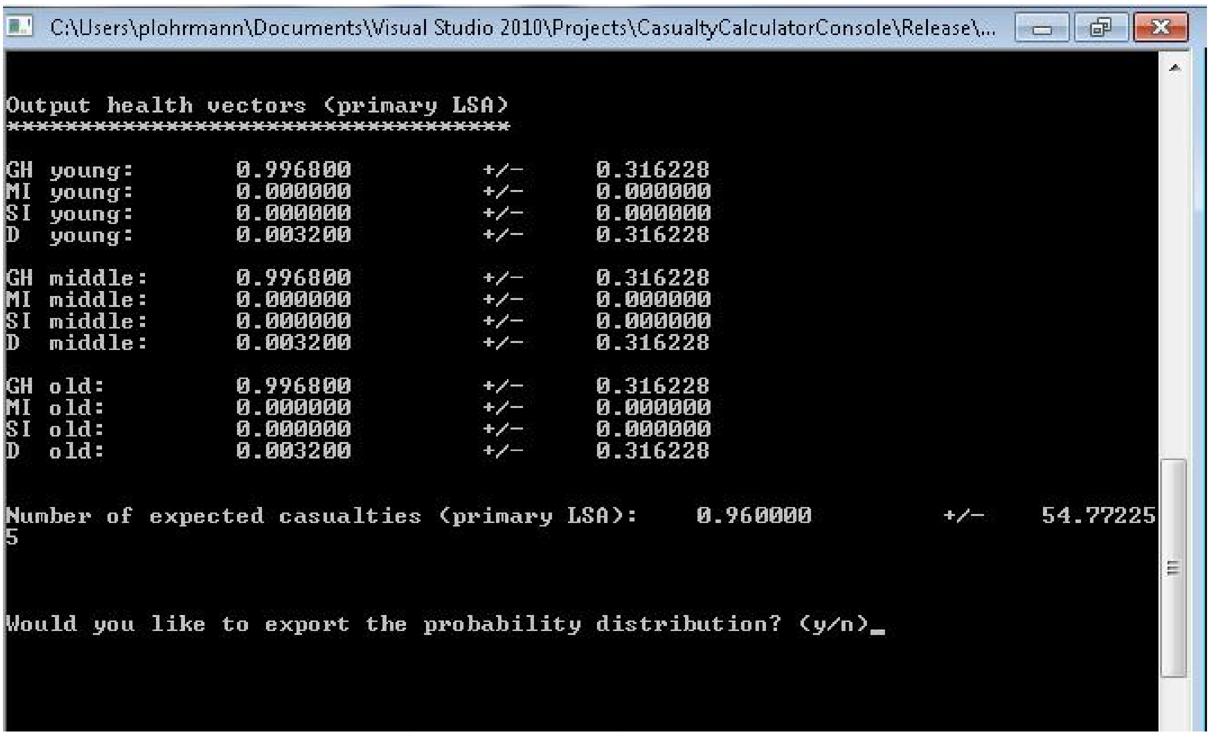

Figure 15: Output on the screen

5. Primary and Secondary LSA

To accurately model the MAR process, we need to take into account the effects of LSA-type hardware obstacles. By this we mean obstacles that are specific to a LSA type and affect all people in this LSA. A typical example is capsizing – we assume that all passengers in the LSA perish in such an event, and hence fatalities in this group of people cannot be treated as independent.

Our approach to this problem works as follows. The software requires as input the number of primary LSA (typically lifeboats) available during the rescue process. If there are enough such LSA, then it is assumed that all passengers are using them and that no secondary LSA (typically liferafts) are needed. However, **if there are not enough primary LSA for all passengers, then it is assumed that all primary LSA are filled completely and that the remaining passengers are using secondary LSA.**

We make three further assumptions. Firstly, we assume that there is **at most one partially full LSA** (of whichever type) and that all other LSA are filled to their maximum capacity. In particular, if only primary LSA are used, then there will be at most one partially full LSA. If secondary LSA are used, then all primary LSA are full and there is at most one partially full secondary LSA.
Secondly, we assume that **the age distribution in each LSA is identical to the age distribution of the whole ship**. This appears reasonable, as the allocation of passengers to LSA is typically done by their cabin number, which can be assumed to be randomly allocated.

