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Deliverable D11.3

Development of means for Ro-Ro ship safe evacuation conditions in relation to fire integrity and walk-off abandonment

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Abstract

One objective of the LASH FIRE project was to develop solutions and recommendations to ensure safe evacuation during safe return to port (considering a fire integrity for 3 hours) and when arriving at foreign port. In this report, the abandonment phase of the ship was therefore considered. For this phase to be possible, the passengers should have gathered first in a designated safe area known as the assembly station in due time. Subsequently, when the means of abandoning the ship become available, the passengers start leaving the ship.

The assembly phase and the abandonment phase were investigated using an evacuation model considering the path toward safe areas, congestion development at the doorways and stairs, also taking into consideration input from an associated study in LASH FIRE on fire integrity. This latter study involved a full Computational Fluid Dynamics (CFD) model of fire propagation, the ship being represented as a multi-compartment system, with a fire ignited in a Ro-Ro space and possibly propagating along the ship. The evacuation considered the travel of passengers and crew modelled as a crowd density tracked along its evacuation path through the successive compartments. Input from the fire integrity study were introduced as penalizing conditions due to heat stress, visibility loss or toxicity, possibly generating obstacles along the evacuation path, or travel speed reduction. The objective was to identify the potential weaknesses and to develop corresponding solutions to ensure safe evacuation.

Results showed that the time required for the assembly phase is by far shorter than the fire development. This step does not require any new specific risk control measure.

The abandonment phase was analysed considering various scenarios and using the geometry of the generic ship Stena Flavia, with all the passengers located in the assembly station. The study first considered scenarios making use of the Ro-Ro space loading ramp or of the pilot doors on either side of the ship, possibly combined with lifeboats. Solutions based on pilot doors were found to be impossible to use on the specific generic ship, because of their location at the same level as the Ro-Ro space, where the fire was possibly in an uncontrolled situation, resulting therefore in an unsafe alternative evacuation path. However, under the assumption of a controlled fire, alternative paths using the pilot door or the bunker door were evaluated and found to give a reasonable evacuation time. The remaining difficulty is to find a solution to overcome the potential height difference towards the quay side, as stairs or ladders would not be a viable solution. A Risk Control Measure based on this solution could not be completely defined for the time being, but should be further considered in future studies. Another alternative solution considered was the use of slides from the assembly station level, which was found as a non-safe solution when discussing this measure with the Maritime Authorities Advisory Group (MAAG) and the Maritime Operators Advisory Group (MOAG) during one of the solution workshops held for the LASH FIRE project. This Risk Control Measure was consequently disregarded.

This action (11-B) of the LASH FIRE project finally led to recommendations for the design of Ro-Ro ships, considering pilot door, or bunker door, as a possible solution for second means of walk-off abandonment, provided a safe path toward these doors is designed and a safe solution is implemented to reach the quay or the sea from the door itself.

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Content

1 Executive summary

1.1 Problem definition

The main goal of Action 11-B was to develop solutions and recommendations to ensure safe evacuation of Ro-Ro ships, both at sea and when arriving at a port, possibly a foreign port. The studied scenarios consider the impact of a fire ignited in the Ro-Ro space, propagating along the ship. This report investigates the two main steps of the evacuation, namely the assembly phase and the ship abandonment phase, involving the fire-induced penalizing conditions for passengers and crew members. The assessment of different means of ship abandonment is presented in order to establish their reliability in terms of evacuation time. Solutions are also discussed considering their applicability and the safety of evacuees.

1.2 Method

The present report is based on tasks T04.8, T05.5, T11.6, T11.7 and T11.8. Conditions for safe evacuation were investigated first to prepare the present deliverable. Then, the evacuation model AMERIGO was used to analyse and compare the different means of ship abandonment. This model estimates the travel time of evacuees in a given geometry of compartments. This is done through the tracking of crowd density in each compartment over time by considering congestion development at doorways. For the ship geometry, the generic ship Stena Flavia was considered. Input regarding fire consequences affecting the evacuation paths were taken from a Computational Fluid Dynamics (CFD) model run in parallel to model the fire integrity.

Among the forecasted risk control measures identified to improve the evacuation safety in case of a Ro-Ro space fire, a selection was made considering the shortest travel times. Then the applicability of the solutions was discussed in successive workshops with the Maritime Authorities Advisory Group (MAAG) and the Maritime Operators Advisory Group (MOAG).

1.3 Results and achievements

Results showed that the time required for all passengers to join the assembly station during the assembly phase is by far shorter than the time for fire propagation. Hence, no additional risk control measure is recommended for this phase.

Then, various scenarios were simulated for the ship abandonment phase. The geometry of Ro-Ro passenger ship Stena Flavia was considered, with all the passengers located in the assembly station (restaurant located on deck 5) when the ship evacuation started. The scenarios considered making use of the Ro-Ro space loading ramp, or of the pilot doors on either side of the ship. An alternative means of abandonment was also defined directly from the assembly station (on deck 5) toward the quay or the sea using additional safety devices (vertical chutes or slides). The simulations provided optimal travel times and people fluxes to design the number of slides or chutes. However, the use of such devices was not recommended by members of the MAAG & MOAG, because of possible injuries for people, or difficulties for people with limited mobility, for old passengers or for children.

The use of pilot doors or bunker doors was not found safe on the specific generic ship since their locations were at the same level as the Ro-Ro space (where a fire was assumed to prevent access to this level). However, provided that a safe path towards the pilot or bunker door can be granted and that means are provided to overcome the potential height difference between the door and the quay, the simulations showed that evacuation through these doors would be efficient. Therefore, in order to provide a second means for walk-off abandonment from a Ro-Ro ship in case of a Ro-Ro space fire, the recommendation is to ensure the fire integrity along the path toward bunker and pilot doors in future designs of Ro-Ro ships.

1.4 Contribution to LASH FIRE objectives

The objective of *WP11 – Containment* was to eliminate significant containment weaknesses, considering smoke, fire and heat integrity. In this frame, Action 11-B aimed at *developing solutions and recommendations to ensure safe evacuation (fire integrity for 3 hours) and when arriving at foreign port*.

This report contributes to the objective of Action 11-B by analysing the appropriateness of different means of ship abandonment with respect to the design and passenger capacity of Ro-Ro ships. Moreover, recommendations were provided regarding the optimal flux of people for the evacuation of a generic ship, as well as possible evacuation measures needed.

1.5 Exploitation and implementation

The results presented in this report can be used to support decision making for evacuation and to guide the design of ships. The present report was prepared after discussions with ship operators and maritime authorities through workshops with LASH FIRE advisory groups MAAG and MOAG. In particular, the suggested solutions regarding the use of lifeboats, slides and escape chutes were reviewed to evaluate their applicability for Ro-Ro ships. Recommendations were made for ship design in future maritime applications, which affects ship yards and ship designers. In particular, to provide a walk-off abandonment possibility from the ship requires a safe path from the assembly station, including sufficient fire integrity towards Ro-Ro spaces, which needs to be ensured in the ship design and construction. Furthermore, ship designers should carry out evacuation simulations to ensure a reasonable evacuation time using the designated side doors. These measures would provide the possibility to use side doors as a secondary means for walk-off abandonment in case of reaching a foreign harbour with a Ro-Ro space fire onboard. However, to actually make use of this possibility, a means to overcome a potential height difference between the door and the quay needs to be provided, most reasonable from the harbour, which has not been further investigated for exploitation in the project.

2 List of symbols and abbreviations

L	Distance from the exit [m]
t_{evac}	Total travel time of evacuees for exiting a single compartment [s]
N	Number of passengers inside a given compartment [pers]
V_{fw}	Free walking speed of passengers [m/s]
α_{ij}	Connection ratio between doorway *i* and doorway *j* [-]
$\Delta\tau_{ij}$	Transit time for a passenger to reach doorway *i* from doorway *j* [s]
φ	Flux of passengers through an exit [pers/s]

AMERIGO	Alternative Model for Evacuation Related to an Idealized conGestion Operation
AS	Assembly Station
ASET	Available Safe Egress Time
CFD	Computational Fluid Dynamics
DR	Disembarkation route
FSA	Fire Safety Assessment
FTP	Flux-Time Product
GA	General Arrangement
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
IMO	International Maritime Organization
IR	Internal report
LSA	Life-Saving Appliances (in the present report, this term includes the embarkation stations and the location of the life-saving appliances)
MAAG	Maritime Authorities Advisory Group
MOAG	Maritime Operators Advisory Group
MSC/Circ.	IMO Marine Safety Committee Circular
MVZ	Main Vertical Zone
OEA	Orderly Evacuation and Abandonment of the ship
PS	Port side of the ship
RHF	Radiative Heat Flux
Ro-Ro	Roll-on/roll-off
RS	Rescue Station
RSET	Required Safe Egress Time
SF	Stena Flavia
SOLAS	Safety of Life at Sea Convention
SRtP	Safe Return to Port
SS	Starboard side of the ship
THF	Total Heat Flux

3 Introduction

Main author of the chapter: Pascal Boulet, LUL.

The safe evacuation of a ship is considered to involve two phases, namely the assembly phase and the abandonment phase. In the assembly phase, the passengers are alerted to travel toward a designated safe area known as the assembly station. When everyone has gathered in the assembly station, the assembly phase is over. Subsequently, once the means of abandoning the ship become available, the abandonment phase of evacuation can start, during which the passengers disembark the ship. In this report, the assembly phase and the abandonment phase of evacuation are analysed using the evacuation model AMERIGO developed at the University of Lorraine in order to identify the potential weaknesses and develop corresponding solutions to ensure safe evacuation. This model uses inputs from a CFD model run by partner RS2N which simulates the fire propagation and provides data for the stresses induced by the fire.

The International Maritime Organization (IMO) has provided guidelines regarding the evacuation of passenger ships via the International Convention for the Safety of Life at Sea (SOLAS) [1-2]. For the abandonment phase of evacuation in particular, SOLAS Chapter III [2] discusses the life-saving appliances and their arrangements for the safe evacuation of ships, e.g., in terms of the required number of lifeboats and their evacuation capacity. Here we consider the aforementioned requirements to evaluate the total evacuation time.

To ensure the adequacy of evacuation measures, it is critical to have a good estimate of the Required Safe Egress Time (RSET). RSET refers to the period of time from the fire ignition to the evacuation of all the passengers. The length of this time is largely dependent on crowd formation or ‘congestion’ near the exits and is therefore governed by the flux of people through the busy exits. To ensure life safety, RSET has to be smaller than the Available Safe Egress Time (ASET). ASET is the period of time from the fire ignition to the moment when evacuation becomes impossible (severe thermal conditions, no evacuation path available, …). The length of this period depends on the spread of fire and smoke inside the ship and how soon that makes the conditions untenable for human safety.

For the abandonment phase of evacuation, the duration of the entire process is mainly affected by the total number of passengers as well as the available means of abandoning the ship, which in turn define the flux of people leaving the ship. The evacuation model estimates the duration of this evacuation process by taking the geometry of the evacuation paths into account, as well as the average behaviour of the evacuees, and the maximum flux of people offered by each means of escape (e.g., lifeboats).

In the following sections, the regulation is first discussed, the evacuation model is presented and evacuation conditions are discussed taking into consideration simulation results for fire integrity. Then, means for safe evacuation are discussed, before providing recommendations for future ship design.

4 Regulation review concerning safe evacuation, fire integrity and walk-off abandonment

This section is extracted from the contribution of B. Vicard and J. Leroux from Bureau Veritas Marine & Offshore. It aims at giving an overview of the requirements applicable to Ro-Ro spaces for this action, i.e. “Ensuring Safe Evacuation”.

4.1 Applicable regulations

The present review is based on the currently applicable regulations and is mainly based on the documents listed in Table 1.

Table 1: List of documents used for the review of regulations for Safe evacuation and Safe Returnto Port(SRtP)

IMO Documents	Safety of Life at Sea (SOLAS) Convention, as amended in 2017
	IMO Circular MSC.1/Circ.1505 “Unified interpretation of SOLAS regulation II-2/13.6”
	IMO Circular MSC.1/Circ.1369 “Interim explanatory notes for the assessment of passenger ship systems' capabilities after a fire or flooding casualty”
IACS & Class Rules	BV NR598 “Implementation of Safe Return to Port and Orderly Evacuation” January 2016
Flag Administration Rules	N/A

4.2 Definitions

This section provides the definitions of key terms used in regulations relevant for this action.

4.2.1 Ro-Ro space, vehicle space and special category space

As per SOLAS II-2/3:

- *“Vehicle spaces are cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion.”*
- *“Ro-Ro spaces are spaces not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction.”*[1]
- *“Special category spaces are those enclosed vehicle spaces above and below the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m.”*

Special category spaces are Ro-Ro spaces to which passengers have access, possibly during the voyage. Special category spaces are the most frequent type of closed Ro-Ro spaces on Ro-Ro passenger ships.

It is to be noted that open Ro-Ro spaces are not considered as special category spaces.

[1] In other words, ro-ro spaces are vehicle spaces into which vehicles can be driven. It is to be noted however that, for the purpose of the application of SOLAS II-2/19, the following interpretation can be found in MSC.1/Circ.1120 and IACS UI SC 85: “Ro-ro spaces include special category spaces and vehicle spaces”

4.2.2 Closed, open and weather deck

As per SOLAS II-2/3:

- A "*weather deck is a deck which is completely exposed to the weather from above and from at least two sides.*"
  IACS UI SC 86 additionally details that: "For the purposes of Reg. II-2/19 a Ro-Ro space fully open above and with full openings in both ends may be treated as a weather deck."
  For practical purposes, drencher fire-extinguishing system cannot be fitted on weather decks due to the absence of deckhead. This criterion is often used for a practical definition of weather decks.
- An open vehicle or Ro-Ro space is "*either open at both ends or [has] an opening at one end and [is] provided with adequate natural ventilation effective over [its] entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides.*"
- A closed vehicle or Ro-Ro space is any vehicle or Ro-Ro space which is neither open nor a weather deck.

As a reference criterion, it can be considered that a vehicle space that needs mechanical ventilation is a closed vehicle space.

4.2.3 Main Vertical Zone

For practical purposes, a main vertical zone (MVZ) is a slice of the ship which is insulated from the rest of the ship and in which the fire safety systems need to be somehow segregated from the other MVZ. MVZ are defined on passenger ships only.

4.3 Requirements

4.3.1 General

This section describes the general requirements related to Safe evacuation and SRtP and provides the associated reference(s) in the regulatory texts.

A number of precautions are taken in order to prevent a fire in the Ro-Ro spaces from jeopardizing escape from other spaces and ship evacuation.

As a general rule, vertical escape ways are categorized as "stairways" (category (2) on passenger ships carrying more than 36 passengers and category (4) on passenger ships carrying not more than 36 passengers), which ensures that they are suitably insulated with respect to Ro-Ro spaces.

In addition, on passenger ships carrying more than 36 passengers, a specific category (category (4)) is defined to cover "Evacuation stations and external escape routes", so that A-60 insulation is required between Ro-Ro spaces and muster stations; lifeboat/liferaft stowage areas as well as their lowering paths.

4.3.2 Escape ways from Ro-Ro spaces

At least two means of escape leading to the embarkation deck are required from Ro-Ro spaces as per SOLAS II-2/13.6, one at the fore end of the space and one at the aft end.

[SOLAS II-2/13.6]

In Ro-Ro passenger ships, designated walkways at least 600mm wide are to be marked and kept clear throughout the Ro-Ro or vehicle spaces.

[SOLAS II-2/13.5.1]

4.3.3 Protection of escape ways from other spaces

SOLAS includes provisions that protect the means of escape from spaces below the Ro-Ro spaces from being cut off by a fire in the Ro-Ro spaces:

- Accommodation spaces, service spaces and control stations are to be provided with two means of escape, one of which is to be an enclosed stairway providing continuous fire shelter up to the embarkation deck. Access from the stairway to the embarkation areas is to be insulated as a stairway, as per SOLAS II-2/13.3.2 and SOLAS II-2/13.3.3; and
- Machinery spaces are to be provided with two means of escape, as per SOLAS II-2/13.4. In addition, SOLAS II-2/13.5.2 makes it clear that, for machinery spaces where crew is normally employed, one of the escape routes is not to pass through Ro-Ro spaces.

In addition, SOLAS II-2/13.7 includes a number of provisions aiming at making the escape routes on Ro-Ro passenger ships as easy and direct as possible, with a view to quicken evacuation if needed, especially:

- Minimum number of changes in direction along a route;
- There should be no need to cross from one side of the ship to the other during escape;
- Passengers should not need to climb more than 2 decks up or down to reach an assembly station; and
- External escape routes are required from open decks.

4.3.4 SRtP regulations

The SRtP regulations are found in SOLAS II-2/21 and 22. They apply only to large passenger ships - including Ro-Ro passenger ships, with length greater than 120 m or with more than 3 MVZ - and aim at ensuring that:

- After a limited fire or flooding casualty, the ship will be able to bring the passengers and crew back to a port without need for evacuation of the ship: This is referred to as “Safe Return to Port”; or
- After a larger fire or flooding casualty, key systems will remain available for 3 hours to support ship evacuation: This is referred to as “Orderly evacuation”.

For practical purposes, it is worth noting that:

- The SRtP regulations do not consider the fire-fighting step, they are focused on ship operational capacities after a casualty, the extent of which is defined; and
- The SRtP regulations do not care about ship structure or stability, they are only focused on systems design.

4.3.4.1 SRtP – Safe Return to Port

The Safe Return to Port regulations are specified in a very goal-based way in SOLAS II-2/21, requiring that a number of safety systems remain operational after a pre-defined fire or flooding casualty – based on the idea that the ship itself is safer than a lifeboat to bring people back to a port. For practical purposes, this requires a higher level of redundancy for those systems since they need to remain fully operational after losing the components located in any one group of spaces which can be affected by a fire or flooding casualty. Where redundancy is not practicable, some key components may also be protected by fire insulation, reinforced pipe thickness etc.

A flooding casualty is defined as the flooding of any single watertight compartment.

[SOLAS II-1/8-1.2]

The fire casualty threshold is defined as – see also the figures below for illustration:

- Any group of spaces enclosed by A-class boundaries if the space where fire is supposed to have originated is protected by a fixed fire-extinguishing system; or
- Any group of spaces enclosed by A-class boundaries and adjacent spaces up to the nearest "A" class boundaries otherwise.

