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A TRAGEDY, A FULL-SCALE FIRE EVACUATION DRILL, AN EMERGENCY EVACUATION SIMULATION.

Luca Fiorentini

TECSA S.r.l.
Via Figino, 101
Pero, Lombardia, 20016, Italy
luca.fiorentini@tecsasrl.it

Salvatore Tafaro

National Fire Corp – Ministry of Interior
Via Antonio Salandra, 39
Messina, Sicilia, 98124, Italy
Salvatore.tafaro@vigilfuoco.it

ABSTRACT

A number of recent severe fires occurred on board roll-on/roll-off (Ro-Ro) ships and these episodes underlined the complexity of emergency management coupled with a severe threat for the passengers.

Authors, given three different opportunities and associated perspectives, will explore the lessons learnt related with risk on board ro-ro ships, considering a real tragedy, a full-scale emergency drill and pedestrian dynamics simulation results.

They will present the "Norman Atlantic" ship fire on the 28th December 2014, resulting in 9 fatalities and 14 people lost at sea (not including number of undocumented migrants on board). Case will be discussed with the support of a formal structured Root Cause Analysis focusing on emergency management and pedestrian dynamics issues, employed during the discussion of the case at the Court. Fire started from the refrigeration unit of a transported truck.

They will then consider, give a fire event on a similar ship, a full-scale drill, organized on the 17th of February 2022 in Messina by the Fire Brigade and carried out involving all the local authorities. The evacuation simulation specifically concerned a fire on the car deck. The aim of the exercise was to test evacuation procedures for all passengers, with particular regard to people with special needs. In order to better coordinate the simulated emergency operations, the Prefecture of Messina also activated the regional centre for emergency and the area emergency plan. All emergency services, including voluntary associations, took part in the drill. Considerations and lessons learnt will be summarized.

Finally, they will consider the contribution of several pedestrian dynamics simulations, conducted on a model using PathFinder, to derive general lessons from variations of the Messina drill.

Aim of the paper is illustrating the results of the studies from three different perspectives: a real fire, a drill, a pool of simulations. Lessons learnt from the three approaches will be compared including a discussion of the work still to be done in the future to avoid the reoccurrence of such severe events that still happens, focusing on a holistic approach to fire safety on board.

BACKGROUND

Maritime transportation of people and goods has always been very important and in the last years its volume and therefore its importance has largely grown. The recent Covid-19 pandemic and the blockade of ports that was experienced underlined the importance of maritime transportation around the world, that has been estimated to be the 80% of the global trade by volume. Also for European Union and developed countries on seaports for the trading of goods is very high. In Europe, where the seaborne traffic represents 20% of the total transport, over 300 ports are very active in general cargo, bulk (liquid/dry), containers and “Ro-Ro”.

A ”Ro-Ro” (Roll-on/Roll-off) ship is a particular ferryboat designed for the transport of wheeled vehicles (on their own wheels), and of loads, arranged on flatbeds or in containers, loaded and unloaded by means of wheeled vehicles in an autonomous manner and without the aid of external mechanical means. No cranes are used and all the content is moved by ramps to different decks, often connected by lifts. Some ferries may carry passengers as well and they are referenced as “Ro-Pax”. In this case, the very configuration of the loading decks is geared for combined transport of lorries and passenger cars and decks often have a lover height suitable for cars and passenger vehicles. “Ro-Ro” and “Ro-Pax” may have different dimensions, from limited sizes useful to cross rivers and marine straits to very big vessels able to face the open sea in different weather conditions for crossings of many days. They are a very successful type of vessels due to their flexible operation and fast speed, so they are very popular in a number of short-sea routes, as those in the Mediterranean sea and in Northern Europe.

Marine accidents have always raised a great concern among safety professionals and some events are infamous for the number of casualties they recorded and/or for the severity of the fires.
“Ro-Ro” ships, and in particular “Ro-Pax”, have always showed a great vulnerability to fires (“Francesca”, “Norman Atlantic”, “Moby Prince”, “Scandinavian Star”, “Sewol”, “Boccaccio”) and a number of incidents, even in the last decade, recorded both severe fires and large number of victims among the passengers. A significant analysis of some events is given in (Baird, 2018) where it is also shown that same causes continue to reappear and while more fatal accidents (76%) occur in developing countries, they still do happen in developed ones (24%). Sixty percent of the 25 vessels included in this study are Ro-Pax ferries.