Thirdly, we assume that **passengers are subject to LSA-type hardware obstacles before they encounter any human factor obstacles**. This simplification is necessary as otherwise the number of scenarios to be considered becomes too large to handle. In practice, this assumption means that if LSA-type hardware obstacles are used, they need to be entered at the beginning of the obstacle string before any human factor obstacles:

$$X_1, \dots, X_k, A_1, \dots, A_l$$

Here X_i stands for the LSA-type hardware obstacles, whereas A_i denotes the human factor obstacles[2].

Let us now turn to how the computations are affected by the presence of LSA-type obstacles. Fortunately, the calculation of expectation values and standard deviations is unchanged and hence remains straightforward. However, the computation of the probability distribution becomes significantly more complicated than the binomial distribution used for the human factor obstacles (see above). To illustrate this fact, let us consider a numerical example.

Assume that there are 200 people on the ship (of any age distribution), each primary LSA (lifeboat) can take 60 people, and there are enough such boats for all passengers (hence no secondary LSA are used). Thus there will be three (full) lifeboats containing 60 people each, and one (partially full) boat containing 20 people.
Let us consider two obstacles: capsizing of a lifeboat (a LSA-type hardware obstacle, affecting everyone in the boat) and hypothermia (a human factor obstacle, affecting passengers individually).
How do we compute the probability to have, say, 100 casualties? We will need to consider the following scenarios:

- No lifeboats are lost, and 100 people die from hypothermia.
- A full lifeboat (60 people) is lost, and 40 passengers die from hypothermia.
- The partially full lifeboat (20 passengers) is lost, and 80 people die from hypothermia.
- Both the partially full and a full lifeboat capsize, and 20 people die from hypothermia.

Note than when calculating the probabilities for a given number of people to die from hypothermia, one needs to take into account the different age groups (older people tend to be more vulnerable).
Thus even with such a small number of passengers, a large number of individual probabilities needs to be computed in order to obtain a single point in the probability distribution. If secondary LSA are used as well, then the number of relevant scenarios becomes larger still – in particular, the people lost due to human factor obstacles must be split between primary and secondary LSA as well as between age groups.

The Casualty Calculator is capable of computing the most general case (for two types of LSA).

[2] It is possible to intersperse the human factor obstacles with further hardware obstacles *as long as these only affect individuals* (for example failure of life vests etc).

Appendix B: Mathematical modelling of Evi.

Definition

Evacuability is defined to be the ability to evacuate a ship environment within a given time for given initial conditions as follows:

$$E = f\{env, d, r(t), s(n_i); t\}$$

where:
env: represents the ship model (geometry, topology, semantics),
d: is the initial distribution (spatial location) of the people on board,
$r(t)$: initial reaction time of people on board(cue perception, interpretation of instructions, ...) and
$s(n_i)$: walking speed of individual people.

Evacuability thus defined represents a risk measure of passengers evacuation expressed as an index.

Evi allows the prediction of passenger mustering in a range of different incidents (fire, collision, progressive flooding) whilst accounting for ship motions.

Evi also models uncertainties as every parameter is modelled as a random variable with a predefined distribution.

Mathematical model

In this section the mathematical modelling of Evi will be presented. For a detailed description please refer to [1].

1. Multi-Agent Modelling

An ‘agent’ is defined as an encapsulation of code and data, which is capable of executing independently the appropriate piece of code depending on its own state (the encapsulated data), the observables (the environment) and the stimuli (messages from other parts of the system or interactively provided).
The agent’s action model is a 'sense-decide-act' loop.
The sense step is the interface of the agent with the data structures representing the environment.
The decision process requires access to the perceived information. It is an access interface between the environment and the agents.
An environment is defined to be an artificial representation of the space where agents evolve.
In the implementation the environment will be an appropriate collection of data structures in the computer.

2. The environment model

Modelling of the environment is one of the most important aspects of multi-agent modelling. This consists of three aspects - geometry, topology and domain semantics. The perception model of the agents will be able to use the information in these three abstractions at different levels of the decision processes.
A multi-deck layout may be modelled as a 2 dimensional *manifold*. The ship area manifold is segmented into convex subsets whose mutual intersection can at most be subsets of one-dimensional topological manifolds for which a Euclidean structure holds. Furthermore, this segmentation is done in such a way that three regions may intersect only at points (i.e. zero-dimensional topological sets). These subsets are called regions and the one-dimensional sub-manifolds (curves) along which two of them intersect are termed gates.
Two regions are called directly connected if they have a common gate. Similarly, gates are defined to be directly connected if they lie on the same region.
This connectivity, for all computation and analysis purposes can be represented by a graph.