[SOLAS II-2/21.3]

Figure 1 : Casualty threshold when the space of fire origin is protected by a fixed fire-extinguishing system - Longitudinal section

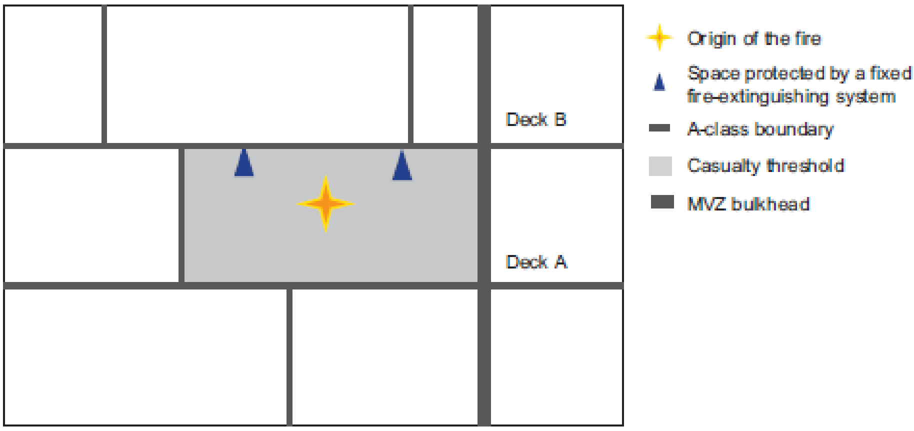
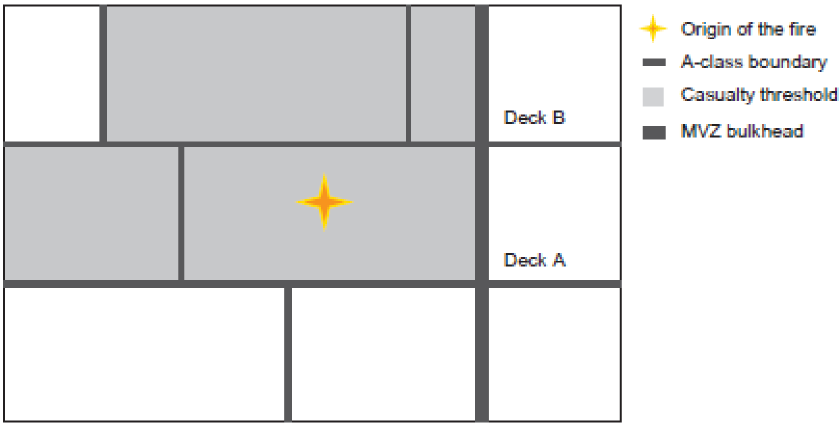


Figure 2 : Casualty threshold when the space of fire origin is not protected by a fixed fire-extinguishing system - Longitudinal section



It is to be noted that the above definition would lead to considering total loss of any garage space as a fire casualty to be considered. For practical purposes however, it is allowed to consider that the fire casualties in the garage spaces do not extend further than two adjacent drencher sections.

[BV NR598 [1.2.1.c]]

The concerned systems are listed below – The systems shown in bold actually serve Ro-Ro spaces and may be involved in fighting a fire in a Ro-Ro space:

- propulsion;
- steering systems and steering-control systems;
- navigational systems;
- systems for fill, transfer and service of fuel oil;

- **internal communication between the bridge, engineering spaces, safety centre, fire-fighting and damage-control teams, and as required for passenger and crew notification and mustering;**
- external communication;
- **fire main system;**
- **fixed fire-extinguishing systems;**
- **fire and smoke detection system;**
- bilge and ballast system;
- power-operated watertight and semi-watertight doors;
- systems intended to support "safe areas", i.e. sanitation, ventilation etc. with a view to bringing the passengers back home with a minimum level of comfort; and
- flooding detection systems.

[SOLAS II-2/21.4]

For practical purposes, BV Class Rules clarify that after a fire casualty affecting a Ro-Ro or vehicle space, the fire main should still be able to cover the vehicle space (possibly using hydrants outside of this space).

[BV NR598 [1.2.1.c]]

4.3.4.2 Orderly evacuation

In case a casualty happens that has a greater extent than the theoretical casualties defined for SRtP, it is reckoned that the ship will have to be evacuated and SOLAS II-2/22 requires that the following systems remain serviceable for at least 3 hours in the remaining MVZ in case of a fire casualty in any one MVZ or horizontal zone, with a view to ensure smooth evacuation of the ship:

- Fire main;
- Internal and external communication systems;
- Bilge systems;
- Lighting along escape routes, at assembly stations and at Life-Saving Appliances (LSA) embarkation stations; and
- Guidance systems for evacuation.

SOLAS II-2/22 requires 3 hours operation for the systems supporting ship evacuation. This duration is a performance requirement for the systems but does not imply that the fire casualty triggering the evacuation of the ship is expected to last 3 hours - indeed, it is to be noted that cabling and piping enclosed in a trunk insulated to A-60 standard may be considered still serviceable even if they pass through the affected MVZ.

The underlying scenario is rather that a fire casualty has occurred and its extent or consequences exceed the level that makes SRtP feasible. In this case, the master is expected to decide ship evacuation and the purpose of the regulation is to ensure that, even with any one MVZ lost, the key systems for evacuation will remain functional. The “orderly evacuation” regulation does not consider how or whether the fire casualty is fought.

5 Numerical simulation of people evacuation in relation to fire integrity

Main authors of the chapter: Anthony Collin, LUL – Bernard Porterie, RS2N.

5.1 Evacuation model

5.1.1 State of the art

For many years, the number of evacuation models has multiplied, and they tend to become more and more popular. They aim at becoming a useful tool to quantify the Required Safe Egress Time (RSET) for fire-safety engineering studies. Depending on the considered scale, evacuation models can be classified into three categories: microscopic (using the scale of individuals), macroscopic (scale of crowd) and mesoscopic (scale of entire building).

The most widely-used model is the microscopic model, in which Lagrangian particles, governed by different forces, represent evacuees that try to reach the exit. Statistics distributions are used to evaluate the characteristics of each evacuee (height or walking speed for example). Examples of microscopic models are the social force model [1], cellular automata models [2], or AI-based models [3]. The most popular tools using this approach are FDS+Evac and PathFinder.

The macroscopic models for fire safety evacuation consider the crowd as a fluid, where the continuum medium is characterized by averaged quantities such as density and mean velocity. In his pioneering work [4], Hughes described the time evolution of people density using a scalar conservation law.

The mesoscopic models do not take an accurate description of the considered building or ship into account for evacuation. The aim is rather to define an evacuation time by considering the time required to pass the doorways and the time necessary to transit between two consecutive doorways. The model proposed by Togawa [5] is the most famous mesoscopic model.

Evacuation in case of fire raises the issues of heat and smoke effects. Current models address these problems considering that the visibility is altered by the smoke and that the speed of individuals may be penalized by heat stresses and toxicity of smoke. Heat flux, temperature, smoke opacity and toxicity must be known, which can be done using fire spread simulations for example. This is the approach presented in the present report.

5.1.2 Numerical approach

AMERIGO, standing for Alternative Model for Evacuation Related to an Idealized congestion Operation, is a mesoscopic evacuation model developed based on an extension of the model proposed by Togawa [5] for the estimation of the evacuation time of a single room:

$$t_{evac} = \begin{cases} \dfrac{L_{max}}{V_{fw}} & \text{when } N_{people} = 1 \\ \dfrac{L_{max}}{V_{fw}} + \dfrac{N_{people}}{\varphi_{max} l} & \text{when } N_{people} > 1 \end{cases}$$

where t_{evac} is the total travel time of people exiting the room, L_{max} is the maximal distance inside the room to the exit, V_{fw} is the free walking speed, N_{people} is the total number of people inside the room, l is the width of the exit and φ_{max} is the maximal linear people flux. Note that in configurations with more than one person in the room, a second term is added to account for the effect of congestion formation behind the doorway.

5.1.2.1 Main assumptions

AMERIGO extends the single room evacuation model proposed by Togawa [5], such that it is adapted to the evacuation of an arbitrary number of interconnected rooms, while all the model parameters are set according to the guidelines of MSC.1/Circ. 1533 [6]. The extended model in based on the following assumptions:

- The escape route used by the evacuees is the shortest path possible, which is determined at the beginning of the evacuation process and cannot be modified during the simulation;
- Between two doorways, the evacuees travel at a fixed and constant speed, denoted here by V_{fw};
- At every doorway, the flux of people leaving the room is limited by an upper bound, denoted here by φ_{max}.
- At the final exit, the flux of people is limited based on the type of the exit used (i.e., ladder, chute, slide, etc.), with a separate upper bond value, denoted by φ_{max2}.

5.1.2.2 Modelling methodology

Based on abovementioned theory and assumptions, AMERIGO considers a balance equation for each doorway in order to determine the flow of people through the doors, taking into account the size of congestion at each instant behind every door, as shown in Figure 3.

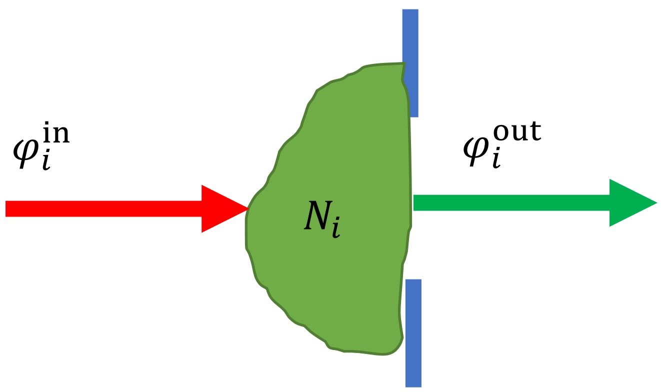


Figure 3. Schematic representation of the congestion behind a doorway.

The congestion behind door *i*, represented by N_i (total number of people waiting in the congestion zone behind the door) is fed by the incoming flux of people, named φ_i^{in}, and the outcoming flux of people, φ_i^{out} which represents the persons leaving the congestion. This last term is bounded by a maximal value, denoted by $\varphi_{i\,max}^{\text{out}}$, which mainly depends on the width of the doorway and varies between 0.9 and 1.2 pers/s/m according to the guidelines of MSC.1/Circ.1533 [6]. Here the term "doorway" can also consider locations where several people fluxes come together, such as corridors and stairs, with the aforementioned values being the average values calculated based on the flux data provided in MSC.1/Circ. 1533. Therefore, the balance equation for doorway *i* can be written as follows:

$$\frac{\mathrm{d}\ N_i\ (t)}{\mathrm{d}\,\mathrm{t}} = \varphi_i^{\text{in}}(t) - \varphi_i^{\text{out}}(t)$$

where φ_i^{out} is bounded as previously mentioned, and its values depend on the flux φ_i^{in}. Depending on whether or not congestion is formed behind the doorway, φ_i^{out} is given by:

$$\varphi_i^{\text{out}}(t) = \begin{cases} \varphi_{i\,max}^{\text{out}} & \text{when} \quad N_i\,(t) > 0 \\ \min\left(\varphi_i^{\text{in}}(t), \varphi_{i\,max}^{\text{out}}\right) & \text{when} \quad N_i\,(t) = 0 \end{cases}$$

where φ_i^{in} is the influx of people feeding the congestion, including firstly people in the space immediately next to door *i* and secondly people from other rooms in transit through this space. Accordingly, φ_i^{in} can be expressed as:

$$\varphi_i^{\text{in}}(t) = \varphi_i^{\text{zone}\,i}(t) + \sum_{\substack{j=1 \\ j\neq i}}^{N_{\text{doorway}}} \alpha_{ij}\varphi_j^{\text{out}}\left(t - \Delta\tau_{ij}\right)$$

where $\varphi_i^{\text{zone}\,i}$ is the flux of people coming from the space immediately next to door *i*, while $\Delta\tau_{ij}$ is the transit time for an evacuee to reach door *i* from door *j*, and $\alpha_{ij} = 1$ if there is a connection between doors *i* and *j*, otherwise α_{ij} is equal to zero.

Considering the abovementioned principles, the simulation of a passenger ship evacuation using AMERIGO involves the following:

1. Defining the geometry of the problem, e.g., the location of passengers, exits, stairs, etc.
2. Application of a pathfinding algorithm to determine the shortest escape path for every location inside the geometry
3. Time loop for each given doorway (or exit):
    a. Calculation of φ_i^{in}, i.e. the flux of people coming towards the door at discrete time t_i;
    b. Calculation of φ_i^{out}, i.e. the flux of people leaving through the door at time t_i;
    c. Calculation of N_i, i.e. the total number of people who are waiting in the congestion zone behind the door at time t_i.
4. Outputting the results of evacuation.

5.1.2.3 Model limitations

The main limitation of the AMERIGO is that it fixes the evacuation paths at the beginning of the simulation and only follows the shortest routes towards the final exits, such that the escape route used by an evacuee cannot be further adjusted according to the evolution of congestion or the development of fire hazards along the path later on. However, the time for evacuation can be updated regularly by setting new fire stresses in terms of obstacles or speed limitation, involved as inputs for a new evacuation time prediction.

5.1.2.4 Input data

The main input data comes from the General Arrangement plan of each ship and includes the following:

- The ship geometry: emergency exits, obstacles, doorways, stairs, etc.
- The initial passenger locations: for each evacuation simulation, the nominal passenger capacities of all the rooms are summed up to determine the total nominal number of passengers, which is then used to populate the evacuation zones. This nominal value is then increased, by 1.5 to 2 times, to conduct a sensitivity analysis and to determine the impact of the number of passengers on the evacuation process.
- The evacuation of lifeboats is considered to be continuous and uninterrupted, with a maximum capacity fixed based on the guidelines of SOLAS [7], i.e., 150 people in 10 min.

Additional inputs can be impacted by the fire development, namely walking speed and obstacle creation.

5.1.2.5 Generic ship geometry

As the evacuation model AMERIGO is implemented in MATLAB, the ship geometry and all the input parameters (such as the initial locations of the passengers) must be readable by MATLAB. Accordingly, the free software QGIS has been used to convert the map of each deck into raw data for MATLAB. This process has been done manually for each deck considering Stena Flavia in the present report.

An example of the generic ship geometry generation is given in Figure 4. As indicated, each wall/obstruction (represented in black), and each doorway (in green), have to be manually redesigned from the general arrangement plan.

The main challenge for the task of geometry generation is the varied forms of source data which were available for the General Arrangement plan of the ships, i.e. PDF files, CAD files, etc. Another challenge is accounting for the many features included in the General Arrangement plan.

Extraction from General Arrangement Plan

Schematic representation used by MATLAB

Figure 4. Generic ship geometry used by MATLAB.

5.1.2.6 Passengers and their locations

This study considers the evacuation of the Ro-Ro passenger ship Stena Flavia. Nominally, there are 466 passengers on this ship (based on the sum of the capacities of the cabins and offices), while the ship can carry a maximum of 880 passengers. Accordingly, first the nominal value of 466 is used as an indication of the average number of passengers for basic evacuation simulations, and then a sensitivity analysis is conducted for each evacuation scenario by increasing the number of passengers up to 2 times the nominal value to determine the impact of the number of passengers on the evacuation.

For the assembly phase passengers are in their cabins, workstations, and offices. The nominal capacity in passengers of each room is used.

For the abandonment phase, all the passengers are assumed to be in the assembly station, i.e. the restaurant on deck 5 of Stena Flavia. The location of this assembly station is available from the General Arrangement plans.

5.1.2.7 Fire occurrence

The various analyses presented in this document assume that the passengers and the means of ship abandonment such as lifeboats are not all simultaneously affected by fire effects, such that there is always one means available that is not compromised by fire. As such, the study focuses on the maximum capacity of the means of ship abandonment and whether they are appropriate with respect to the total number of passengers on the ship. Correspondingly, the optimal flux of people at the final means of abandonment is determined, such that the evacuation time is adequate before fire effects become an issue.

5.1.2.8 Expected outputs

For each numerical simulation, a single means of abandonment is selected for the evacuation of passengers. The main result consists of the total evacuation time for a given scenario (a single part of RSET dedicated to the travelling time), while the number of passengers and the location of the available means of abandonment are changed through the different scenarios of the sensitivity analysis to evaluate their impact on the evacuation process.

Note that the results of evacuation time presented when considering the assembly phase corresponds to the sum of the travel time of passengers plus their reaction time before starting to evacuate, with characteristic values set by the regulation prescription.

When simulating the ship abandonment phase on the contrary, the evacuation time corresponds to the sum of the travel time of passengers and the time they require to disembark the ship via the target means of abandonment. The reaction time of the passengers is ignored because the passengers are assumed to be ready for evacuation in the assembly station.

5.2 Fire propagation model

5.2.1 State of the art

Fire risk assessment in multicompartment enclosures is a major issue with consequences for lives, properties, structures, activities and environment. Protection and evacuation of people in fire situation is an absolute priority. Hence, it is crucial to rapidly detect fires and deal with them. Research and development on fire spread models in multi-compartment enclosures underwent several evolutions in the past decades. Until the early 2000s, such models were often developed using a purely probabilistic approach because of the difficulty to consider all the physical factors affecting the growth and spread of smoke and fire. In [8], Ramachandran outlined and analysed the significant studies until the year 2002 that are based on the following approaches: epidemic model [9], [10], random-walk theory [11], [12], Markov processes [13] [14] [15], percolation processes [16], [17] and probabilistic networks [18], [19]. As mentioned by Ramachandran in his study [8], these models do not allow to correctly model the propagation of the fire in a multi-compartment enclosure because of many reasons, mainly their incapacity to take into account the dynamics of the propagation process or the physics of the interaction between compartments within small and long distances. Therefore, deterministic [20] [21]

[22] [23] [24] [25], probabilistic [26] [27] [28] [29] [30] [31] and Bayesian [32] [33] network models including all or part of the physical aspects related to the fire spread in multi-compartment enclosures were developed. Moreover, only two of them [24] [26] are also devoted to the simulation of smoke propagation.

The proposed approach in the LASH FIRE project is based on a variant of the so-called small-world network model [34], which considers probabilistic local contacts between neighbouring compartments and long-range contacts between distant compartments via ventilation ducts. It considers the dynamic nature of fire and smoke spread between compartments.

5.2.2 Model overview

Input data must be provided to the evacuation model for fire, heat and smoke propagation. These data are obtained from simulations combining a CFD code and a network model to evaluate the consequences of a fire from a Ro-Ro space on people, either joining the Assembly Station (AS) during the assembly phase, or leaving the AS during the disembarkment phase. The paths used by the persons to move from their current position to the AS or from the AS to the EMBARKATION STATION, are analysed. Evacuation simulations are performed to assess fire integrity for both SRtP and Orderly Evacuation and Abandonment of the ship (OEA) scenarios.

CFD model

The CFD model used to simulate fire and smoke spread in Ro-Ro spaces is derived from the open-source academic version of the code SAFIR developed by B. Porterie at the lab. IUSTI, Marseille. A detailed description of the CFD code is out of the scope of this report and the reader could find more details in [35]. As the fire-induced flow is a low-speed flow, the physical modelling used in SAFIR is based on the low-Mach number assumption, which removes the acoustic waves from the equations and only keeps thermodynamic pressure time variations. The gas phase is computed by solving the set of Favre-averaged conservation equations of mass, momentum, energy, and species, together with transport equations for the turbulent kinetic energy and its rate of dissipation. Turbulence is modelled using the standard k-ε model, with additional buoyancy-driven production/destruction and classical wall laws. Turbulent combustion is based on the Eddy Dissipation Model and the one-step irreversible chemistry is assumed. The radiation model is based on the grey assumption and requires the solution of the radiative transfer equation, where the gas absorption coefficient is calculated as the sum of the contributions from the soot and combustion products. The evolution of the soot volume fraction is described via one conservation equation by assuming that a certain amount of fuel is simply converted to soot with an empirical soot conversion factor. The three-dimensional conjugated heat and mass transfer problem at any gas-solid interface inside the computational domain (here, vehicles and bulkheads) is solved using a blocking-off region procedure [36] [37]. Wall conduction is considered through the one-dimensional Fourier's equation. The general resolution algorithm is totally implicit, the time step limitations being due to the unsteadiness of the fire-induced flow.