Majority of the fire started on-board without collision. Only in 2022 two Ro-Pax fires have been published in the international news: Olympia on the 18 February (Figure 1) and Stena Scandica on the 29 August (Figure 2). In all the recorded cases the incident posed a great threat to the passengers due to the large number of them onboard, the number of different assets, the presence of hazardous chemicals. External factors (meteo conditions) played a fundamental role with an impact on external emergency services. Emergency management activities and communication among the crew and from the crew to passengers, coupled with a non-complete efficiency of fire detection and fire protection system also have been recorded as escalation promoting factors.

It is possible to say that many cases show accident dynamics and root causes entirely similar and therefore worthy of further investigation.

Figure 1: Olympia fire (©Ansa)

Figure 2: Stena Scandica fire (©Il Mattino)

The testimonies that are often recorded are particularly effective in portraying the severity of the fire and the vulnerability of the occupants: *"It looked like the apocalypse, a scene I hope in my life never to see again, people climbing on anything because their feet were burning, the soles of their shoes were melting on the hot metal sheets, a crowd gone mad"* (Norman Atlantic disaster, [2022]).

This awareness led the development of a number of experts working groups for the study of fire risk and fire safety strategies aboard this kind of vessels. Activity is focusing on observed similarities among the incidents, taking advantage of specific insights, often supported by experiments, simulations, etc.

Fire risk management aboard "Ro-Ro" ships can be managed considering a number of different insights, gained by different paths and with proper methods, as suggested by risk management standards such as (ISO, 2018) and (IEC, 2019):

- lessons learnt from real accidents;
- risk assessments;
- full-scale experiments and drills.

Methods include simulations and modelling with specific tools, eventually used in combination, to investigate specific aspects.

The purpose of this paper is not to detail the activities conducted in the three approaches followed, but to show how an integral approach can ensure a better understanding of the issue. In fact, it is assumed that the issue may become even more urgent if one considers the increasing size of ferries, the expansion of fleets, the use of new fuels (LNG, ammonia, etc.), the indirect pressure of commercial needs, and the consequent desire to proceed as far as possible with the journey times and preparation times.

In particular, some insights will be presented and summarized related to:

- a root cause analysis of a real incident and the activities subsequently conducted to understand alternative scenarios as conditions change;
- an evacuation full-scale drill;
- evacuation simulation activities performed by a specialized tool.

Therefore, both aspects related to fire dynamics and aspects related to emergency evacuation of passengers will be covered.

TRAGEDY

The Norman Atlantic fire: brief description of the incident

The ferryboat Norman Atlantic (Figure 3) was an Italian ship rented by a Greek company for ferry crossing between the two countries.

Figure 3: Norman Atlantic Ro-Ro cargo ship

The night of the incident, the route Patras – Igoumenitsa – Ancona was planned, and 55 crew members were on board. Incident lasted for several hours, days in the inner decks, and showed, since the beginning a significant severity, resulting in emergency services difficulties (Figure 4) and extensive damages (Figure 5).