In ship layout regions are defined as cabins, corridors, public areas (or subsets of these), each with its own co-ordinate system and connectivity, defined by gates (real or artificial doors). Figure 16 below illustrates this concept.

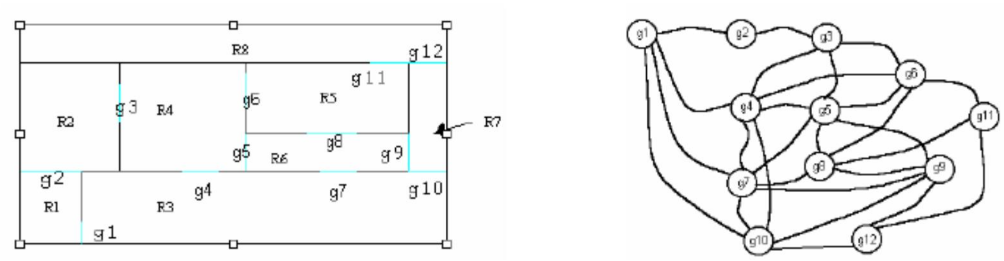

Figure 16: Example of regions and gates and the corresponding connectivity (gate) graph [Error! Reference source not found.]

The path of the agents leading to the embarkation station is determined by searching the connectivity graph. A depth first exhaustive search over the gate graph is used in Evi to choose the optimal path (shortest path) to be used for high level planning activities.

3. High level planning: Path planning and graph search

The path-planning algorithm computes the distance from the Assembly station to all the doors in the graph in a pre processing phase (before the actual simulation start) and the information about the distance is stored with each door.
When an agent is located in a region, the distance information from each door of the region can be obtained, thus allowing the agent to use the shortest path leading to the destination area. Re-planning during the evacuation is still possible if for some reason (dense crowd for example) the path is blocked. Figure 17 below illustrates the path planning for a simple graph.

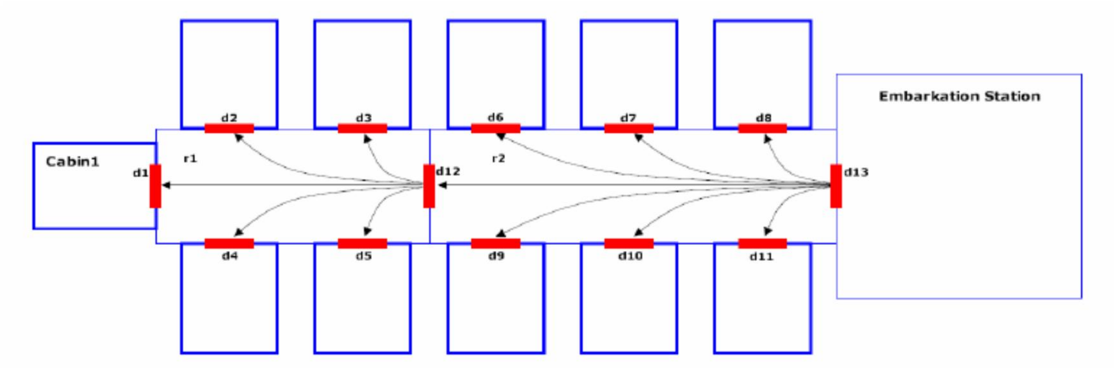

Figure 17: Example of path planning

4. Low level planning: Steering of agents

Pursuit of a static target acts to steer the agent towards a specified position in global space. This behaviour adjusts the agent so that the velocity is radially aligned towards the target. The "desired velocity" is a vector in the direction from the agent to the target representing global "flow speed", adjusted on the basis of local density.
The steering vector is the difference between the desired velocity and the agent's current velocity, as shown in Figure 18.
In the absence of any obstacle and other evacuees, every agent will "flow" along the evacuation direction field (passing through the gates unobstructed), otherwise avoidance heuristics are used to avoid collision with the neighbouring agents and obstacles present along the evacuation path.