To meet the challenge of fire and smoke simulations in Ro-Ro spaces, the original version of SAFIR has been extended in three ways.

Firstly, the spread of fire from one vehicle to another was considered. The FTP method was chosen to estimate the time required to ignite a vehicle exposed to fire. Originally defined by Smith and Satija [38], FTP is a concept which predicts the time to piloted ignition of a combustible material exposed to incident radiation. The concept was then extended by Smith and Green [39], Toal et al. [40], and Shields et al. [41]. The method was then further improved by Shields et al. [42] and Silcock et al. [43] to include materials (plastics and timber) of different thermal thicknesses.

The concept is that when a combustible material is exposed to an external heat flux, the FTP accumulates until it exceeds a critical value and the material ignites, thus giving the time to ignition.

In terms of mathematical formulation, the accumulation of FTP is calculated at every time step such that:

$$FTP_i = \sum_{i=1}^{m} (\dot{q}"_i - \dot{q}"_{cr})^n \Delta t_i$$

where n is a power law exponent, Δt_i is the i^{th} time increment, $\dot{q}"_i$ is the total heat flux (kW/m²) received by the vehicle at i^{th} time increment, and $\dot{q}"_{cr}$ is the critical heat flux (kW/m²) of the combustible material. Ignition occurs when FTP_i exceeds a critical value FTP_{cr}.

Thus, for this study, the FTP method is used to obtain the ignition time of a subsequent vehicle with respect to the ignition and burning of a preceding vehicle, as well as the ignition time of targets. The FTP method has the advantage of allowing ignition predictions to be more general than the classical thermal solutions by allowing the power law index to be chosen to provide the best fit to the experimental ignition data rather than forcing a solution based on the physical thickness of the sample [44].

In [44], FTP parameters are given for the components which are likely to be ignited first on a vehicle (Table 2)

Table 2: Power lax index, critical FTP and heat flux values for selected components (extracted from [44]).

Component	Power law index	FTP_{cr} $(kW.s^n/m^2)$	$\dot{q}"_{cr}$ (kW/m^2)
Mudflap	1.5	3258	5.7
Rubber tyre	1.5	9828	8.0
Bumper trim	2.0	21862	3.1
Wheel arch	2.0	50234	0.0

For this study, it is hypothesised that components which are made from rubber are likely to be ignited first as compared to other components.

For targets, the FTP parameters are known for a wide range of solid materials [45]. Targets made of PVC, representative of electrical panels or cable trays, are given as an example, but the damage of targets made of another material can be done *a posteriori*, the evolution of the received fluxes being recorded over time.

Secondly, it has been extended to provide a complete set of data for the risk and evacuation models in terms of toxicity, visibility, and thermal constraints (temperature and heat flux) on cargo, ship structure and specific targets. This required to compute gas concentrations, temperature, radiative and total heat flux at specified locations.

Thirdly, heat and smoke detector models have been implemented in SAFIR.

The model for the detector sensing element temperature is based on a convective heat transfer process. The first order differential equation that describes the rate of temperature increase of the sensing element is [46]:

$$\frac{dT_s}{dt} = \frac{u^{0.5}}{RTI}(T - T_s)$$

where T_s is the temperature of the sensing element, RTI its response time index, and u the gas speed at detector location. The value of RTI used in the simulations is that used in FIRESAFE II [47], i.e., 100 $m^{1/2}s^{1/2}$.

For smoke detectors, the model is slightly different. It is based on the change in the mass fraction of smoke in the sensing chamber that can be found by solving the following equation [47]:

$$\frac{dY_c}{dt} = \frac{(Y_e - Y_c)}{L/u}$$

where Y_e is the mass fraction of smoke in the free stream (kg/kg) and L the characteristic length of the detector geometry (m). The default detector parameters are for the Heskestad model with a characteristic length of 1.8 m. Then, the predicted mass fraction of smoke in the sensing chamber $Y_c(t)$ can be converted into an expression for the percent obscuration per unit length by computing:

$$Obs = \left(1 - e^{-\kappa_m \rho Y_c l}\right) \times 100\% \; per\ length\ l$$

where κ_m is the mass extinction coefficient, ρ is the density of gas at detector location, and l is the length over which the light is attenuated (here, 1 m). For most flaming fuels, suggested value for κ_m is 8700 m^2/kg [48].

In accordance with EN 54:2001 and IEC 60092:504 (FSS Ch. 9 §2.3.1 and MSC/Circ.1035 [49]), the upper and lower limits of activation temperature have been chosen at 54 and 78°C respectively for heat detectors, and a percentage obscuration value of 12.5 %/m for the activation of smoke detectors.

Network model

A probabilistic network model is used for the accommodations. It is based on a polydisperse (i.e., compartments may differ in size) and amorphous (i.e., no geometrical regularity) network of ship compartments. The dynamic nature of the model is based on time-dependent normal probability density functions of fire development (flashover, fully developed fire, and decay phase) and fire transmission between compartments through the walls and openings.

The network model is largely inspired by the one presented in [50]. However, extensions have been made to adapt the model to the specificities of Ro-Ro ships:

- At the compartment scale, the mean durations of the fire phases and fire transmission through the walls were determined by a zone model, considering the effects of fire load, compartment geometry, ventilation, and insulation systems.
- The zone model also provides the flow rate of smoke coming out of the fire compartment, as well as its temperature and density. To account for the decrease in smoke temperature as a function of distance from the fire source the correlation of Bailey et al. [51] was used:

  $$log\left(\frac{T_f(x) - T_{amb}}{T_{f0} - T_{amb}}\right) \cong 0.003 - 0.018\,x$$

  where $T_f(x)$ is the smoke temperature at the distance x from the fire room, T_{f0} is the smoke temperature in the fire room (i.e., at $x = 0$), and T_{amb} the ambiant temperature.

Given the probabilistic nature of the network model, statistical averages of fire phases and transmission times are calculated from a large number of samples. Preliminary computations show that 100 samples are sufficient to achieve good statistical accuracy.

5.2.3 Simulation of fire propagation in RoRo-decks

Design fires for vehicles and accommodation compartments must be provided.

A heavy goods vehicle (HGV) is considered as the vehicle design fire, with a peak value of the heat release rate (HRR) of 40 MW, based on the recommendations from various guidelines [52] [53] [54]. The HRR-time curve is obtained by downscaling the experimental curve of the 72 MW truck fire given in [55]. The resulting HRR curve is shown in Figure 5.

As previously stated, the network model uses a compartment-scale zone model. Therefore, a design fire is required for each type of accommodation compartment (e.g., cabins, bar lounges, offices) based on the combustible elements and load contained therein. In the simulations, it was assumed that the time evolution of the HRR follows three phases: a growth phase, followed by a phase where the HRR is constant, then a decay phase until extinction. Both growth and decay phases follow a t-squared curve. The calculation of HRR requires knowledge of the initial fuel mass m_0, the maximum of HRR, HRR_{max} and the growth constant α_c, but also the percentage p of the initial fuel mass beyond which fire decay occurs. When the compartment contains more than one fuel type, the total HRR is the sum of the HRRs calculated for each type. As an example, Figure 6 shows the HRR curve for the Autopullman compartment and the adjacent hall on deck 5 of the Stena Flavia.

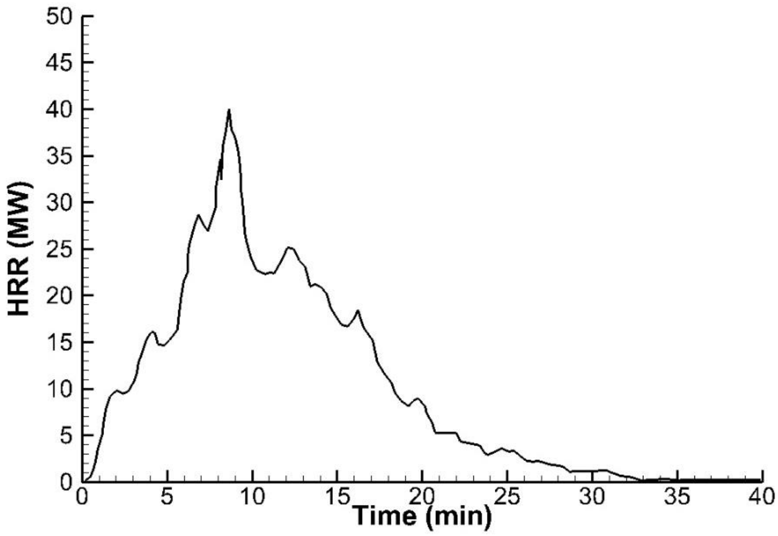


Figure 5. Heat release rate of a 40 MW HGV truck (deduced from [55]).

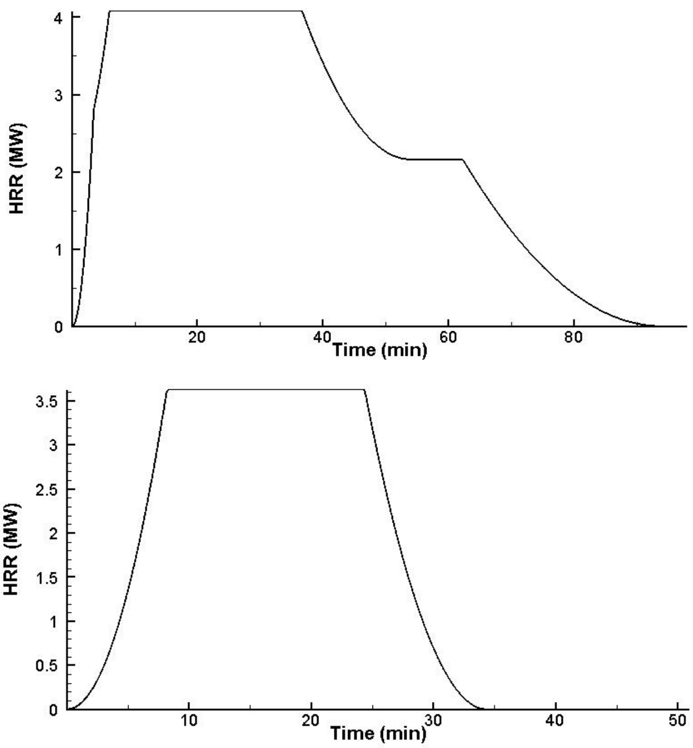


Figure 6. Design fires for the Autopullman compartment (top) and the hall (bottom) of the Stena Flavia deck 5.

5.2.4 Simulation scenarios

The selected scenarios for the fire simulations aboard the Stena Flavia (SF) are given in Table 3. They correspond to different locations of the fire origin (Figure 7) and wind conditions for the open Ro-Ro spaces. This study also includes accidental scenarios influencing the transmission of fire and smoke from the Ro-Ro spaces to the assembly and evacuation areas, and thus fire integrity:

- Scenario 3.1: the openings around the LSA on both sides of the ship were closed (see Figure 8), which limits external flames and the transport of smoke to the upper decks.

- Scenario 3.2: at time t_1, a large amount of smoke (here, 1 kg/s) coming from the fire on deck 4 enters in the accommodations at point E (Figure 9), due a door defect. Based on CFD results, the time t_1 is estimated to be about 30 min.

- Scenario 3.3: at time t_1, fire spreads from deck 4 to deck 5 at point B, due to an insulation defect (Figure 7). The results obtained by the SAFIR code for scenario 3 show that the fire on deck 4 generates very high total heat flux (THF) on the ceiling that can lead to the destruction of the ceiling insulation, resulting in the transmission of fire to the accommodations and the ignition of the Autopullman compartment on deck 5. As shown in Figure 10, the A-30 ceiling insulation material is exposed to THF that exceeds 80 kW/m² for about 3 min, between 29 min and 32 min, which can cause its destruction. Therefore, the time t_1 is estimated to be 29 min.

- Scenario 3.4: at time t_1, fire spreads from deck 4 to deck 5 at point G, due to an insulation defect (Figure 9). As done for scenario 3.3, the time t_1 is estimated from the time evolution of the THF received by the deck 4 ceiling below the stairwell; it is about 6 min (see Figure 11). The stairwell is just above the first truck on fire, which explains this very short delay.

These scenarios were added to study the influence on fire consequences to people of accidental situations such as a loss of integrity of the insulation system or a loss of containment of the Ro-Ro space where the fire starts.

Table 3: Simulation scenarios.

<table>
<tr><th>Scenario</th><th>Ship</th><th>Fire location</th><th>Wind</th><th>Notes</th></tr>
<tr><td>1</td><td rowspan="10">SF</td><td rowspan="2">Open Ro-Ro space – Deck 4 - Centreline (Point A)</td><td>-</td><td rowspan="3">No loss of insulation system integrity or Ro-Ro space containment</td></tr>
<tr><td>2</td><td>18 knots headwind</td></tr>
<tr><td>3</td><td rowspan="6">Open Ro-Ro space – Deck 4 - Centreline (Point B)</td><td>-</td></tr>
<tr><td>3.1</td><td>-</td><td>No loss of insulation system integrity or Ro-Ro space containment
Deck 4 openings around the LSA on both sides of the ship are closed</td></tr>
<tr><td>3.2</td><td>-</td><td>No loss of insulation system integrity
At time $t_1 \approx 30$ min, a large amount of smoke, here 1 kg/s, enters in the accommodations, at point E, due to a door defect</td></tr>
<tr><td>3.3</td><td>-</td><td>No loss of Ro-Ro space containment
At time $t_1 \approx 29$ min, fire spreads from deck 4 to deck 5 at point F, due to insulation defect.</td></tr>
<tr><td>3.4</td><td>-</td><td>No loss of Ro-Ro space containment
At time $t_1 \approx 6$ min, fire spreads from deck 4 to deck 5 at point G, due to insulation defect.</td></tr>
<tr><td>4</td><td>18 knots headwind</td><td rowspan="3">No loss of insulation system integrity or Ro-Ro space containment</td></tr>
<tr><td>5</td><td>Open Ro-Ro space – Deck 4 - Starboard side (Point C)</td><td>-</td></tr>
<tr><td>6</td><td>Closed Ro-Ro space – Deck 3 - Centreline (Point D)</td><td>-</td></tr>
</table>

The generic model of the Stena Flavia is used to determine the ship geometry, including the location and dimensions of exits, obstacles, openings, and doorways.

The model input data and parameters, such as the computational domain, the initial and boundary conditions, as well as detector and sensor location maps, were defined with WP4 partners for each fire scenario. Figure 9 shows the location of the sensors in the LSA and DR.

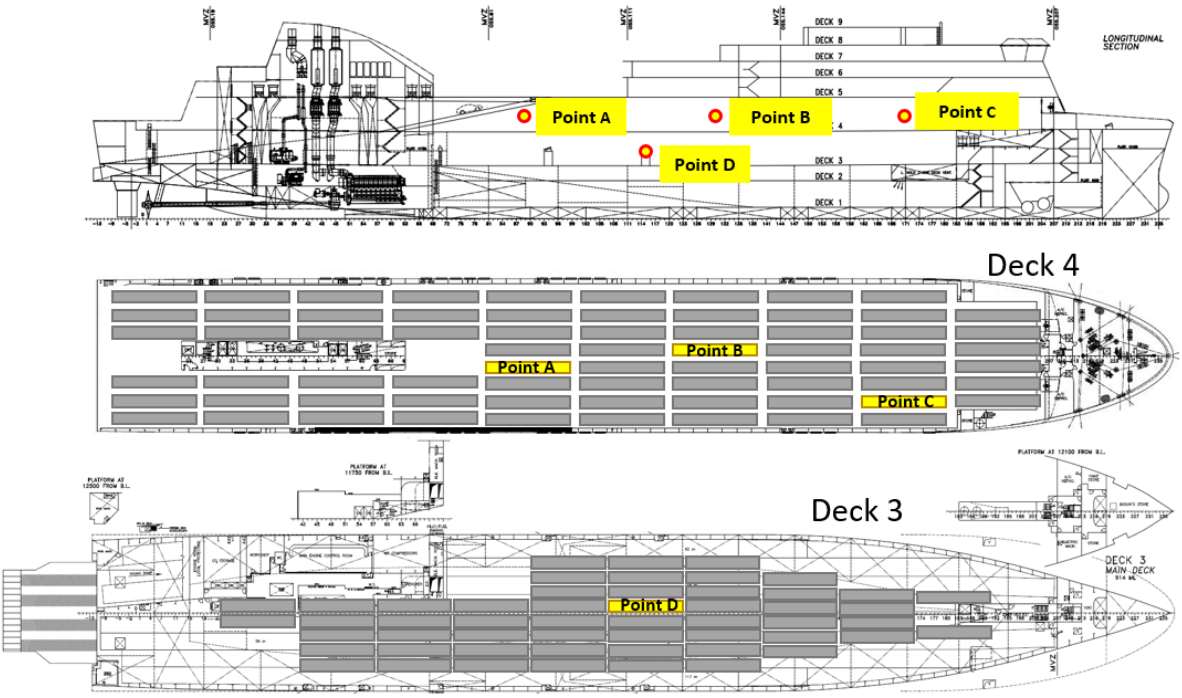


Figure 7. Fire starting points considered in the Stena Flavia simulations.

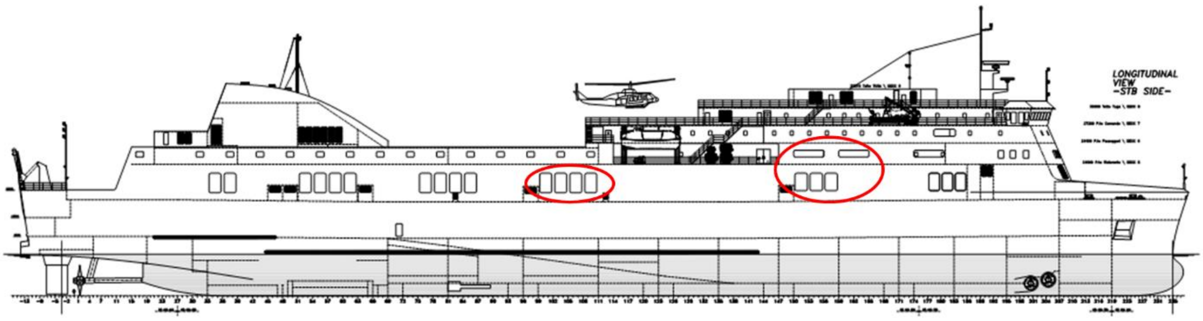


Figure 8. Area (red circle) where the openings around the LSA on both sides of the ship were closed for Scenario 3.1.