Figure 4: Ship during the emergency

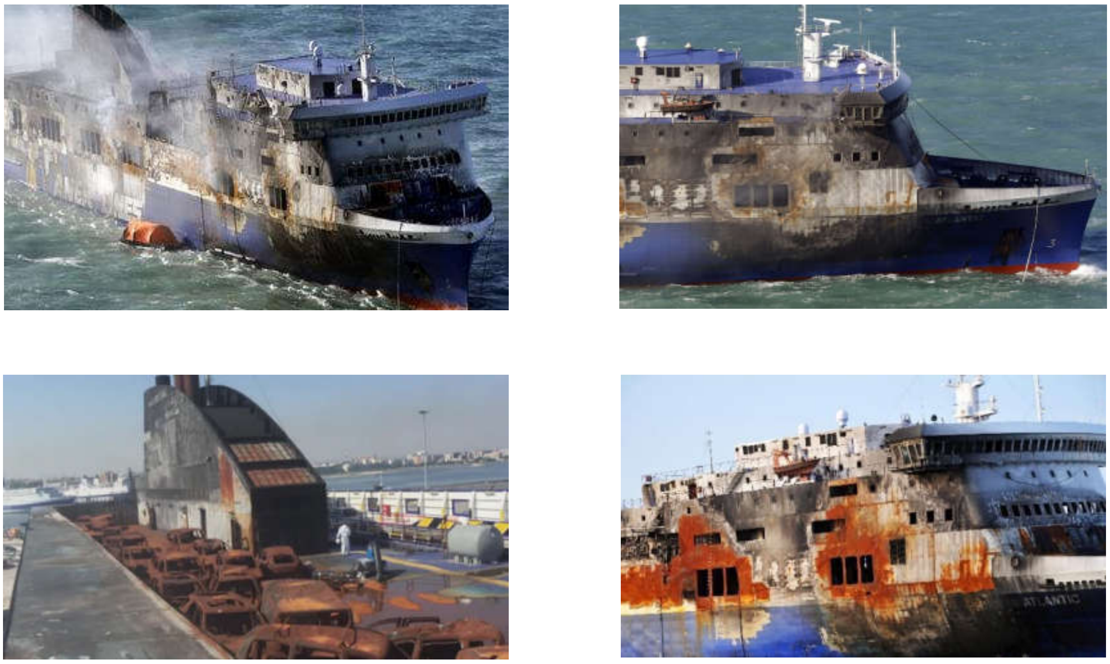


Figure 5: Resulting damages

When leaving from Igoumenitsa to Ancona, at 23.28 of 27/12/2014, the cargo consisted of about 130 heavy vehicles, 417 passengers and 88 cars. The navigation was regular until 03.23 (UTC), when the fire alarm sprang into action on deck 4, near the frame #156. Because of a smoke sighting coming out from the lateral openings of the deck, a sailor was appointed to carry out an inspection on deck 4. He referred that the alarm was attributable to the smoke coming from the auxiliary diesel engine belonging to a reefer truck, which was not connected to the electrical supply of the ship. After few minutes, at 03.27, the Master brought himself to the flying bridge deck on the starboard side and observed the flames coming out from the openings of deck 4. The 1st Engineer Officer activated the manual deluge system (known as "drencher"), following the Master's order. Meantime, the Chief Engineer Officer and his personnel abandoned the Engine Room because of the excessive smoke, while the two engines of the ship stopped definitively. The ship went in a black-out and the emergency generator, placed on deck 8, was incapable of providing energy to the emergency utilities, including the emergency pump. At the same time, the cooling team uselessly tried to cool the deck 5, but steam came from the fire hoses, instead of liquid water. The emergency management, especially during its first stages, revealed as chaotic. During the rescue operations, some passengers fell into the sea, while others threw the remaining life rafts in the sea, with no possibility to properly use them. At the end of the Search And Rescue operations, 452 people were rescued, including 3 illegal immigrants; 9 victims and 14 lost in the sea were also counted. The ship was then tugged to Bari, where it has been under the lens of the investigators. Main timeline of the incident initial phases is given in Figure 6.