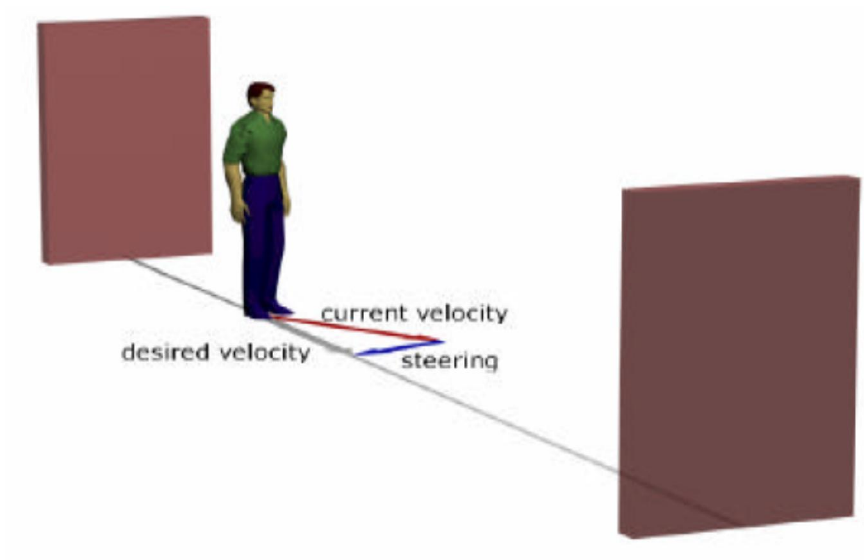

Figure 18: Steering of agents

5. Modelling human behaviour

There is a large number of parameters that are likely to affect the evolution and the outcome of an evacuation scenario. Some are related to the population profile (number, age, gender, persons of impaired mobility and so on), passenger distribution

(spatial and temporal) and crew number, distribution and functionality in any given crisis. Others are related to behavioural aspects.
In Evi people on board are treated as agents moving in a "command" and "decision" structure.

6. Synchronisation

One of the most important aspects of the microscopic behaviour algorithms is the synchronisation between agents. Considering the total number of entities (agents) in the simulation of an evacuation scenario, updating each one of them at the same time would require substantial parallel processing of the information. Such capability might not be readily available in most personal computers.

In Evi, the update process is performed in two steps.

1. **First**: the Perception–Decision Phase, where all agents calculate / update their information using one environment state but do not move (they perceive the update in parallel).
    - Perception phase:

      The perception algorithm checks the space (in the form of discreet directions) around the agent for boundaries and other agents.
      The calculation stops if a direction is found where the agent can progress without reaching any walls or interfering with other agents.
    - Decision phase:

      The decision algorithm uses a rational rule-based process to select the action to take for the current time step. The decision process makes use of information on the previous time step combined with information acquired from the Perception algorithm.
      Before entering the decision process, the algorithm first gathers state information from the current environment that may affect the perception process. This includes update of the desired travel direction, consideration of the current waypoint and selection of the current maximum speed taking into account environmental and well-being parameters (i.e. effect of ship motions, smoke and toxicity).

2. **Second**: the action phase where agents carry out their calculated / updated actions.

7. Speed of advance

The speed of agents varies according to a number of parameters pertaining to ship/sea environment, the scenario in question and the passenger distribution and profile which in turn are described by an even larger number of parameters such as passenger age, gender, physical location and position on vessel, signage, crew guiding and ship motion, to mention but a few.
According to the IMO Guidelines [2], the speed of an agent is determined by the density of the crowd in the region.
The crowd density corresponding to an evacuee in an escape route describes the number of persons divided by the available escape route area pertinent to the space

where the evacuee is located. As the model geometry is reproduced to exact measurements of the actual vessel, the density calculations are deemed to be very accurate.
The available escape route area is determined by the actual overlapping area between the regions (e.g. corridors, stairways, etc), and a density rectangle (2.14m x 2.14m was identified as the best choice) that moves with the agent, as shown in Figure 19.

Additionally, when long queues form, the effect on speed of advance is calculated rigorously on the basis of the queue length.