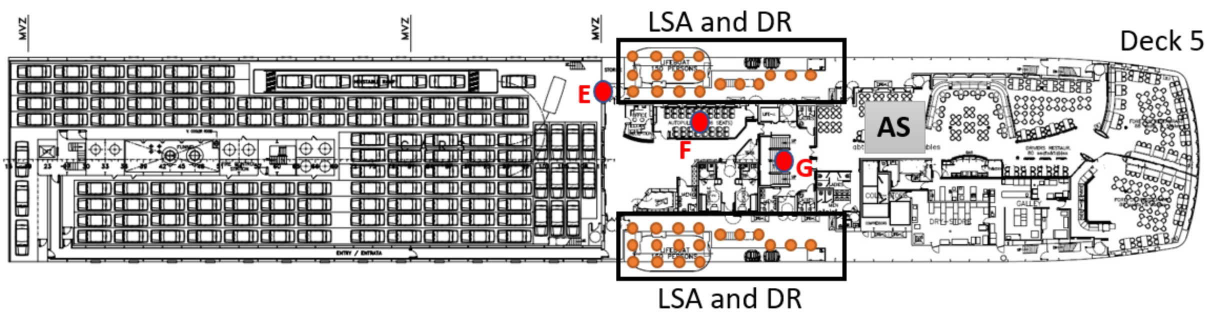


Figure 9. Locations of fire/smoke starting points in the accommodations of the Stena Flavia for scenarios 3.2 (point E), 3.3 (point F), and 3.4 (point G), locations of sensors in the LSA and DR (orange circles), and location of the AS.

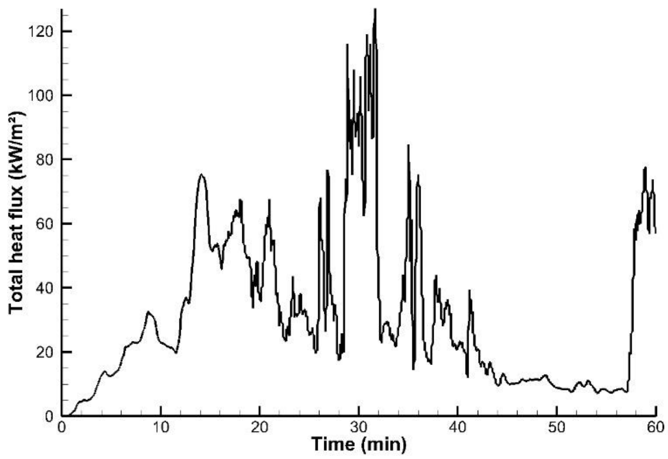


Figure 10. Time evolution of the total heat flux received by the deck 4 ceiling below the Autopullman compartment.

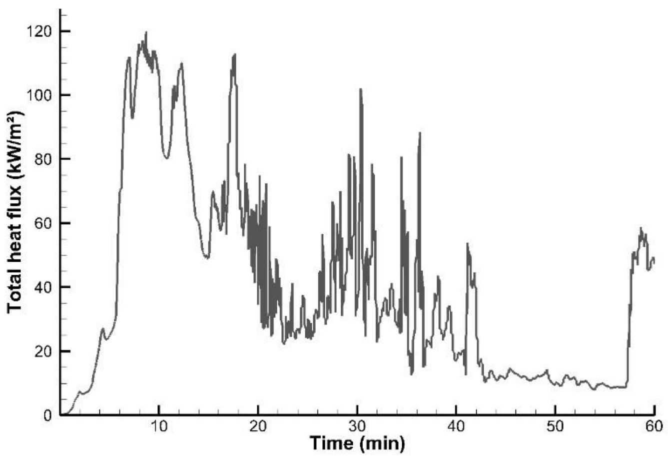


Figure 11. Time evolution of the total heat flux received by the deck 4 ceiling below the stairwell.

For the simulations, we recall that:

- The vehicle load capacity is assumed to be 100% and the HGV trucks are placed very close to each other, with a spacing of about 50 cm in both horizontal directions.
- Regarding the ignition of a vehicle by the FTP method, the rubber components are likely to ignite first compared to the other components.
- The average fuel molecule considered in the simulations is $C_{6.3}H_{7.1}O_{0.8}$, with soot and CO yields taken equal to 0.06 g/g and 0.1 g/g respectively. These relatively high values correspond to the combustion products of a mix of polymers (e.g., polystyrene or polyurethane) and cellulosic fuels, representative of the commodities carried by the goods vehicles.
- According to the General Arrangement Plan, 466 passengers and staff members are on board the Stena Flavia. When the fire alarm goes off, they are in their cabins, workstations, and offices. The nominal capacity in passengers of each room is used.
- According to MSC.1/Circ. 1533 [6], model parameters used in AMERIGO are set to 1.02 m/s for the free walking speed of persons on board and 1.10 pers/s/m for the maximal people flow density per meter at doorway.

- The free walking speed is decreased by 52% in stairs.
- The Assembly Station for the Stena Flavia is the restaurant located at Deck 5.
- Although the criterion threshold of 500 ppm for 20 min cumulative exposure time is considered, it cannot be used for passenger evacuation because it depends on the path followed by each passenger during his or her evacuation, which is not available by the evacuation model.

Different evacuation scenarios can be investigated depending on the reaction time of the people on board once the alarm is triggered: immediate or early evacuation at the fire alarm, daytime scenario (5 min reaction time) or night-time scenario (10 min reaction time). For the current simulations, the latter adverse scenario and early detection (when the fire is detected) are considered. Detection times of heat or smoke detectors are provided by the CFD model.

6 Evacuation in relation to fire integrity

Main authors of the chapter: Anthony Collin, LUL and Bernard Porterie, RS2N.

6.1 Fire consequences to persons onboard

Fire consequences to persons on board are evaluated, based on tenability threshold value(s) given in the previous section:

- For scenarios 1 to 5 in the LSA and DR, from CFD simulations, by monitoring the time evolutions of CO mole fraction, gas temperature, and soot volume fraction, and thus visibility. For the radiative heat flux, the levels of exposure are evaluated from 2D fields obtained at a height of 1.80 m in the LSA and DR of deck 5.
- For accidental scenarios 3.2 to 3.4, from network model simulations, by monitoring the time evolution of the smoke interface height in the AS of the Stena Flavia, here the restaurant located on deck 5.
- For the other fire scenarios, where there is no loss of insulation system integrity or Ro-Ro space containment, the accommodation spaces, including the AS, are not affected by the fire, nor by the smoke.

Although the CFD simulations only cover one hour of fire, the results obtained allow in some cases to evaluate fire integrity over a period of 3 hours, according to SRtP and OEA regulations.

It is worth noticing that all simulations never consider firefighting means (it would be beyond the possibilities of such a fine CFD simulation without losing result reliability, because of the need for assumptions on the firefighting effect which are usually rough considering the challenging task of addressing suppression mechanisms). Hence, present subsection draws trends on fire stresses possibly affecting the evacuation conditions and leads to recommendations, but cannot be considered as a complete performance evaluation of fire integrity in fully realistic conditions.

Regardless of the scenario, persons on board are never exposed to a CO concentration of 500 ppm for 20 min, suggesting that the 1200 ppm criterion is the most relevant.

The analysis of simulation results leads to the following comments.

- Scenario 1 (Figure 12):
  LSA and DR are safe for approximately the first 11 min of fire.
  On the starboard side, after 11 min of fire, one or more tenability criteria are exceeded. After 1 h of fire, the CO concentration has already decreased to acceptable levels (due to a decrease in HRR, as shown in IR04.21), but visibility and temperature tenability criteria remain too high for safe evacuation. The radiative heat flux drops below 2.5 kW/m² after 57 minutes of fire (Figure 13) and it no longer exceeds this value afterwards.
  On the portside, evacuation becomes safe after 48 min of fire, with visibility less than 10 m. Although not shown, the radiative heat flux no longer exceeds the tenability criterion (2.5 kW/m²) from 46 min of fire.

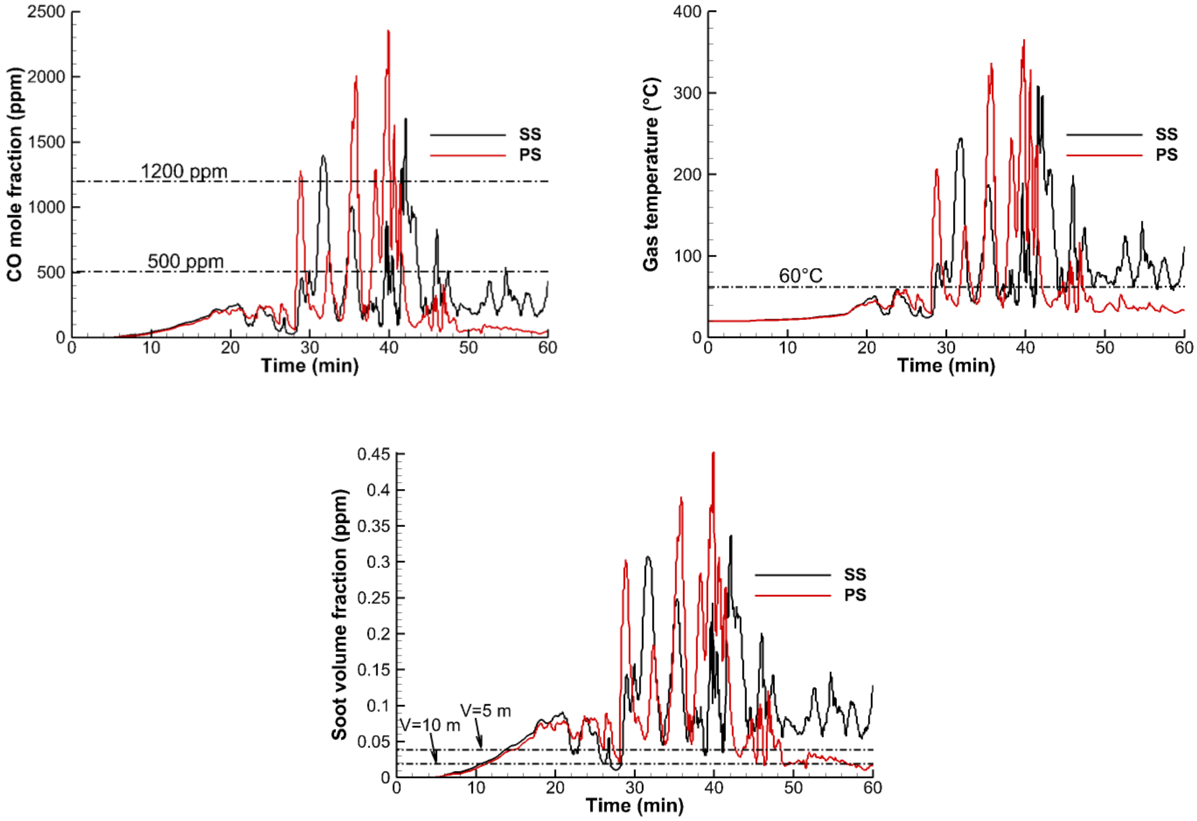


Figure 12. Scenario 1: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

Figure 13.: Scenario 1: 2D field of the incident radiative heat flux obtained at a height of 1.80 m in the LSA and DR of deck 5 after 57 min of fire. Black areas correspond to areas where the radiative heat flux is greater than 2.5 kW/m².

- Scenario 2 (Figure 14): The 18-knot headwind pushes the smoke aft, making the LSA and DR safe on both sides of the Stena Flavia for most of the fire. The visibility and gas temperature criteria are only exceeded for a short period of time, between approximately 19 and 27 min. The radiative heat flux never exceeds 2 kW/m² in the LSA and DR, as shown in Figure 15 when the exposure to the radiative heat flux in the LSA and DR is maximum.

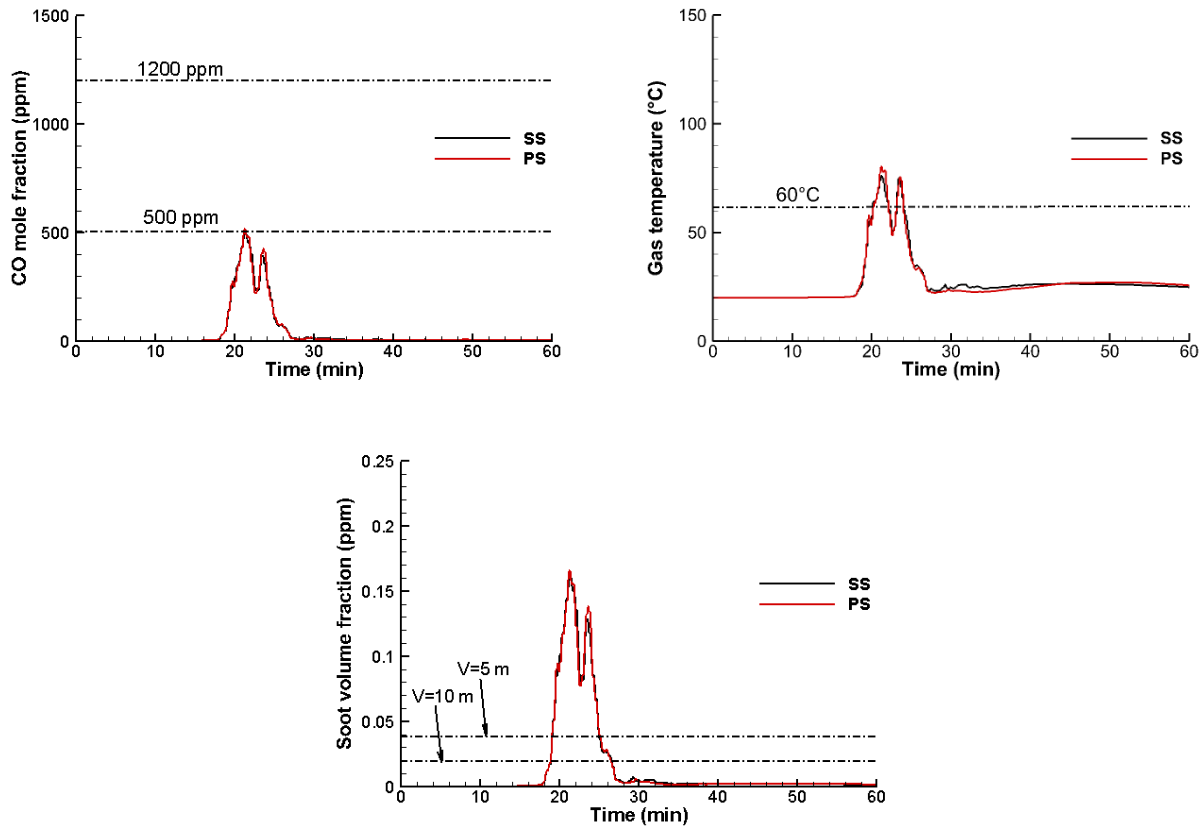


Figure 14: Scenario 2: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

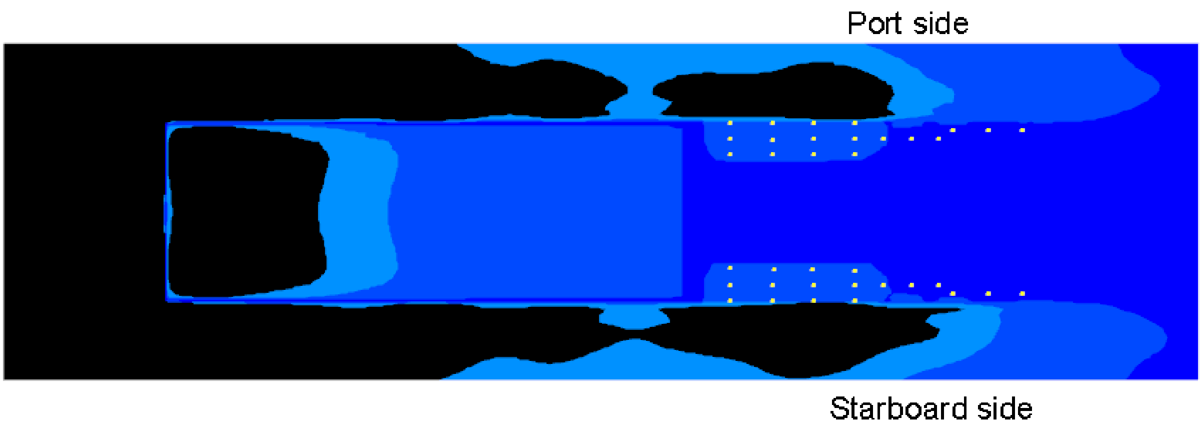


Figure 15: Scenario 2: 2D field of the incident radiative heat flux obtained at a height of 1.80 m in the LSA and DR of deck 5 after 41 min of fire, when the radiative exposure is maximum. Black areas correspond to areas where the radiative heat flux is greater than 2.5 kW/m².

- Scenarios 3 and 3.2-3.4 (Figure 16 to Figure 19): LSA and DR are safe during the first 10 min of fire. After 41 min of fire, people in the LSA and DR could be exposed to a level of radiative exposure higher than 2.5 kW/m² (Figure 17). However, beyond 41 min, this level is no longer reached. The most restrictive criterion is visibility since it makes LSA and DR impractical after 1 h of fire.