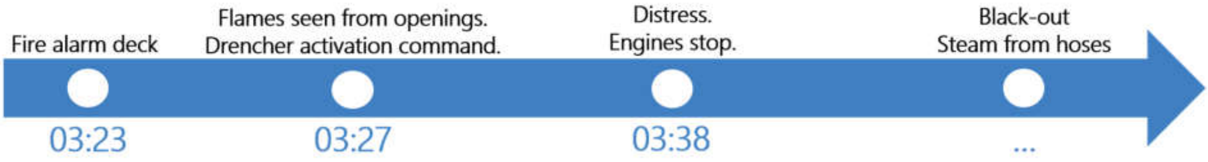


Figure 6: Timeline of the initial phases of the incident

Fire investigation team, goals and methodology

The reconstruction of the facts that led to the Norman Atlantic fire, including its dynamics and the research of the root causes, has been based mainly on the data from the Voyage Data Recorder (VDR), the testimonies from the interrogatories, the documentations taken on board and from the ship-owner, the transcription of the audio communications, the census operations about the vehicles on garage decks and the collected evidence. The investigation team, appointed by the Court, aimed at better conducting its tasks, was divided into 5 sub-teams to face the following five topics, which resulted critical since the beginnings: vehicles embarkation, evacuation and emergency management, fire dynamics, ship automation and onboard IT and electronic plant design. In this essay, the topic addressed is "the fire dynamics", and the relevant investigation aspects related to it. The used approach was multidisciplinary, to face such a complex system (i.e. full of relations and interconnections, as the "ship" system is, because of the crew, a chain of command, procedures, alarms, plant-men interfaces, and so on).

The method required constant comparisons and sharing the results among the different sub-teams. On the fire topic, the investigation activities were aimed at finding its causes, the most probable source of ignition and its location onboard, including those elements that facilitated its propagation, to reconstruct the fire dynamics and the reasons why the safety systems were ineffective. The "conic spiral" has been the pursued methodology. The first useful information has been extracted from the already-known data (available using the original documentation), to delineate the "stage zero" and to define a first distinction between what was necessary to examine in depth through further investigations and what was not of interest. The investigation scope has been made smaller by repeating this basic step, focusing the attention on the details progressively emerging. Regarding the fire, the investigation team was made up of B. Chiaia (Team Leader), L. Marmo (expert in chemistry and fire dynamics), L. Fiorentini (expert in advanced simulations in Computational Fluid Dynamics) and R. Sicari (expert in firefighting system in the maritime industry). Moreover, the multidisciplinary approach often required to interface with A. Cantelli Forti (expert in digital memories for maritime apparatus).

Root Cause Analysis: immediate and root causes of the incident

The team performed a Root Cause Analysis (RCA) to investigate the Norman Atlantic Fire. The recursive questioning of "why", starting from the "main event" (i.e. the Norman Atlantic Fire), has brought the team in driving the investigation, including the collection and the analysis of the evidence, to find the immediate and the root causes of the incident. It is outside of the scope of this paper to illustrate the outcome of the RCA in its entirety since the derived logic tree has several ramifications, whose immediate causes embrace different types of human errors and whose root causes involve both design aspects and the fire safety management system. It is clear that the main event has been the consequence of the failures of different sets of safeguards, which are now discussed. The fire dampers for the garage ventilation were found opened, so favoring the fire propagation to the other decks different from the 4th, where the fire started. One contributory cause is the positioning of the local commands for closing the dampers: indeed, the majority of them is placed on deck 4, and only a limited number of them can be controlled remotely, in a safer position. The possibility of continuing to feed the drencher system (manual deluge) after the occurrence of the blackout is guaranteed by the emergency pump, which never started. This was because of the emergency generator that, even if its engine started, was not capable of supplying the energy to the final utilities, because of an electrical fault due to the propagation of the flames in other spaces of the ship that damaged the electrical cables. Moreover, it should be noted that even a correct supply of energy during the blackout at the emergency pump could not pump the water inside the garage deck because the intercept valve between the emergency pump and the drencher collector was found closed. The managerial causes (related to the internal procedures, habits, and so on), if any, of this singular context, will be probably clarified during the trial. However, even if the intercept valve would be found open, the zones activated by the operator in the drencher room (i.e. the valve house, where the distribution of the drencher water is set) were wrong. Indeed, the four zones activated were on deck 3, while it is clear that the fire should be faced on deck 4 (as correctly ordered by the Master). A possible contributory cause is the drencher plan, provided as documentation inside the drencher room to the operator that intends to activate the system. In this scheme, the decks of the ship are named with their English names (e.g. deck 4 was named "Weather Deck"), while the order given by the Master was to "activate the drencher at deck number 4". Therefore, there is not a full alignment between the order of the Master, that needs to be elaborated, and the documentation available in drencher room. Also, the plan contained some errors in locating the drencher room on the "weather deck" (deck 4) instead of the "main deck" (deck 3), where it actually is.