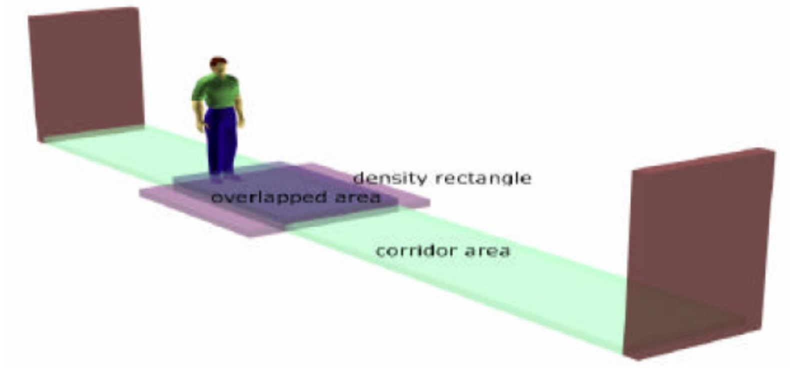

Figure 19: Density area

8. Effect of ship motion

With time, humans can adapt to small regular motions and constant acceleration but when they become unpredictable, the feedback system used by the body makes corrections too late and cannot anticipate the movements. The body concentrates instead on maintaining balance and forward motion will suffer as a result.
A way to model the reduction of speed is to relate it to the roll angle.

Few studies have been undertaken on the effect of inclination on the speed of people's movement but none has been particularly comprehensive and all have used young and physically fit subjects. The results of some of these studies using motion platforms imply that ship listing of up to 15-20° has little influence on the pedestrian walking speeds. Meanwhile, at the other extreme, it may be assumed that walking stops when the heel angles reach 30-35°. Considering these key facts, the speed reduction relationship as depicted in Figure 20 is used in the evacuation simulation software. Here, no reduction occurs up to 20° and thereafter a linear reduction with angle occurs until 35° where walking is assumed to be impossible [3].

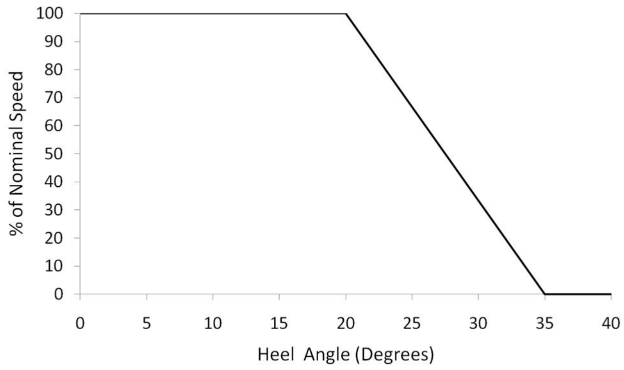

Figure 20: Speed reduction function

9. Handrail Dependence [3]

One major effect of the flooding scenario is that the evacuating people are reliant on handrails for balance. This can occur at high heel angles for instance above 10°, or at accelerations in excess of 0.5m/s2.

This changes the use of the available space, as the people can no longer use the entire width of the space for egress. Furthermore, people tend to leave a larger space between themselves and the person in front.

In the evacuation simulation software, the agents moving up and down stairs must stay close to the (lower) wall of the spaces to mimic the use of the handrails, and try to maintain a distance of at least 0.5m to the person in front.

10. References

1. *"A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance-Based Evaluation"*. D.Vassalos, H. Kim, G. Christiansen and J. Majumder. Pedestrian and Evacuation Dynamics – April 4-6, 2001 – Duisburg.
2. "*Guidelines for evacuation analysis for new and existing passenger ships*", IMO MSC.1/Circ 1238 2007.
3. "*Evacuability of a flooded passenger ship*". A. Pennycott, Y. Hifi. 4th international Maritime Conference on Design for safety. Italy October 2010.

Appendix C: Deck plans of the Estonia.