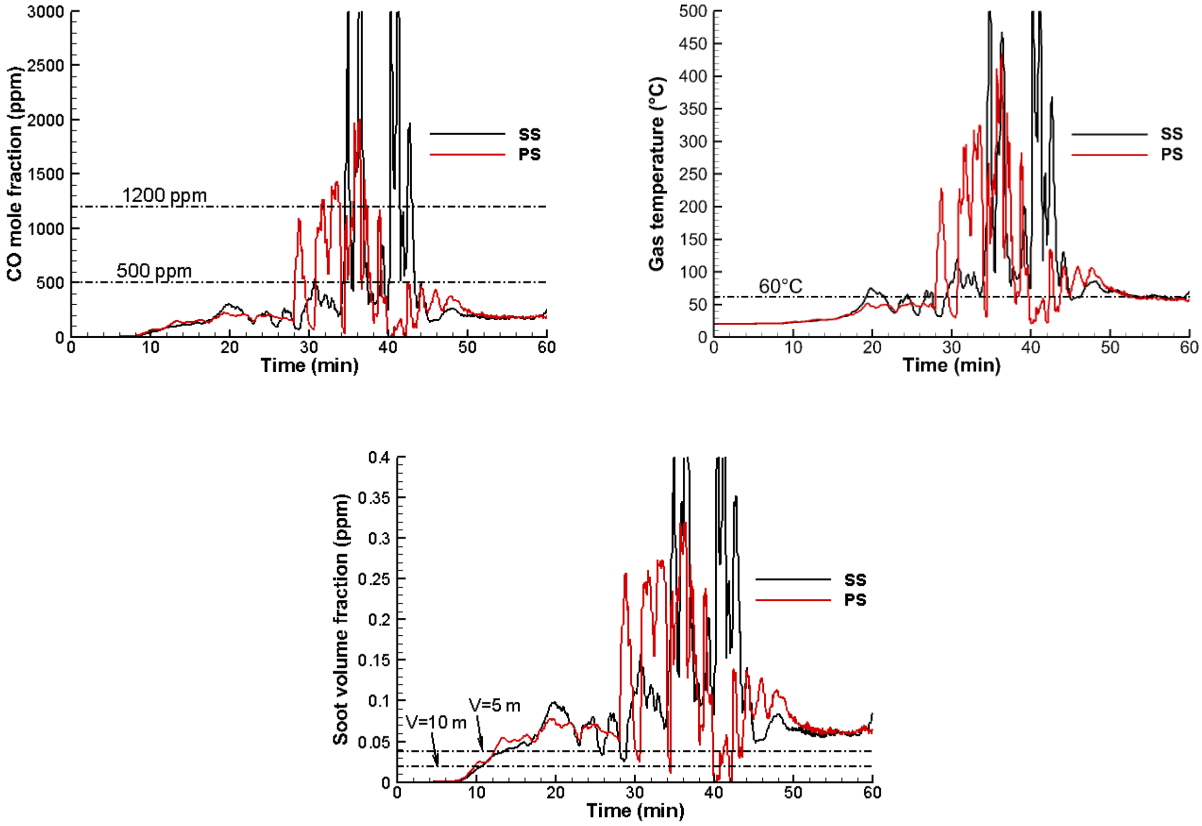


Figure 16. Scenarios 3 and 3.2-3.4: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

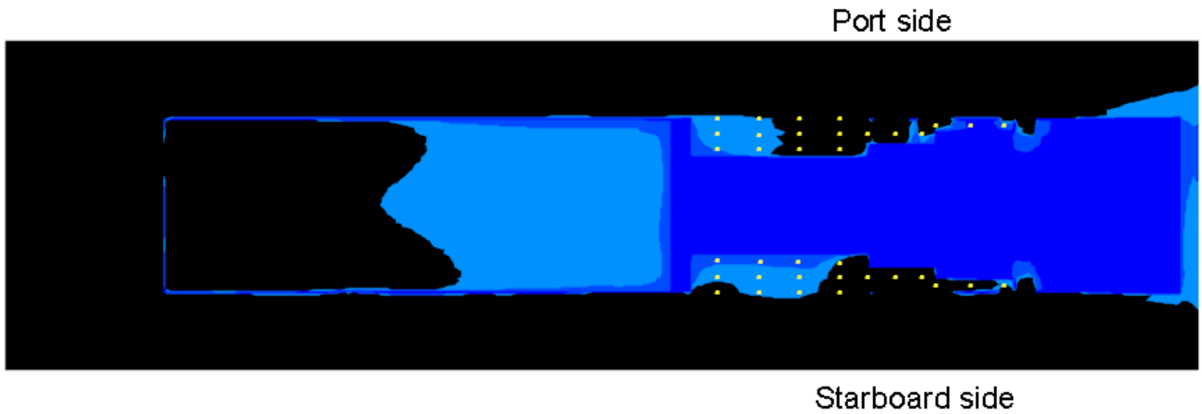


Figure 17. Scenario 3: 2D field of the incident radiative heat flux obtained at a height of 1.80 m in the LSA and DR of Deck 5 after 41 min of fire. Black areas correspond to areas where the radiative heat flux is greater than 2.5 kW/m².

For the accidental scenarios, due to a loss of insulation system integrity or Ro-Ro space containment, AS quickly become untenable. This is shown in Figure 18 and Figure 19, where the smoke interface falls below 1.80 m in height at $t \approx t_1 + 35$ min, $t_1 + 20$ min, and $t_1 + 12$ min for scenarios 3.2, 3.3 and 3.4, respectively. For each fire scenario, t_1 is the time at which fire and/or smoke reaches deck 5.

The simulation results of Figure 19 could be used to reallocate safer areas or define alternative evacuation routes.

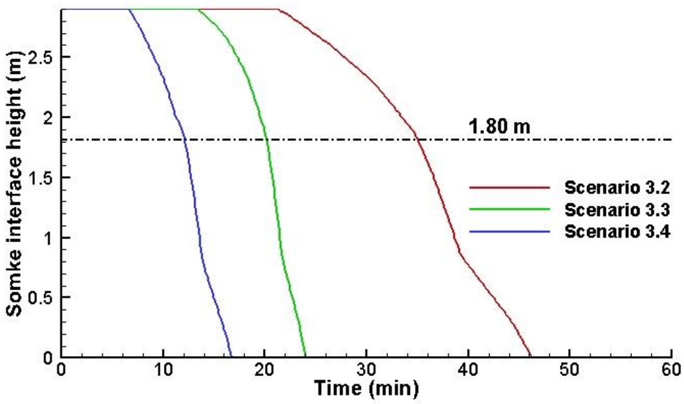


Figure 18: Scenarios 3.2-3.4: time evolution of the smoke interface height in the AS of the Stena Flavia, here the restaurant located on deck 5. The origin of time is the time at which fire and/or smoke reaches deck 5.

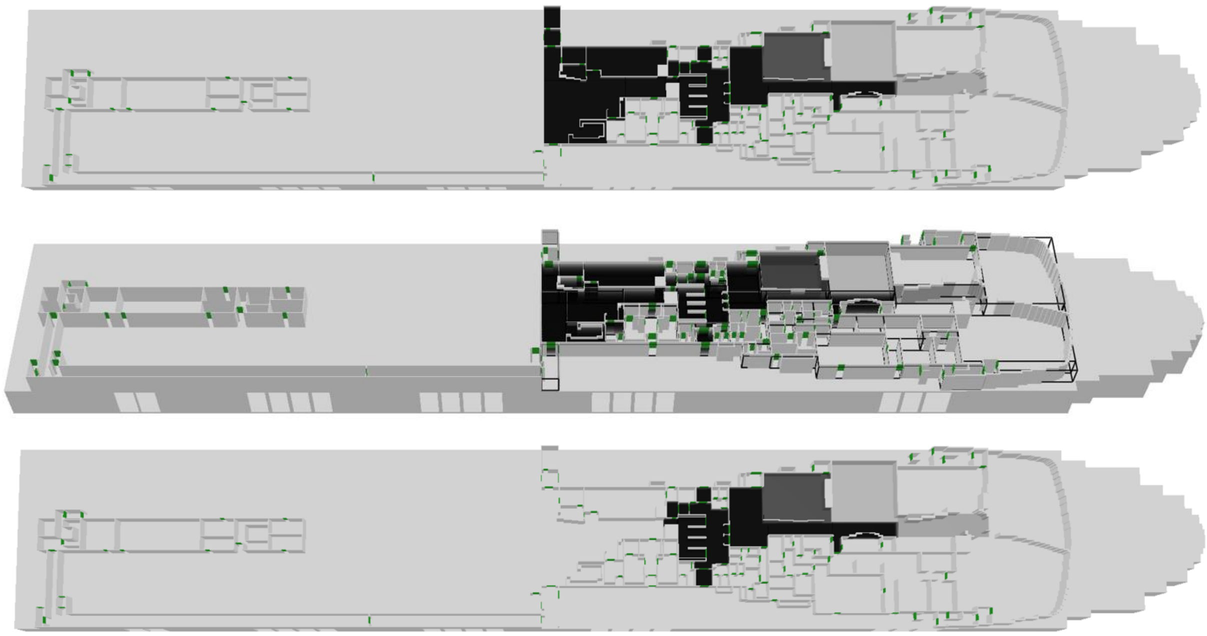


Figure 19 : Scenarios 3.2-3.4 (from top to bottom): smoke spread throughout deck 5 just as the smoke reaches the AS for scenarios 3.2 to 3.4 (from top to bottom).

- Scenario 3.1 (Figure 20-21): Closing the openings around the LSA on both sides of the ship significantly reduces the impact of fire and smoke in the LSA and DR. This can be observed by comparing fire consequences for the present scenario with those obtained for scenario 3 (Figure 16). It appears that LSA and DR are much safer. Short-lived peaks in gas temperature and soot volume fraction appear when the HRR is maximum, at approximately 36 min. After 36 min of fire, evacuation can be done safely, with a visibility of 5 m or more on the portside and no restriction on the starboard side.

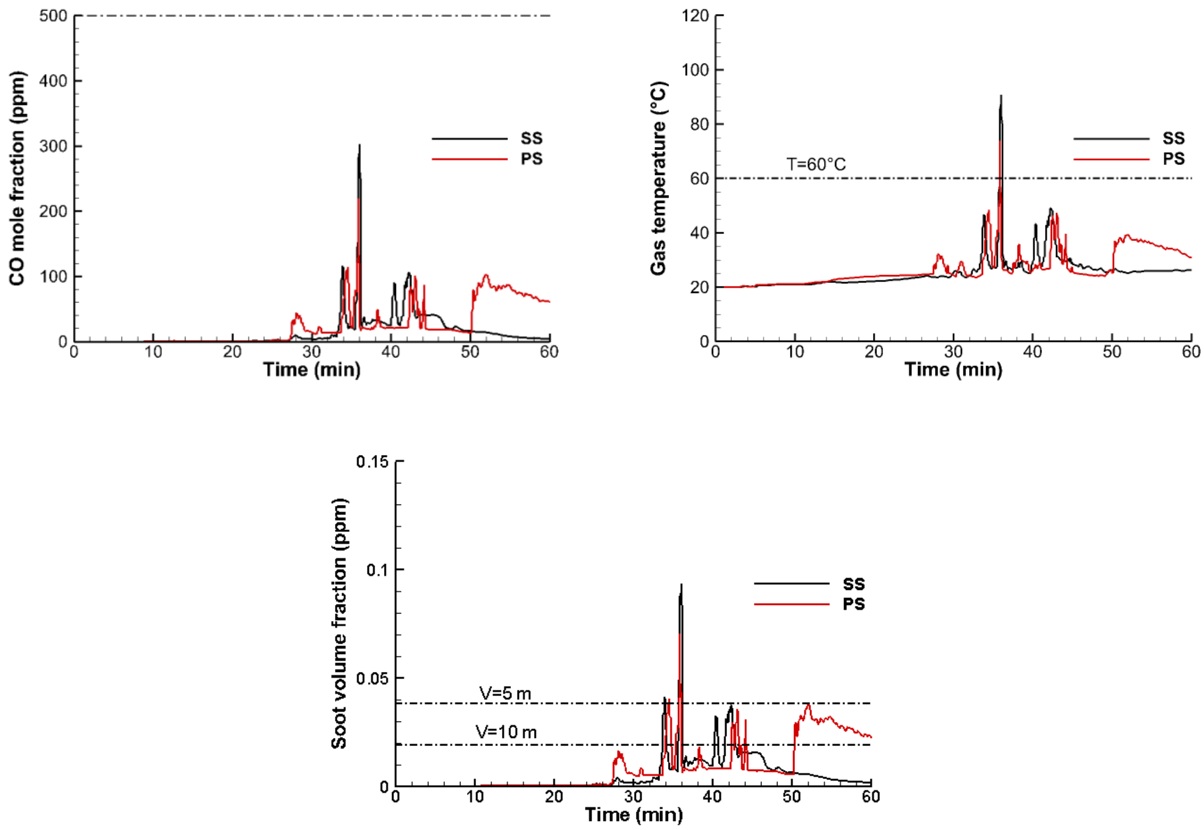


Figure 20. Scenario 3.1: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

Figure 21. Scenario 3.1: 2D field of the incident radiative heat flux obtained at a height of 1.80 m in the LSA and DR of Deck 5 after 41 min of fire. Black areas correspond to areas where the radiative heat flux is greater than 2.5 kW/m².

- Scenario 4 (Figure 22): The 18-knot headwind pushes the smoke aft, making the LSA and DR safe for most of the fire, except for short-lived peaks in the time evolutions of gas temperature and soot volume fraction at approximately 18 and 37 min. The radiative heat flux never exceeds 2.5 kW/m². Due to the short duration and low levels of exposure to heat and smoke, evacuation can be done safely on both sides of the ship.

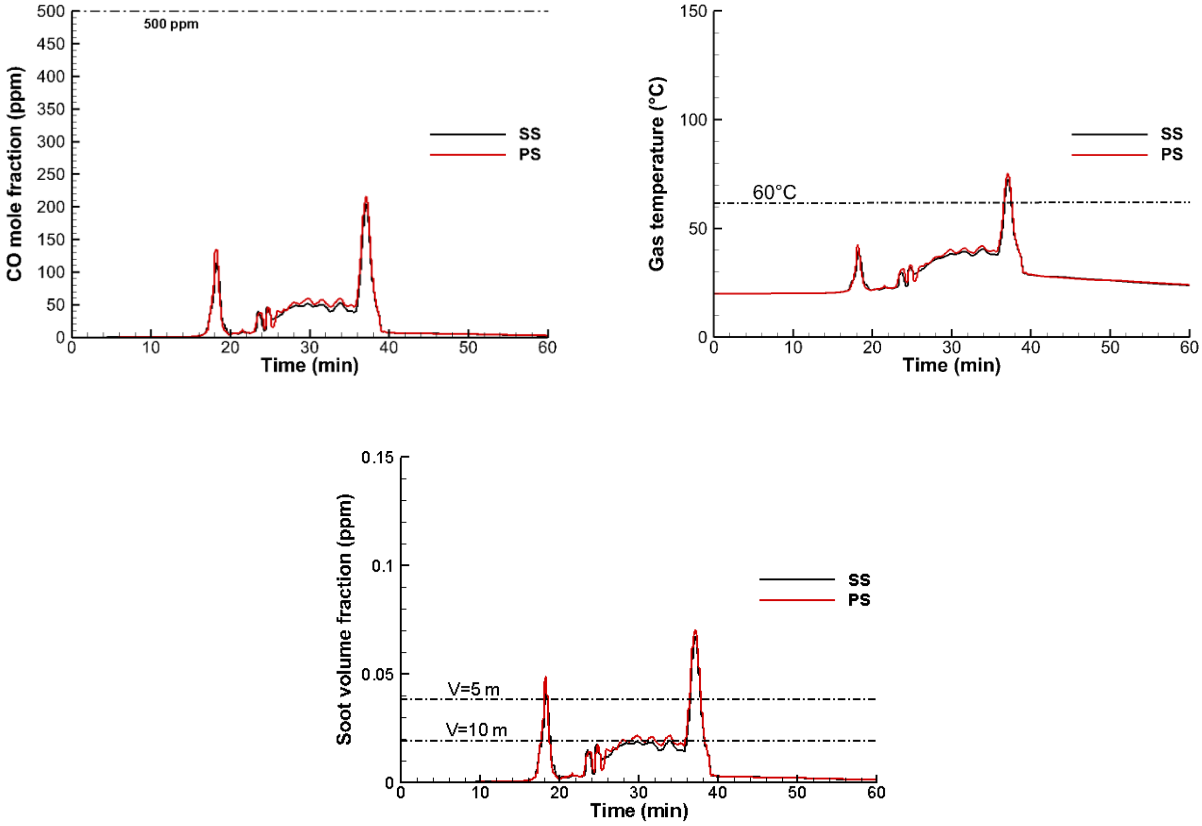
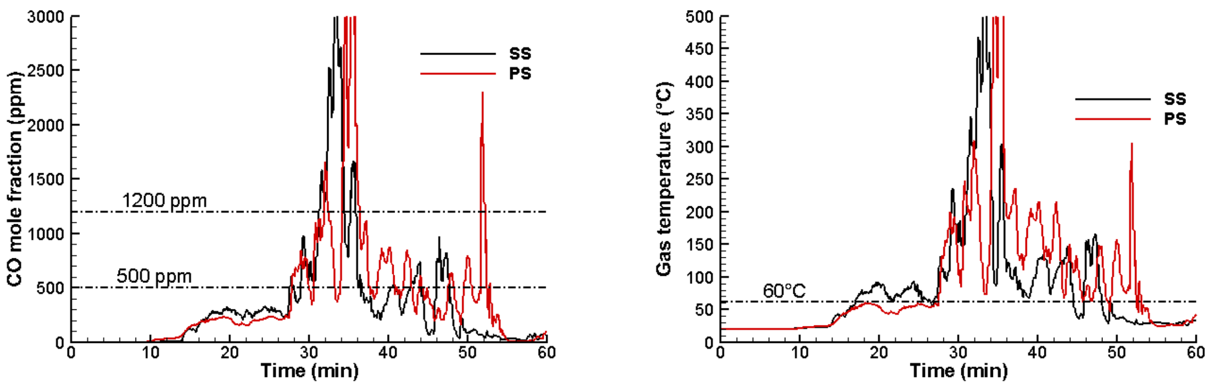


Figure 22. Scenario 4: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

- Scenario 5 (Figure 23): LSA and DR are safe during the first 14 min of fire. This is followed by a long period where tenability criteria are mostly exceeded. Conditions in the LSA and DR become almost tenable again after 54 min of fire on both sides of the Stena Flavia.



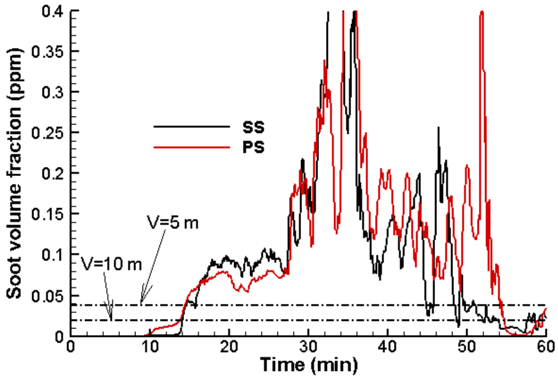


Figure 23. Scenario 5: time evolutions of maximum CO mole fraction, gas temperature, and soot volume fraction at the monitored points in the LSA and DR on both sides of the Stena Flavia (SS = starboard side, PS = portside).

- Scenario 6: Although not shown herein, simulation results from fire scenario 6 reveal that the LSA, DR and AS remain safe for evacuation at all times.

The consequences of fire to people in the LSA, DR and AS are summarized in Table 4 for the selected fire scenarios. The following conclusions can be drawn:

- Fire scenario 1: people can stay in the AS until they can join the LSA on the portside, 48 min after fire ignition.
- Fire scenario 2: people can stay in the AS and join the LSA on both sides of the ship, after 27 min of fire.
- Fire scenarios 3, and 3.2 to 3.4: due to the severity of fire, people cannot reach the LSA before the consequences of the fire have diminished significantly. After 1 h of fire, the LSA and DR still cannot be used. Longer simulations are required to evaluate fire integrity over a period of 3 hours (OEA evacuation scenario). However, fire consequences can be expected to decrease rapidly since the fire is in the decay phase (the HRR is less than 200 MW after 1 h of fire). The impact of heat and smoke on people in the LSA and DR could be reduced by the use of water mists.
  When there is no loss of insulation integrity or Ro-Ro space containment (fire scenario 3), people can stay in the AS. Otherwise (fire scenarios 3.2 to 3.4), their integrity is compromised. The compartmentation of the accommodation spaces, with smoke-tight doors, would prevent the filling of these areas by smoke.
- Fire scenarios 3.1 and 5: people can stay in the AS until they can join the LSA after 36 min and 54 min of fire, respectively.
- Fire scenarios 4 and 6: people can always evacuate safely.

Provided people can stay long enough in the AS, a safe and orderly evacuation is ensured for fire scenarios 1, 2, 3.1, 4, 5 and 6.

Table 4: Summary of fire consequences to people for the selected scenarios.