The confusion increases if we think that a "weather deck" is, by definition, an open deck, while in all the technical drawings of the Norman Atlantic this terminology was referred to the deck 4, a closed deck with openings just below the open deck (deck 5).

However, even if the drencher would be activated at deck 4, the operator opened 4 zones versus the maximum allowable of 2, according to the drencher manual, to ensure its extinguishing performances: this incorrect operation could be addressed to an ineffective training. However, the timeline reconstruction of the event and the advanced simulations in Computational Fluid Dynamics (CFD), conducted with FDS with the support of Pyrosim, revealed that even a correct activation of the drencher system would not have extinguished the fire, but only controlled it, because of its belated activation.

The reasons for such late intervention are mainly attributable to a self-evident underestimation of the problem by the crew. Indeed, regardless the alarms provided by the Fire Detection System, the order of the Master to activate the drencher arrives when the fire is already fully developed, and the flames come out from the openings of deck 4.

The outcomes of the inspection conducted by the sailor at deck 4 are the main cause of this underestimation. Indeed, the inspection was required because of some uncertainties over traces of smoke coming out from the openings of deck 4, which were confused with reflections of the sea. The inspection was also hurried because of the difficulties of the sailors (not fit for purpose) in passing through the narrow spaces between the heavy vehicles. At the end of the inspection, the sailor clarified that the alarms detected at the bridge were attributable to the smoke produced by the auxiliary diesel engine of a reefer truck. The crew members, being aware of this illegal practice, accepted it overestimating their capability to take under control such a hazardous situation. Being alerted by other alarms, the 1st deck officer asked the sailor to perform a further inspection, but this was deliberately never carried out

The Root Cause Analysis revealed that the crew members agreed in having reefer trucks not connected to the electrical supply of the ship, because they embarked a higher number of reefers respect to the number of available reefer sockets, violating the prescription of a correct embarkation for commercial purposes.

Finally, the flames, the smoke and the alarms recorded are all consequences of the first hotbed in deck 4 that the sailor did not find during his inspection.

The malfunction of an auxiliary diesel engine of one of the loaded vehicles can be considered the most likely cause for the ignition. This probability must be regarded as higher for those vehicles equipped with an auxiliary diesel generator at the service of the refrigerator system or at the service of the oxygen pumping in the water tanks for the transportation of alive fishes.

The usage of these diesel engines is forbidden inside the garage of the ship, because they should be used only when the vehicle is in motion, being cooled by air.
The trucks, the oil in their tanks and the olive oil (including pomace) transported by some of them represented the combustible materials.
The openings of deck 4 continuously provided the oxygen, arising serious questions about its design.

Therefore, the fire triangle was satisfied.

Main elements of the RCA are summarized in Figures 7, 8, 9, 10, 11, 12, 13, 14.