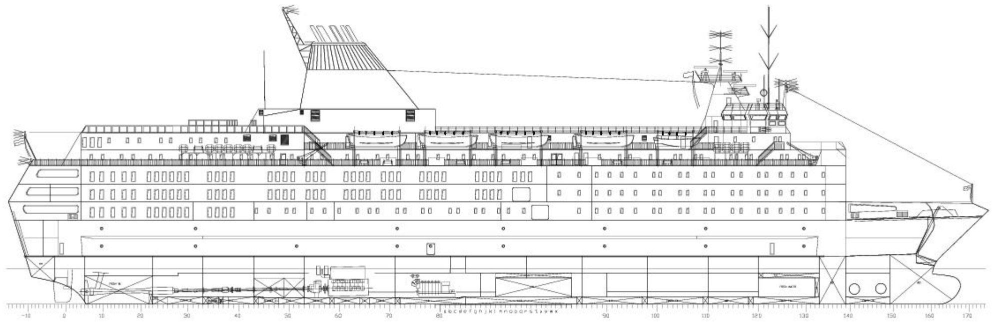

Figure 21: Profile

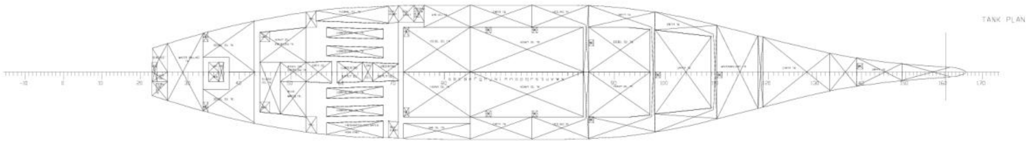

Figure 22: Tank plan

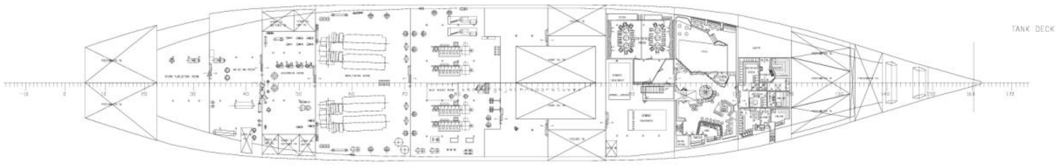

Figure 23: Tank deck

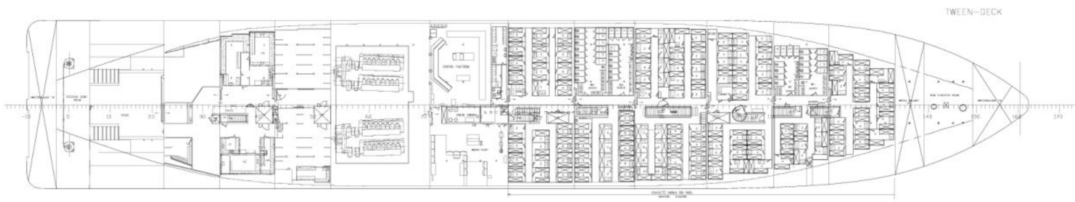

Figure 24 : Tween deck

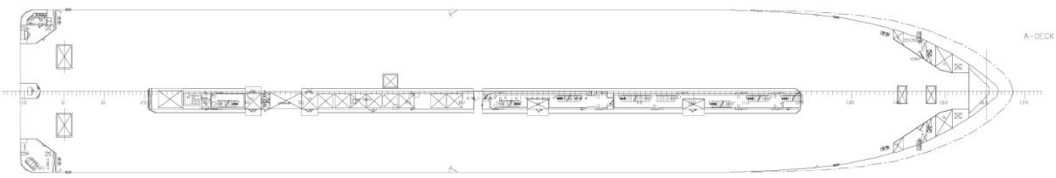

Figure 25: Deck A

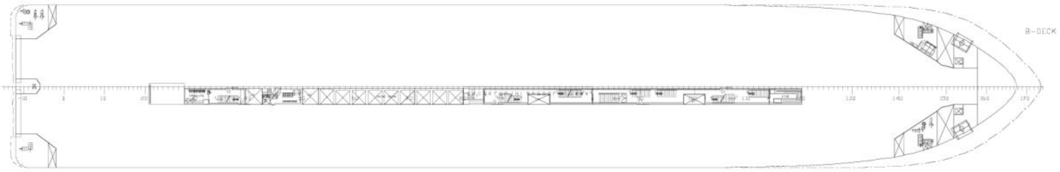

Figure 26: Deck B