Scenario	Fire integrity in the AS	Fire integrity in the LSA and DR over a period of 1h
1	Safe	Starboard side: safe for $t \lesssim 11$ min* Portside: safe for $t \lesssim 11$ min and $t > 48$ min
2	Safe	Safe on both sides of the ship for $t < 19$ min and $t > 27$ min
3	Safe	Safe for $t \lesssim 10$ min The most restrictive criterion is visibility since it makes LSA and DR impractical after 1 h of fire*
3.1	Safe	Short-lived peaks of gas temperature and smoke at $t \approx 36$ min (when the HRR is max.). After 36 min of fire, evacuation can be done safely, with a visibility of 5 m or more on the portside and no restriction on the starboard side.
3.2	Unsafe for $t \gtrsim t_1 + 35$ min with $t_1 = 30$ min	Safe for $t \lesssim 10$ min The most restrictive criterion is visibility since it makes LSA and DR impractical after 1 h of fire*
3.3	Unsafe for $t \gtrsim t_1 + 20$ min with $t_1 \approx 29$ min	
3.4	Unsafe for $t \gtrsim t_1 + 12$ min with $t_1 = 6$ min	
4	Safe	Due to the short duration and low levels of exposure to heat and smoke, evacuation can be done safely on both sides of the ship
5	Safe	Safe for $t \lesssim 14$ min LSA and DR are expected to become tenable after 54 min of fire on both sides oft he ship
6	Safe	Safe at all times

*Need for longer simulations to cover 3 hours of fire for the OEA evacuation scenario.

6.2 Conclusions considering fire integrity in view of evacuation evaluation

Numerical simulations have been performed to assess fire integrity, in view of investigating both phases of the evacuation depending on whether the persons on board are moving from their actual position to the assembly stations (AS) or from the AS to the embarkation stations.

An analysis of the simulation results allows the following conclusions to be drawn considering fire integrity:

- Results obtained for the selected fire scenarios on the Stena Flavia show that fire and smoke could be contained in the space of origin by closing the openings in the Ro-Ro spaces around the embarkation station, avoiding thermal bridging on the deck partitions and ensuring that the integrity of thermal insulation is maintained.
- If people can stay in the Assembly Station long enough, waiting for the fire to decay, a safe and orderly evacuation can be ensured for most of the fire scenarios studied (i.e., for fire scenarios 1, 2, 3.1, 4, 5 and 6 in Table 3). The path to reach the embarkation station may depend on the fire source location.
- The most serious fire scenario (fire scenario 3, and therefore 3.2 to 3.4) corresponds to a well-ventilated fire originated from the centerline of the closed Ro-Ro space (Deck 4 of the Stena Flavia). For this scenario, embarkation station and disembarkation route cannot be safely used

by people during the first hour of fire. Fire integrity over a 3-hour period (OEA evacuation scenario) requires longer simulations to be assessed. Water mists could be used, which would reduce the impact of heat and smoke on people in the embarkation station and along the disembarkation route.

When the smoke can reach the accommodations spaces due to insulation or containment defect (fire scenarios 3.2 to 3.4), the AS are no longer safe. A way to protect some places from smoke can be well-designed compartmentation of accommodation spaces, with smoke-tight doors.

- The selected fire scenarios may be considered as extreme scenarios since all the cargo in the Ro-Ro space where the fire broke out has burned, without any means of firefighting having been engaged. Lesser consequences of fire are expected if firefighting action is taken.

Above-mentioned recommendations, i.e. closing the openings in the Ro-Ro spaces, avoiding thermal bridging between decks, ensuring thermal insulation integrity, or use of water mists, are left as possible solutions to be investigated in future design studies or safety projects.

6.3 Assembly phase

6.3.1 Assembly phase without thermal constraints

The configuration used is the one of the Ro-Ro ship Stena Flavia. The considered geometry includes all decks. According to the General Arrangement Plan, 466 passengers and staff members are considered in this scenario. They are initially located in their cabins, workstations, or offices. As a reference case, no fire accident is considered here.

The model parameters are set to:

- 1.02 m/s for the free walking speed. This average value considers the categories of population (table 3.1 from MSC 1 Circ.1533 [6]) and the walking speed on flat terrain (table 3.4 from MSC 1 Circ.1533 [6]);
- 1.10 pers/s/m for the maximal people flow density per meter at doorway (from Annex 2, page 2 from MSC 1 Circ.1533 [6]).
- The free walking speed is decreased by 52% in stairs according to Table 3.5 from MSC 1 Circ.1533 [6].

For this scenario, the AS is the restaurant located at Deck #5 of Ro-Ro ship Stena Flavia. No fire is considered for this first reference scenario. The main result provided by AMERIGO is the travel duration distribution used by evacuees to reach a safe place. This result takes the ship geometry and the congestion phenomenon into account.

Figure 24 gives an example of travel duration distribution for an evacuation drill concerning the Ro-Ro ship Stena Flavia. The main results show that 183 s are needed for each evacuee to reach the LSA. In considering the reaction time of 5 min for a daytime scenario or 10 min for a night-time scenario, the total evacuation time is estimated between 483 and 783 seconds. This time interval can be compared with the ones defined to ensure the fire integrity of the ship: the assembly station is never impacted in normal conditions, especially at such a short time after fire ignition.

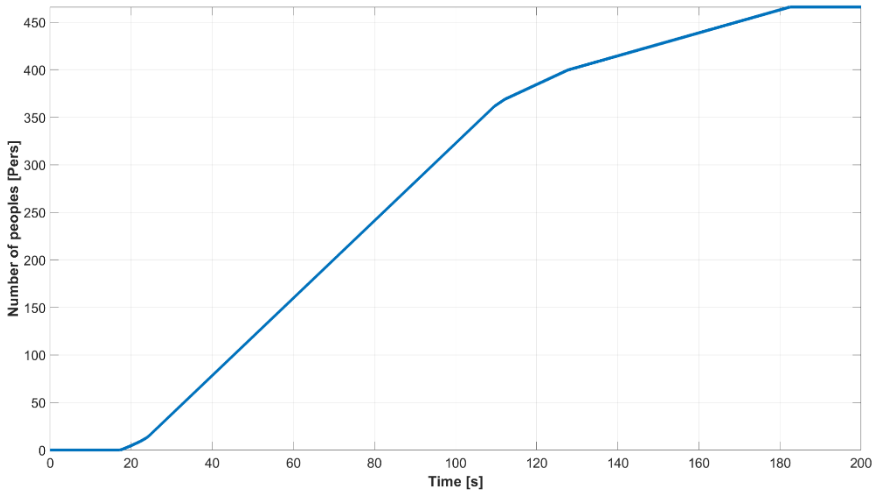


Figure 24. Travel duration distribution for an evacuation drill of Stena Flavia without fire. The restaurant is considered as the LSA and is used as target for the first step of evacuation.

The more sensitive doorways can be identified by analysing in detail the results provided by AMERIGO. Figure 25 illustrates the rate of use for the most important doorways. The results indicate that the main stairs, shown with an orange circle in Figure 26 are very useful for evacuation. Moreover, the main door which leads to the cabins at Deck 6 (in red in Figure 26) is a sensitive doorway too (almost 100 passengers use it for their evacuation).

The second most sensitive locations inside the ship are the doorways where the evacuees wait for a long time to escape. This information is given in Figure 27. Unsurprisingly, the biggest waiting line is on the main stairs. Among the following thresholds lesser sensitive, we notice that secondary stairs at Deck 5 (located in blue circles in Figure 26) slow down the evacuation. Up to 50 passengers can wait behind these thresholds before leaving this deck.

These first results on evacuation without considering a fire scenario draw some prospective on the sensitive locations.

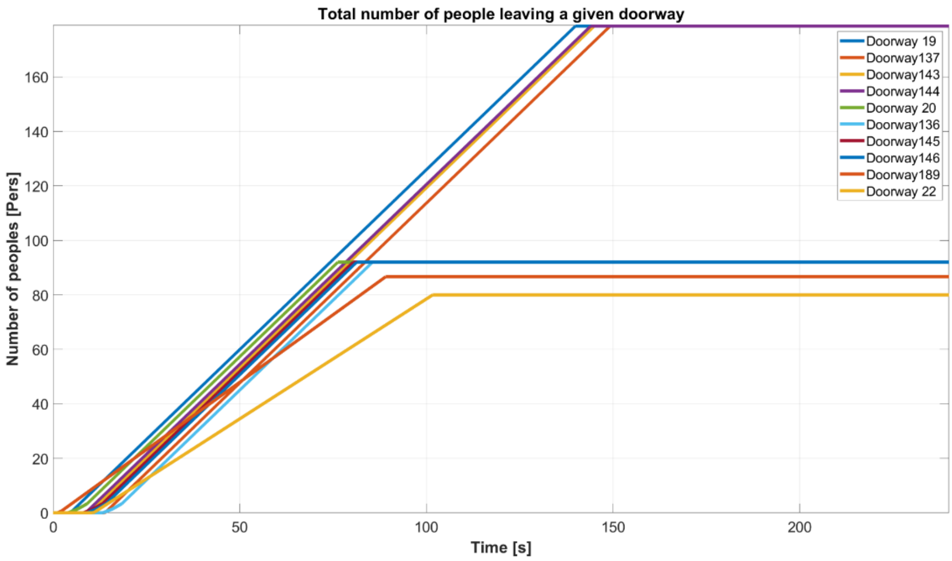


Figure 25. Evolution of the total number of evacuees using a given doorway according to time.

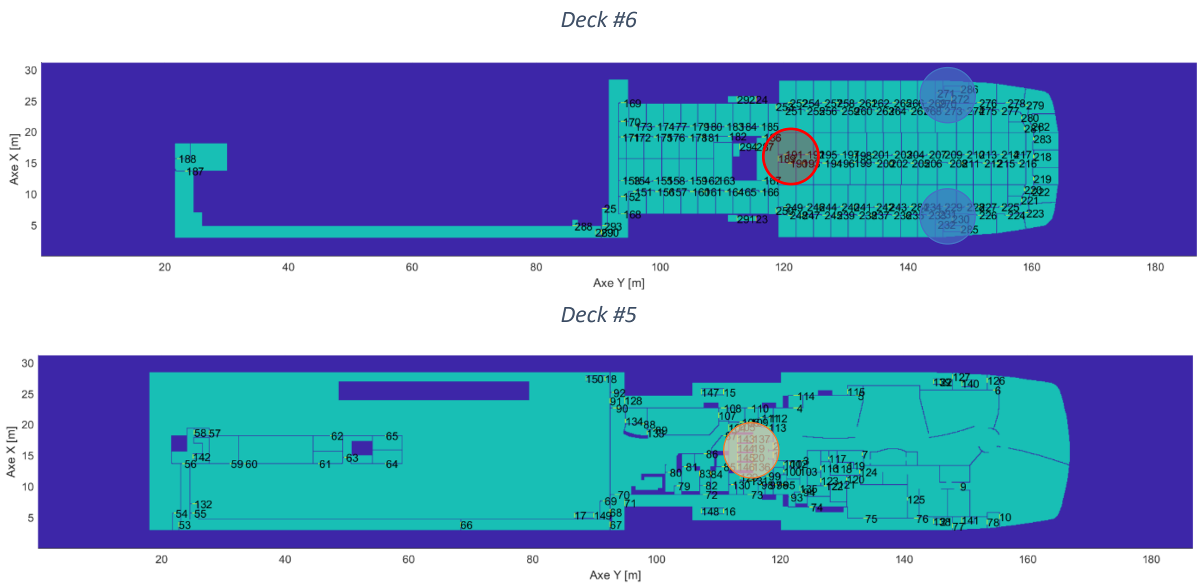


Figure 26. 2D representation of Ro-Ro ship Stena Flavia.

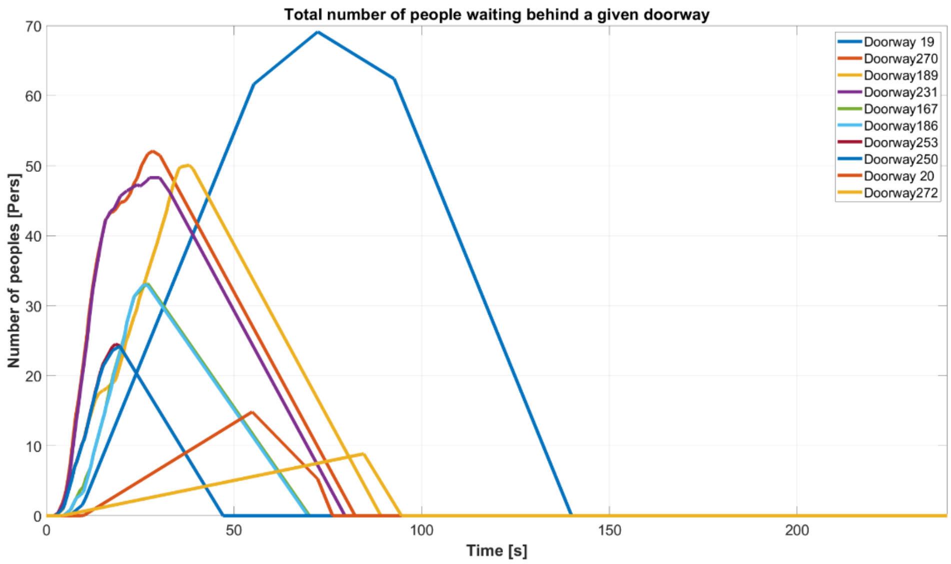


Figure 27. Total number of people waiting behind a doorway distribution against time.

6.3.2 Assembly phase with fire accident in accommodations

Based on previous section results, several scenarios have been considered to challenge the evacuation phase. In the first case, one of the most used doorways has been blocked (now considered as an obstacle as if it was highly impacted by a fire). It is the doorway number 189 on Deck 6 (located in red circle in Figure 28). The updated numerical simulation shows that the travel duration is still about 183s (+ 1% compared with the reference case). Hence, no recommended improvements is needed for this doorway, a 2nd path exists for a quick and safe evacuation.

A second disturbance is focused on the stairwells between Deck 6 and Deck 5. The doorway number 270, represented in Figure 29 by a red circle is supposed to be blocked by a fire. In this configuration, the travel duration for evacuation is increased from 183 s (for the reference case) to 223 s (+23%). This increase is not significant if the reaction time is also taken into account, namely 5 min for a day time scenario or 10 min for a night time scenario. Here again, the results show that a 2nd path exists for passengers to reach the assembly station.

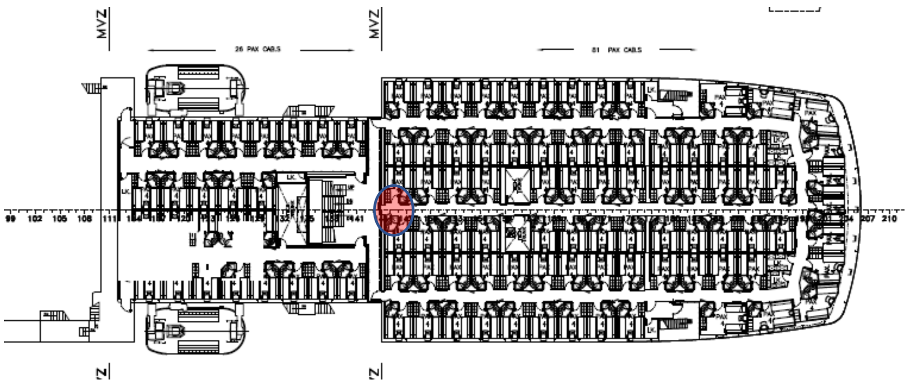


Figure 28 - Location of the blocked doorway in accommodations.

As a conclusion, we can note that the architecture of Stena Flavia is well designed: the passengers have at their disposal several possible exits to safely reach the embarkation station.

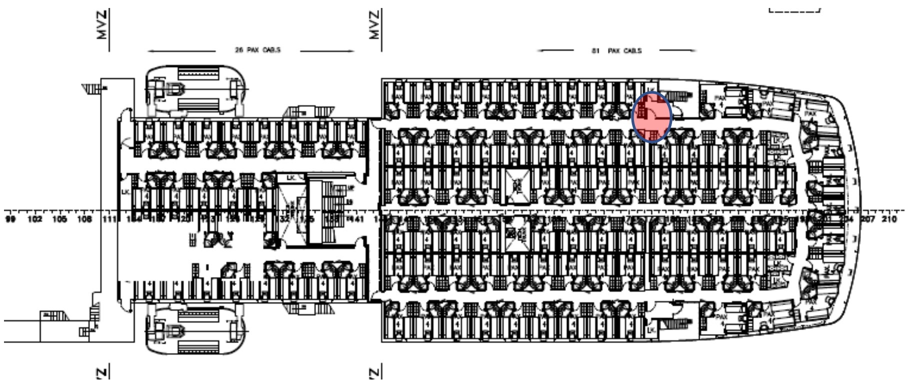


Figure 29- Location of the blocked stairwell in accommodations.

6.3.3 Sensitivity analysis on the width of the doorways

As previously mentioned, doorways can be over-crowded, and the people flux at these locations can reach its maximal value. To improve the travelling time, a sensitivity analysis has been carried out to identify the possible effect of the doorway width on the assembly phase, here again, without the thermal constraint imposed by a fire. The underlying idea was to evaluate the gain if a risk control measure of enlarging the path toward the safety area was prescribed.

The simulations show that changing the width of the doors by 20% only changes the total evacuation time by 5%, because the flow of people inside the ship is mainly limited by the severe bottlenecks created in the stairwells, not behind the doors.

A change in the ship geometry (concerning the doorway width) is not an option which significantly improves the time required for the assembly phase.

6.3.3.1 Assembly phase with fire accident in Autopullman compartment

In this next scenario, we consider a fictitious fire accident. The fire starts at the Autopullman compartment on Deck 5. At this first moment, the fire is detected. In this configuration, all the doors are considered as opened. Based on simulation results obtained from the network model (Scenario 3.3

in Table 3), smoke spreads through Deck 5 and after several minutes reach Deck 6 and Deck 7 through the staircases.

The passengers escape toward the restaurant at Deck 5 since it represents the AS for Stena Flavia.

For the evacuation, we consider several scenarios:

- **Scenario 1** - An early evacuation, where the passengers try to reach the AS immediately when the fire alarm is triggered. In these conditions, the evacuees are not altered in their evacuation by the thermal constraints imposed by the fire.
- **Scenario 2** - In a daytime scenario, 5 minutes are necessary for passengers to take some information before to start their own evacuation (according to MSC.1/Circ.1533)
- **Scenario 3** - In a night-time scenario, the passengers start their evacuation 10 minutes after the fire is triggered.

466 passengers are considered. The free walking speed is 1.02 m/s according to the assumption that the evacuees are a panel consisting of males 30-50 years old from table 3.4 in the appendix to the *Guidelines for the advanced evacuation analysis of new and existing ships.* The people flux at a doorway is limited to 1.1 pers/m/s according to MSC.1/Circ.1533, Annex 2.

In this configuration, the fire starts in the Autopullman room at Deck 5 as it is presented in Figure 30(a). The fire spreads quickly in the adjacent rooms, as it can be seen in Figure 30(b). At this time of the fire propagation, both the temperature threshold and the maximal soot concentration are exceeded, and these spaces are no longer accessible to passengers.