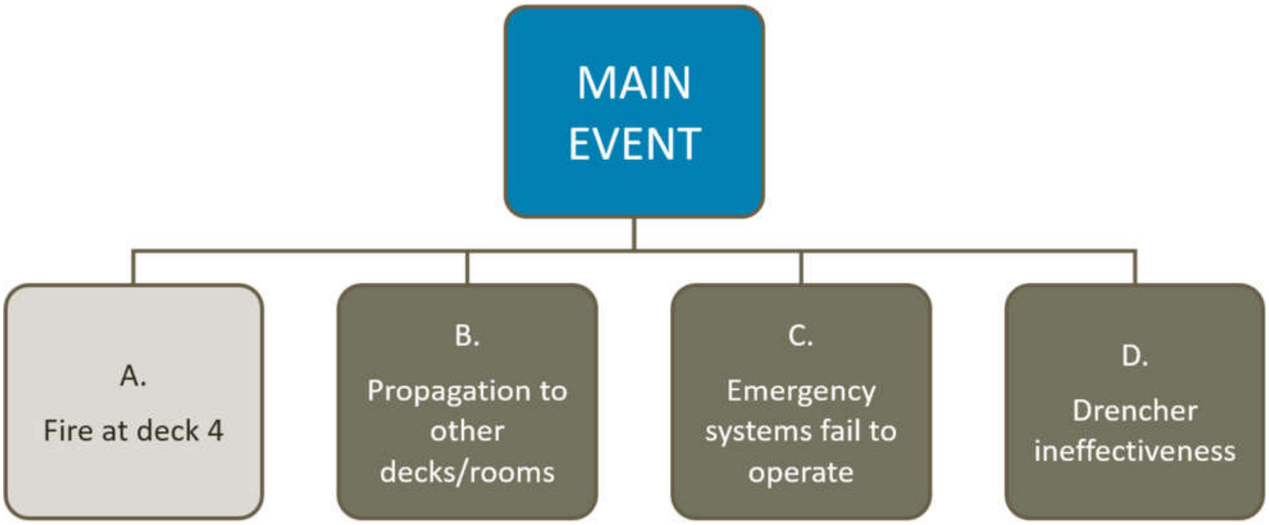


Figure 7: RCA scheme 1/8

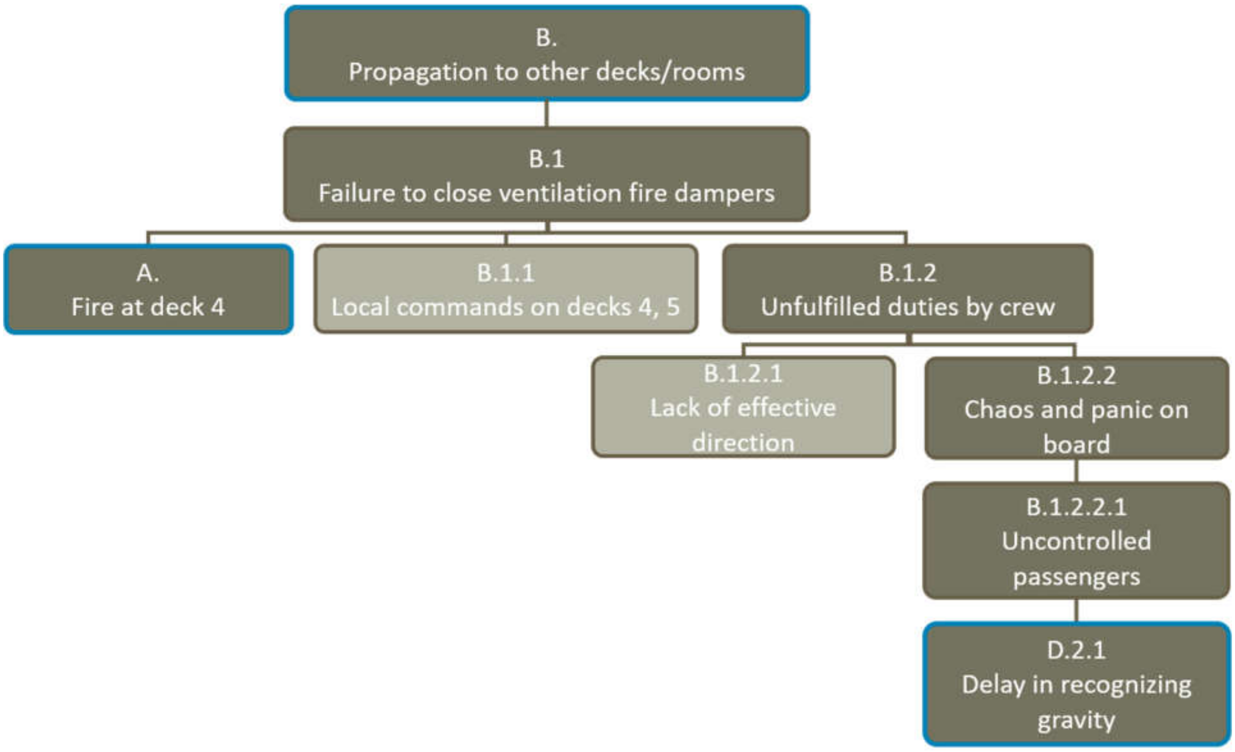