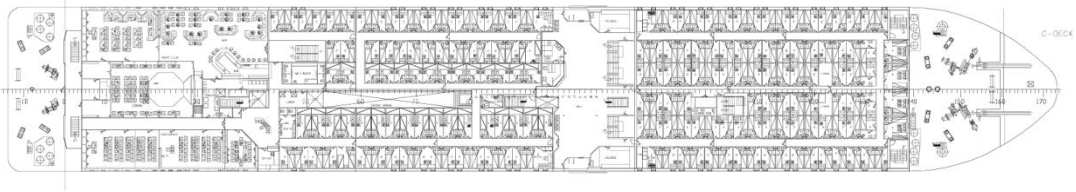

Figure 27: Deck C

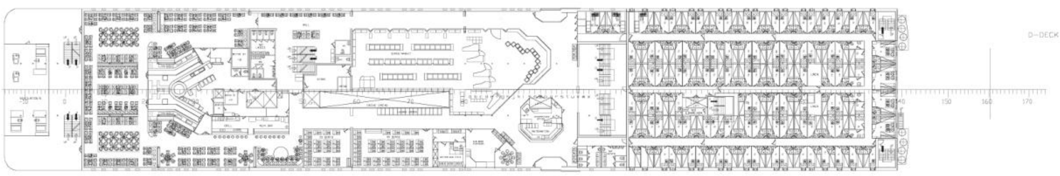

Figure 28: Deck D

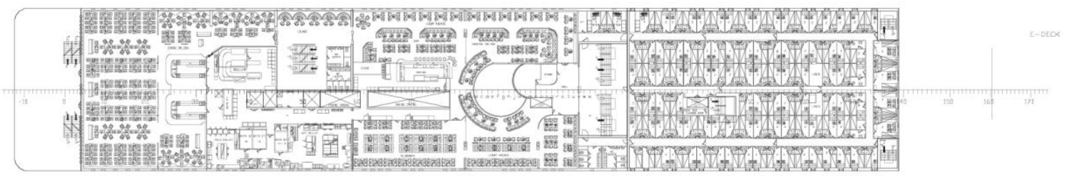

Figure 29: Deck E

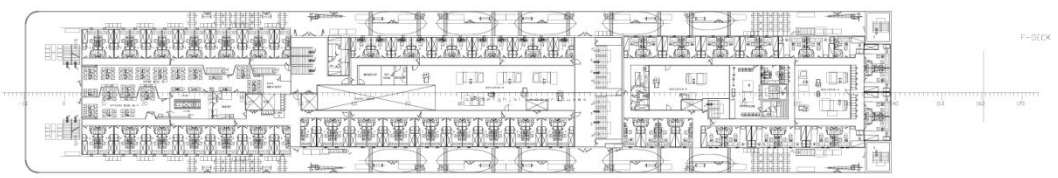

Figure 30: Deck F

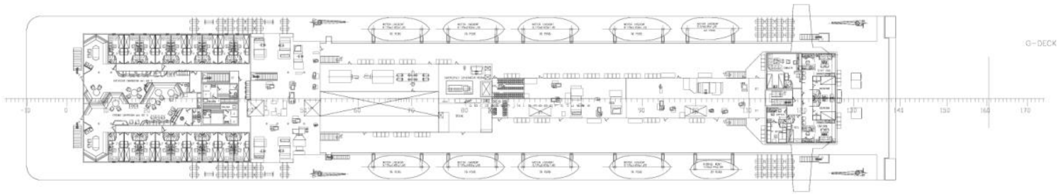

Figure 31: Deck G

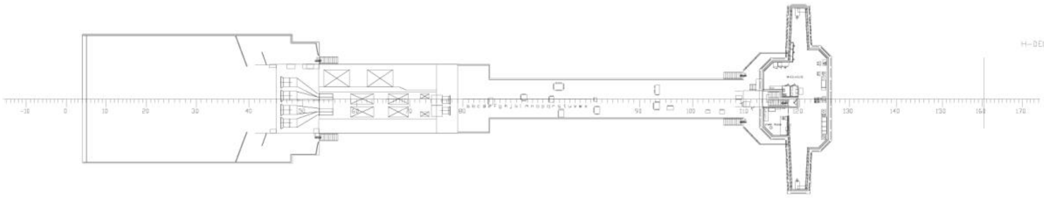

Figure 32: Deck H