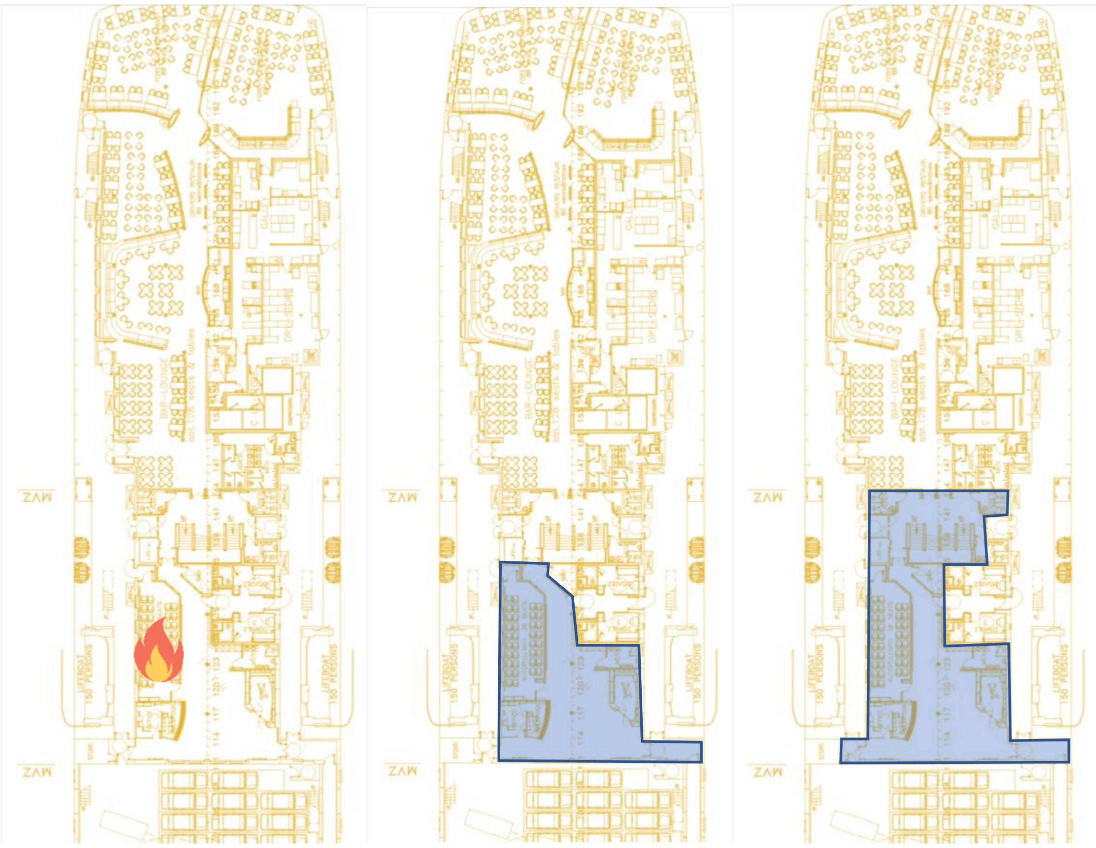
Ten minutes after the fire ignition, the smoke reaches the main staircases and quickly spreads to Deck 6 and Deck 7, as can be observed in Figure 30(c). Here, the staircases are not available for the evacuees and the main entrances to access to the restaurant (Assembly Station) are blocked by too important thermal constraints.

This scenario has been selected because the fire impacts the main entrances to the restaurant (Assembly Station) and may influence the global behaviour of passengers during their evacuation.

Figure 31 presents the distributions of the people reaching the Assembly Station for the three scenarios. When the evacuation is started at the same time than the fire detection, 232 seconds are necessary for all passengers to muster to the restaurant. This evacuation time (<4 min) is smaller than the one which characterized the fire spread: indeed, 10 minutes are necessary for the fire to impact some sensitivity space in the ship to penalize the evacuation (see Figure 30(a)-(c)).

When the evacuation begins at 5 minutes after the fire detection, the evacuation time remains the same, about 232 seconds. The evacuation time is not affected by the fire constraints because the spaces impacted by the smoke (see Cf. Figure 30(b)) are not used by the evacuees. The main staircases remain clear, and a quick and safe evacuation can occur.

When the evacuation decision is delayed, in a night-time scenario, all the passengers are in a safety place in 262 seconds. Here, as the main staircases are blocked, the evacuees should find a second path to reach the restaurant (Assembly Station), which affects slightly the evacuation time, increased by about 30 seconds. Despite this slight increase in the travel time, people can still reach the AS.



(a) Ignition (b) After 5 min (c) After 10 min

Figure 30. Fire development on Stena Flavia at Deck 5. Definition of areas impinging by the thermal constraints from fire in blue.

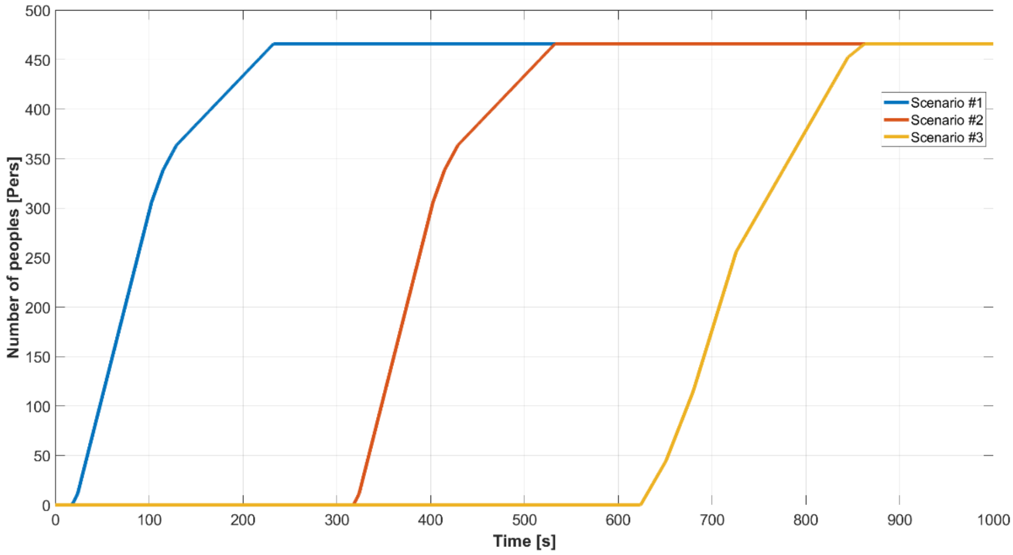


Figure 31. Number of people evolution against time for the three scenarios.

6.3.4 Conclusions for the assembly phase

Consequences on evacuation can be summarized as follows for the assembly phase:

- We can note that the architecture of the considered ship is well designed since the passengers have at their disposal several possible exits to safely reach the Assembly Station.
- In view of the above findings, as long as the passengers are warned to gather in the assembly station quickly after the detection of fire, the estimated evacuation times are by far much shorter than the time after which evacuation is not possible from the accommodation areas.
- Additional measures like doors enlarging, or insulation improvements, would not be justified as they would not result in significant condition improvements (passengers and crew can apparently reach the AS in safe conditions with the current design).

6.4 Ship abandonment - Development of means for Ro-Ro ship safe evacuation in relation to fire integrity

In this section, the second phase of evacuation is now considered: abandonment phase with people starting their evacuation from the assembly station, considering that the latter is still under safe conditions.

All the tested solutions are based on existing devices or exits, i.e., the Ro-Ro space loading ramp, the pilot doors, and the lifeboats. Simulated times for ship abandonment are compared to a reference time computed first.

6.4.1 Evacuation by Ro-Ro space loading ramp (primary solution)

The primary evacuation solution involves the use of the Ro-Ro space loading ramp at the rear side of the ship. This ramp is located on deck 3 as depicted in Figure 32 and is considered to be the normal path of abandonment. Note that leaving the ship through this means of abandonment requires the passengers to travel down two floors because the assembly station is on deck 5.

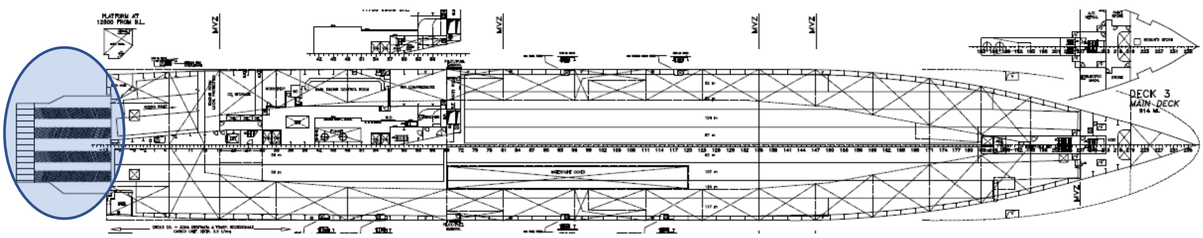


Figure 32. Location of Ro-Ro space loading ramp on deck 3.

Table 5. Results of evacuation using the Ro-Ro space loading ramp on deck 3 (solution 1).

Configuration	466 persons	699 persons	932 persons
Time of 1st evacuee	2 min and 19 s	2 min and 19 s	2 min and 19 s
Abandonment time	11 min and 9 s	15 min and 32 s	19 min and 57 s

The results of evacuation using the Ro-Ro space loading ramp are summarized in Table 5. They show that it takes 2 min and 19 s for the first passenger to disembark the ship, while a period of about 11 min is required to evacuate 466 passengers. Moreover, the results show that the evacuation time is increased significantly at higher numbers of passengers, because people must travel through two floors of stairs to reach the Ro-Ro space loading ramp, and their speed of travel is limited in the stairs, so a major congestion is formed.

6.4.2 Evacuation by a pilot door on the port side

The second option of ship abandonment is the use of the pilot door that is available on the port side of the ship, as depicted in Figure 33. Like the Ro-Ro space loading ramp, this pilot door is located on deck 3.

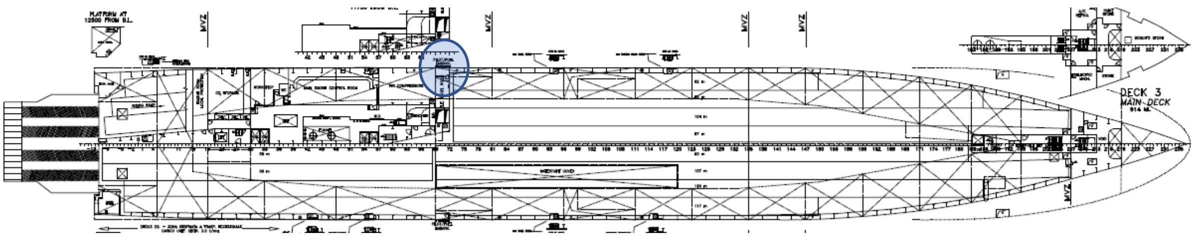


Figure 33. Location of the pilot door on the port side of deck 3.

As indicated in Table 6, compared to the primary solution of using the Ro-Ro space loading ramp, the use of the pilot door on the port side of the ship leads to evacuation times that are up to 27% longer, i.e. additional evacuation time of over 4 min and 30 s. This is not surprising because the passengers must go through an increased number of doorways in this case, facing congestions during their escape. As a result, the use of this pilot door alone is a less efficient solution for ship abandonment, even if the computed time is not dramatically increased.

Table 6. Results of evacuation using the pilot door at the port side of deck 3

Configuration	466 persons	699 persons	932 persons
Time of 1st evacuee	1 min and 57 s	1 min and 57 s	1 min and 57 s
Abandonment time	13 min and 47 s	19 min and 20 s	25 min and 33 s
Ratio to solution 1*	+ 23%	+ 26%	+ 27%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.4.3 Evacuation by a pilot door on the starboard side

There is a second pilot door located on the starboard side of deck 3, as shown in Figure 34. This pilot door is considered here as another means for ship abandonment and the corresponding evacuation efficiency is compared to the previous solutions.

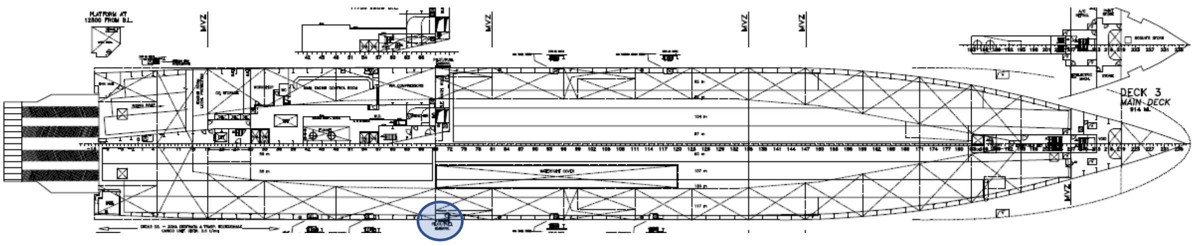


Figure 34. Location of the pilot door on the starboard side of deck 3.

The results of evacuation using the pilot door on the starboard side of deck 3 are presented in Table 7. In this scenario, the evacuation times are very similar to those of the pilot door on the port side. This is because the major congestion areas faced by the passengers are the same for both the pilot doors. These areas consist of the stairs and the doorways connecting the assembly station on deck 5 to either of the pilot doors on deck 3.

Based on these results, the experience of the MAAG&MOAG was requested to further evaluate the relevance of the solution. Beside the slight increase in the evacuation time, the use of the pilot doors is not an acceptable solution for ship abandonment because pilot doors are not designed for passenger use. The question of a safe way to reach the quay or the sea is another key point. Actually, the Ro-Ro space loading ramp usually remains by far safer and more practical to use.

Table 7. Results of evacuation using the pilot door on the starboard side of deck 3

Configuration	466 persons	699 persons	932 persons
Time of 1st evacuee	1 min and 57 s	1 min and 57 s	1 min and 57 s
Abandonment time	13 min and 42 s	19 min and 36 s	25 min and 29 s
Ratio to solution 1*	+ 22%	+ 26%	+ 27%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.4.4 Evacuation by lifeboats on the port side

Another possible solution for ship abandonment is the use of lifeboats. According to the International Convention for the Safety of Life at Sea (SOLAS) [7], the lifeboats should be capable of being launched at their full capacity of passengers in 10 min, while every lifeboat has a maximum capacity of 150 persons (see chapter 3 of SOLAS, regulations 31/1.5 and 41/2.1).

In order to include the abovementioned evacuation rate with the lifeboats in the simulations, an exit with a flux capacity of 0.25 pers/s is considered, i.e., continuous and successive use of one lifeboat at a time and with no interruption. The first simulation considers such an evacuation from the port side on deck 5, as shown in Figure 35, and the results of evacuation time are presented in Table 8. The results show that the first passenger leaves the ship in 12 s because the exit assigned to the lifeboats is located next to the assembly station on deck 5. Nevertheless, the total evacuation time is ultimately limited by the formation of congestion inside the ship and the limited capacity of the final exit (0.25 pers/s). Correspondingly, it takes more than 39 to 77 min for 466 to 932 passengers to evacuate the ship through this means of abandonment. Accordingly, it can be concluded that the successive use of one lifeboat at a time is not an efficient solution for the evacuation from the port side of the ship.

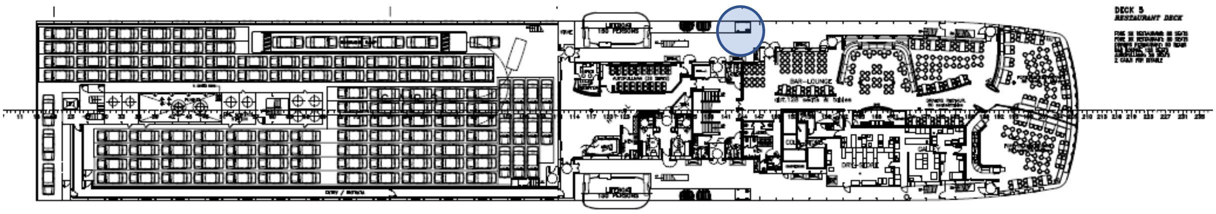


Figure 35. Location of the exit considered in AMERIGO simulations for lifeboat evacuation from the port side of deck 5.

Table 8. Results of evacuation using the lifeboats on the port side of deck 5

Configuration	466 persons	699 persons	932 persons
Time of 1st evacuee	12 s	12 s	12 s
Abandonment time	38 min and 56 s	58 min and 21 s	77 min and 46 s
Ratio to solution 1*	+ 249%	+ 275%	+ 289%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.4.5 Evacuation by lifeboats on the starboard side

The lifeboats can also be used on the starboard side of the ship, as depicted in Figure 36. As mentioned in the previous section, the lifeboats are to be launched at their full capacity of passengers in 10 min, while every lifeboat has a maximum capacity of 150 persons [2].

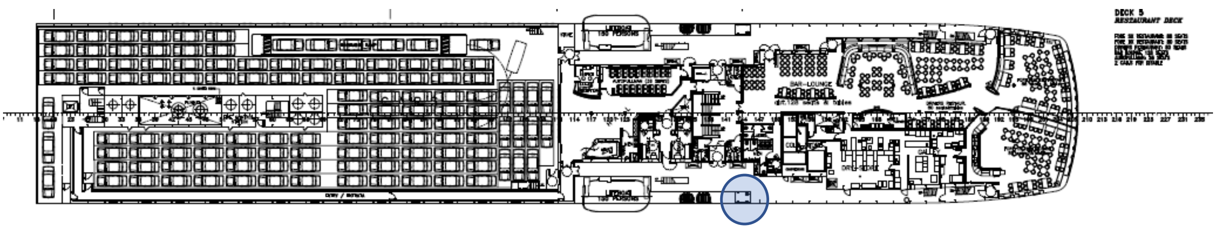


Figure 36 Location of the exit considered in AMERIGO simulations for lifeboat evacuation from the starboard side of deck 5.

The results of evacuation using lifeboats on the starboard side of the ship are presented in Table 9. In this case, the evacuation time is over 8 to 15 min shorter compared to evacuation using lifeboats from the port side (comparing Tables 8 and 9). However, the evacuation times offered by this solution are by far longer than those offered by the primary solution of using the embarkation platform, with differences in evacuation time of over 181 to 213%.

Table 9. Results of evacuation using the lifeboats on the starboard side of deck 5

Configuration	466 persons	699 persons	932 persons
Time of 1st evacuee	19 s	19 s	19 s
Abandonment time	31 min and 22 s	46 min and 55 s	62 min and 29 s
Ratio to solution 1*	+ 181%	+ 202%	+ 213%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.5 Sensitivity analysis toward an optimized second path for abandonment

Among the solutions considered so far, the best abandonment solution is found to be the use of the Ro-Ro space loading ramp, offering an evacuation time of 11 to 20 min for 466 to 932 passengers. Note that we considered here the ship without vehicles penalizing the walking speed. However, the main drawback of this solution is that this means of evacuation is located on deck 3, such that a big part of the evacuation time is spent within major congestion areas inside or behind the stairs that connect the assembly station on deck 5 to the Ro-Ro space loading ramp on deck 3. Moreover, it assumes that the travel path for abandonment is safe, not impacted by the fire. Finally, this option is only available if the ship can dock at a port. As such, this option is not possible at sea and may not be possible near a port if the ramp is not compatible with the given port (which could be foreign) or in cases where the coastal state authorities and harbour master do not permit the ship to approach the port with active fire development on the ship.