Figure 8: RCA scheme 2/8

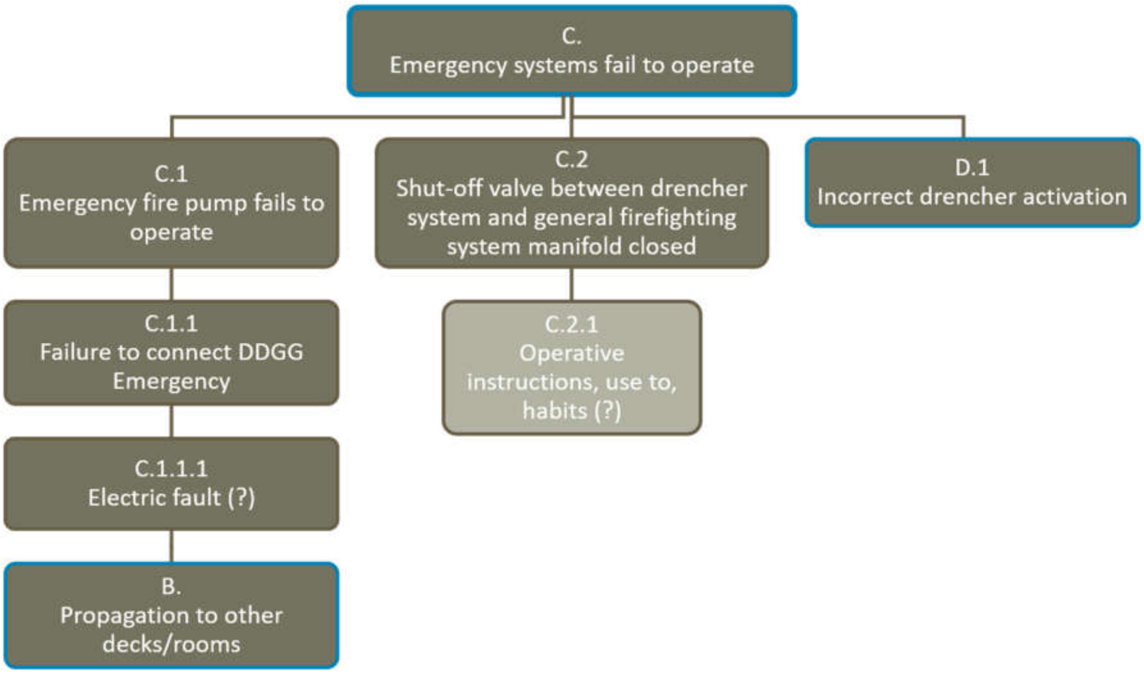


Figure 9: RCA scheme 3/8

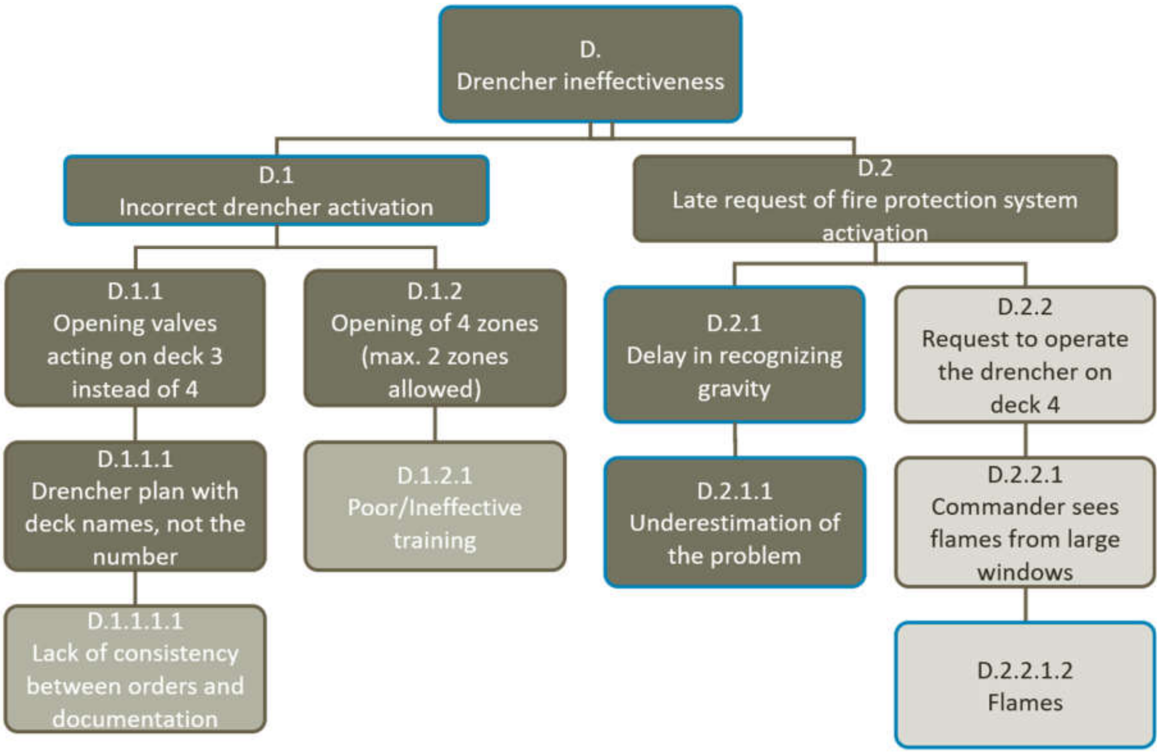