As a result, a second path for ship abandonment must be considered to allow evacuating the passengers as fast as possible. In this section, we investigate such a means of abandonment using a sensitivity analysis, to identify the optimal flux of people that should leave the ship from deck 5 (i.e., where the assembly station is located).

6.5.1 Sensitivity on abandonment from the starboard side

For the first sensitivity analysis scenario, 30 simulations have been conducted using a fictitious means of abandonment on the starboard side of deck 5 as depicted in Figure 37, with a maximum evacuation capacity fixed at a value ranging from 0.11 to 5.5 pers/s/m in order to determine the optimal flux of people, considering either 466, 699 or 932 passengers on the ship.

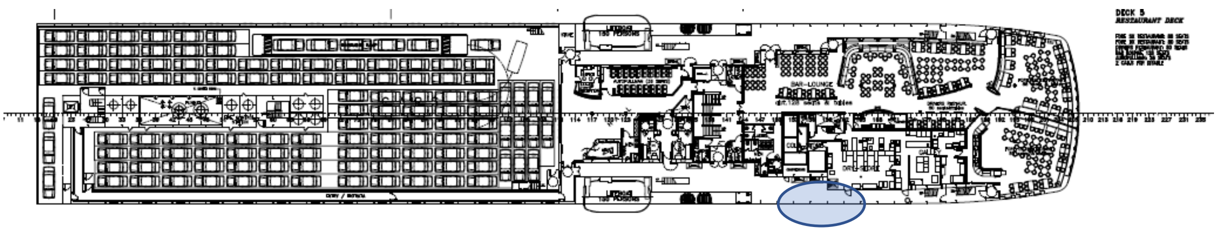


Figure 37. The fictitious means of abandonment considered on the starboard side of deck 5 for the sensitivity analysis.

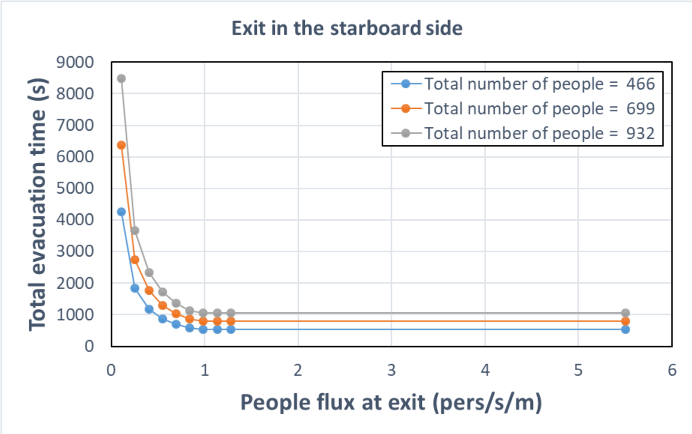


Figure 38. Results of evacuation time versus the flux of people through a fictitious exit on the starboard side of deck 5.

The results of evacuation time using the fictitious exit on the starboard side of deck 5 are presented in Figure 38. The maximum possible flux through the exit is 0.99 pers/s/m for all the configurations (above this threshold the evacuation time does not decrease any lower). The results of evacuation time using this optimal flux are shown in Table 10 in comparison with the results of evacuation time using the Ro-Ro space loading ramp. These results suggest that the optimized exit allows an evacuation time that is up to 19% shorter than that obtained using the Ro-Ro space loading ramp.

Table 10. Evacuation times with the maximum flux of people via a means of abandonment on the starboard side of deck 5

Configuration	466 persons	699 persons	932 persons
Abandonment time	9 min and 5 s	13 min and 25 s	17 min and 47 s
Ratio to solution 1*	- 19%	- 14%	- 11%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.5.2 Abandonment from the port side

For the second sensitivity analysis scenario, the fictitious means of abandonment is considered on the port side of deck 5 as depicted in Figure 39. As in the first scenario, 30 simulations have been conducted, considering the exit to have a maximum evacuation capacity fixed at a value ranging from 0.11 to 5.5 pers/s/m in order to determine the optimal flux of people, with either 466, 699 or 932 passengers on the ship.

The results of evacuation time using the fictitious exit on the port side of deck 5 are presented in Figure 40. In this case, the maximum possible flux of people is identified to be 1.28 pers/s/m. This value is higher than the one found for the starboard side of the ship. Therefore, the evacuation times are shorter in this case, ranging from about 6 to 12 min for 466 to 932 passengers. Accordingly, the optimization of evacuation is more efficient for the port side of the ship, and this is due to the geometry of the ship which offers more alternative routes (i.e., more doorways) to the passengers in the assembly station when they evacuate through the port side of the ship. The results of evacuation time using this optimal flux are shown in Table 11 in comparison with the results of evacuation time using the Ro-Ro space loading ramp. These results suggest that the optimized exit on the port side allows an evacuation time that is up to 44% shorter than that obtained using the Ro-Ro space loading ramp.

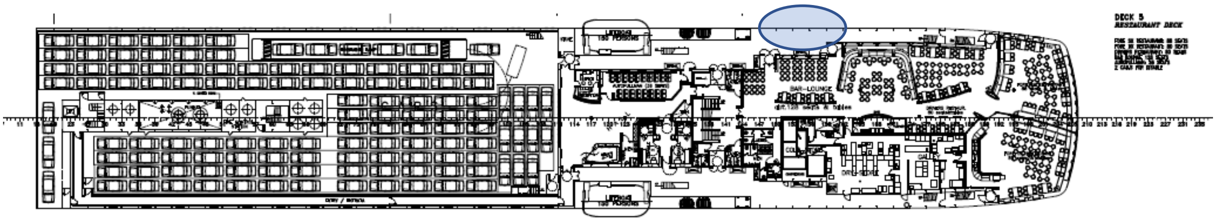


Figure 39. The fictitious means of abandonment considered on the port side of deck 5 for the sensitivity analysis.

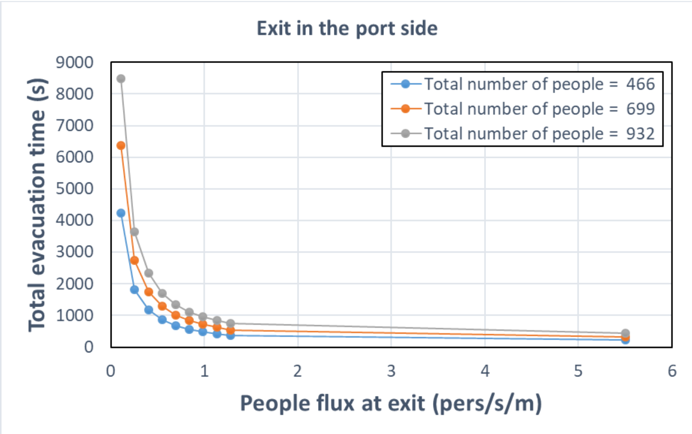


Figure 40. Results of evacuation time versus the flux of people through the final exit on the port side of deck 5.

Table 11. Evacuation times with the maximum flux of people via a means of abandonment on the port side of deck 5

Configuration	466 persons	699 persons	932 persons
Abandonment time	6 min and 13 s	9 min and 6 s	12 min and 17 s
Ratio to solution 1*	- 44%	- 42%	- 38%

* Solution 1 is the use of the Ro-Ro space loading ramp.

6.5.3 Alternative means of abandonment with the optimized flux of people

In order to provide the optimized flux of people identified in sections 4.5.1 and 4.5.2, i.e., 1.28 pers/s/m on the port side and 0.99 pers/s/m on the starboard side, one possible solution is to use an appropriate number of evacuation slides as depicted in Figure 41. Based on the data of an evacuation drill performed on the Airbus plane A380 in 2006 [56], 873 people could be evacuated in 80 seconds with 8 slides of 2 lanes, which is equivalent to an evacuation flux of 0.69 pers/s/lane. Therefore, the appropriate number of evacuation slides to use on either side of the ship is 2 slides of 2 lanes (which is equivalent to a flux of 2.76 pers/s). Note that the Airbus inflatable slides are deployable on the ground (packed size of each slide ≈ 0.91m x 0.76m x 0.30m, with an activation cylinder of 12 L and 200 atm Nitrogen), which can be used for evacuation at a port. However, the Ro-Ro space loading ramp is usually considered safer and more practical to use at the port. Therefore, the use of slides was imagined to be limited to only highly urgent situations or for evacuation at sea.

Figure 41. Examples of evacuation slides for ship abandonment.

The second solution is to use escape chutes as depicted in Figure 42. For this type of devices, the people flux is estimated to be 0.11 pers/s/chute based on the marine evacuation system of Viking LifeCraft [57] which can evacuate 812 persons in 30 min using 4 escape chutes. As a result, the optimal flux of people identified in sections 4.5.1 and 4.5.2, i.e., 1.28 pers/s/m on the port side and 0.99 pers/s/m on the starboard side, can be achieved using 12 escape chutes for each side of the ship (which is equivalent to a flux of 1.32 pers/s).

However, this solution may only be practical for evacuation at ports where only the chute itself is required (≈ 0.8 m diameter), because the required space for the devices that are used for evacuation at sea is likely not available (packed size ≈ 16 m x 2.7 m x 2.6 m for a system with 4 chutes).

Both solutions rise questions of possible injuries for evacuees and difficulties for people with limited mobility, which were discussed with MAAG&MOAG in particular (this is considered in section 8 *Integration evaluation*).

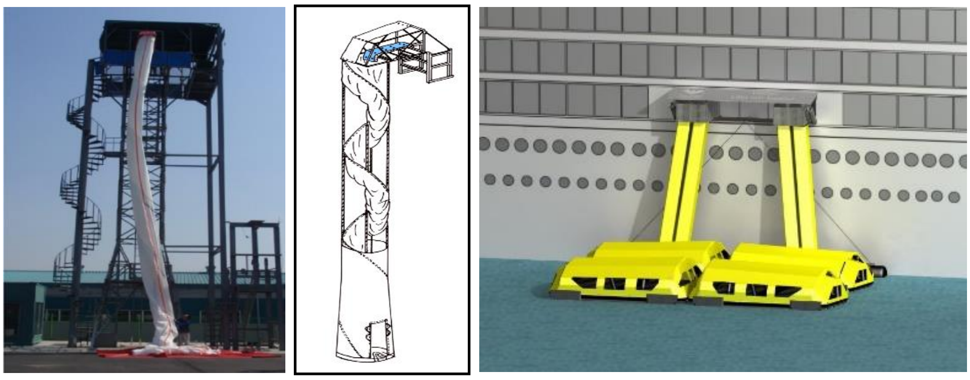


Figure 42. Examples of escape chutes for ship abandonment.

7 Performance assessment

Main author of the chapter: Pascal Boulet, LUL.

As planned in the LASH FIRE project, the performance assessment of evacuation solutions was achieved through numerical simulations with the AMERIGO model. Based on the investigations reported in section 6, the main observations are the following:

- No supplementary Risk Control Measure is needed for the assembly phase. Based on the example of the Ro-Ro passenger generic ship Stena Flavia, the current design provides paths and conditions such that the time required for joining the AS is shorter than the fire development. This can be considered as a performance assessment of the current design of the ship. Additional measures like enlarging doors and corridors, improving insulation in some sensitive places, or search for alternate paths, do not provide a significant safety improvement because the main part of the evacuation time is indeed the reaction time. If the fire is detected in due time, the travel time itself is not a weakness of the evacuation process.
- The abandonment phase of ship evacuation was also analysed using the evacuation model AMERIGO. This was to assess and compare different means of ship abandonment in order to establish their reliability in terms of evacuation time. The generic ship Stena Flavia was also considered for the performance assessment. Regarding the existing means of abandonment, the best solution in terms of evacuation time was found to be the use of the Ro-Ro space loading ramp, yielding an evacuation time between 11 and 20 min when considering 466 to 932 passengers, respectively. However, the main drawback of this solution is that the means of evacuation is located on deck 3, such that a big part of the evacuation time is spent within major congestion areas inside or behind the stairs that connect the assembly station on deck 5 to the Ro-Ro space loading ramp on deck 3. Moreover, this option is not possible at sea and may not be possible near a port if the ramp is not compatible (e.g., at a foreign port) or in cases where the coastal state authorities and harbour master do not permit the ship to approach the port with active fire development on the ship. The use of lifeboats requires a significantly higher time for ship abandonment, about 31 to 79 minutes depending on the number of passengers.

  Second paths for walk-off abandonment were investigated: (i) a direct evacuation from the deck where the assembly station is located, down to the quay or the sea, involving alternate means to join a safe area; (ii) the use of existing doors, namely pilot doors or bunker doors as an alternate walk-off abandonment.

  Provided that a direct evacuation from deck 5 – where the assembly station is located – can be organized, the performance assessment identified the optimal flux of people. Based on the sensitivity analysis performed through 60 simulations, it was found that the maximum possible flux of people through an evacuation means near the assembly station is 1.28 pers/s/m on the port side of the ship, which can reduce the evacuation time by up to 44%, and 0.99 pers/s/m on the starboard side of the ship, which can reduce the evacuation time by up to 19% with respect to the evacuation time obtained using the Ro-Ro space loading ramp. Such an optimal flux can be achieved using 2 slides of 2 lanes on either side of the ship. Alternatively, 12 escape chutes will be necessary on each side of the ship to achieve the aforementioned fluxes. A decrease in the number of slides or chutes will induce an increase in the time required for ship abandonment. However, as explained in the next section dedicated to integration evaluation, time for evacuation is not the only decision-making criterion. The use of slides or chutes may cause injuries for passengers and might not be a safe alternate solution.

This is why another walk-off ship abandonment solution was sought. Performance assessment of alternate paths toward pilot doors or bunker doors show that the evacuation time remains of the same order as the reference time using the Ro-Ro space loading ramp. However, here again, no safe solution that can be provided from the ship exists to join the quay or the sea from the door, except ladder or additional devices like slides or chutes, which are not thought safe enough. A set of stairs on wheels could be provided from the quay, but this should be asked as a requirement in all potential foreign harbours (which is a recommendation beyond the LASH FIRE project scope).

8 Integration evaluation and cost assessment

Main author of the chapter: Pascal Boulet, LUL.

This section was written based on the present numerical study followed by exchanges with MAAG&MOAG, discussions with ship operators and meetings with WP04 and WP05. The solution workshops held within the LASH FIRE project and the decision taken during the Steering Group meetings led to disregard the measures found as possible alternate solutions for evacuation. Different explanations are given below :

- Beside the conclusions on the time required for ship abandonment, a Risk Control Measure (RCM) based on slides or chutes could cause injuries to evacuees or difficulties for some passengers (either old passengers, children, or people with limited mobility).
- The use of pilot doors or bunker doors, or a combination of both which was also investigated, rise at least three problems : (i) the guidance of passengers by the crew is thought as a first difficulty, (ii) these doors are at the same level as the Ro-Ro space, where the fire was supposed to have a severe impact and this does not provide a safe way to evacuate without strongly improving the fire safety along this path, or changing the location of these doors in future ship design, (iii) after reaching the door, a way has to be found to reach the quay or the sea (and here again neither the use of slide, ladder or any stair from the quay is favoured by the ship operators).

In the end, the present study provides inputs for the evacuation conditions and for an evaluation of the current design in relation to evacuation and fire integrity. It shows that the assembly phase should not raise any difficulty. It also investigates some possible second paths for ship abandonment, but the forecasted solutions would require further investigation.

Note that some fire scenarios showed possible difficulties related to fire integrity, which could be avoided by either closing the openings in the Ro-Ro spaces, avoiding thermal bridging between decks, ensuring thermal insulation integrity, or using water mists in accommodation areas. These hypothetic solutions are left to be investigated in future design studies or safety projects. These are only recommendations, as the present study was not yet mature enough to assess the performances of corresponding measures.

Based on above-listed conclusions, the second recommendation is to consider in future designs the possible use of pilot doors for second path for evacuation. For that, the path from the assembly station toward the door should consider an improved fire integrity. In particular, they should not be located near the Ro-Ro spaces, if possible.

As it can be understood from above, cost assessment of the investigated solutions was not considered, as the solutions were finally disregarded due to a lack of practical applicability or a need for consolidated performance assessment. Additional costs were initially forecasted for the new required devices (slides, chutes), for crew training, or for suitable insulation of the evacuation path. These costs should be taken into account in future designs, but this was found beyond the scope of the present project, which will rather focus on other solutions with a more realistic applicability.

9 Conclusion

Main author of the chapter: Pascal Boulet, LUL.

This report investigated the appropriateness of different means of ship abandonment with respect to the design and passenger capacity of Ro-Ro ships. Recommendations were provided regarding the evacuation of a generic ship, as well as possible evacuation measures needed.

Evacuation conditions in relation to fire integrity were investigated based on numerical simulations, considering a generic Ro-Ro passenger ship (Stena Flavia) and a scenario with a fire starting in the Ro-Ro space, possibly propagating along the ship. An evacuation model was used, considering fire stresses taken as input from a CFD model used to predict the fire propagation. The assembly phase (crew and passengers joining the assembly station after the fire detection) and the ship abandonment (travel from assembly station to leave the ship) were both considered. The main conclusions can be summarized as follows:

- The time required for the assembly phase is by far shorter than the fire propagation. Hence, no specific Risk Control Measure may provide a significant improvement that could justify additional regulation or cost.
- Alternative paths for ship abandonment were investigated, comparing the time required for evacuation with a reference time obtained for an evacuation path using the Ro-Ro space loading ramp. In order to consider a possible emergency call to a foreign port, solutions were forecasted based on the use of other existing exits (pilot doors or bunker doors), or a direct evacuation from the assembly station (which requires new means to reach the quay or the sea like slides which were initially found as the best solution owing to their common use in planes in particular). Such solutions offer a second path for evacuation theoretically, and if the time for evacuation is the only criterion under consideration.
- However, the use of slides (or chutes) would not provide a safe way to evacuate, in particular for children, old people, or people with limited mobility. This solution was found to have a poor applicability.
- An alternative walk-off abandonment possibility based on the use of a side door (pilot door or bunker door) is recommended, but this requires tackling two main difficulties: (i) to provide a safe path between the assembly station and the side door in case of fire in the Ro-Ro space, (ii) to ensure that a device is available to go from the side door to the quay, allowing a safe walk-off abandonment.

Beside a better understanding of the evacuation conditions and quantitative assessment of the current conditions for evacuation on Ro-Ro ships, Action 11-B also provided possible recommendations for the future design of ships. As side doors could offer an alternative walk-off ship evacuation possibility, especially in case of return to a foreign port, the ship should be designed with a safe path from the assembly station to the side door/s. In particular, improved fire integrity should be provided on the Ro-Ro space levels. Furthermore, simulations should be carried out for the evacuation path using the side doors, to guarantee a reasonable evacuation time. A safe way for reaching the quay from the door should also be considered, but this is something that would need to be guaranteed in all harbours in that case.

Additional suggestions that could lead to improved fire integrity include permanently closing openings of Ro-Ro spaces, avoiding thermal bridging between decks, or to use water mist in the accommodation area. These solutions are addressed in other actions of the LASHFIRE project and could be investigated in future design studies or safety projects.

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