Figure 10: RCA scheme 4/8

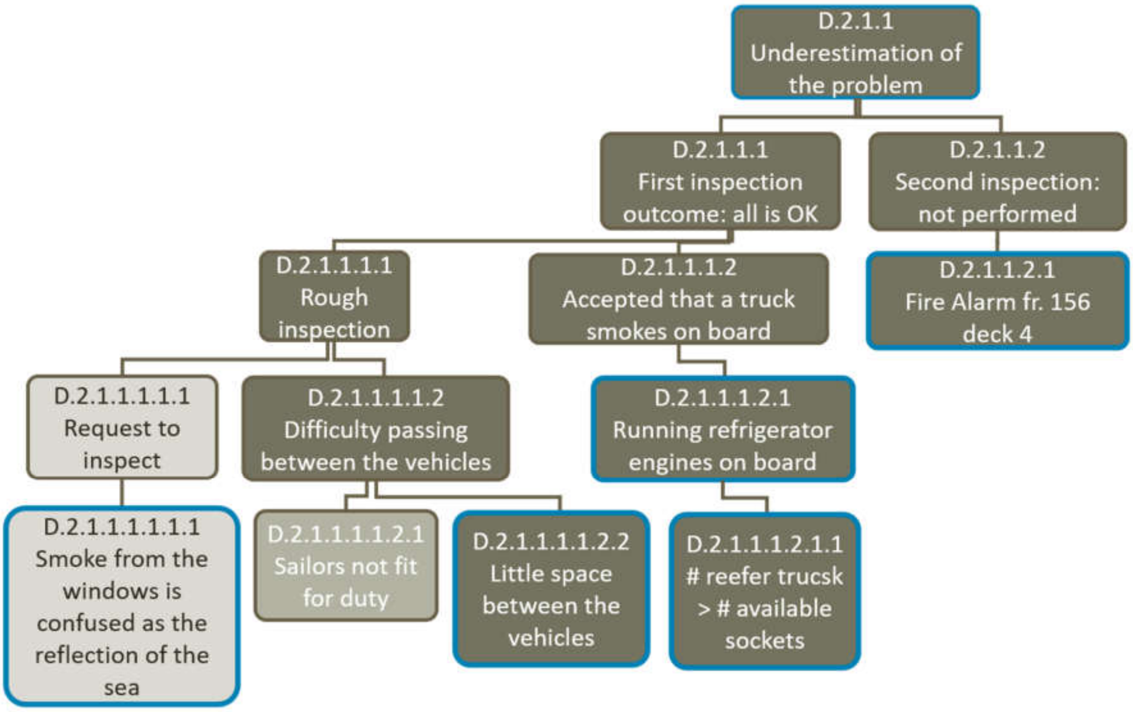


Figure 11: RCA scheme 5/8

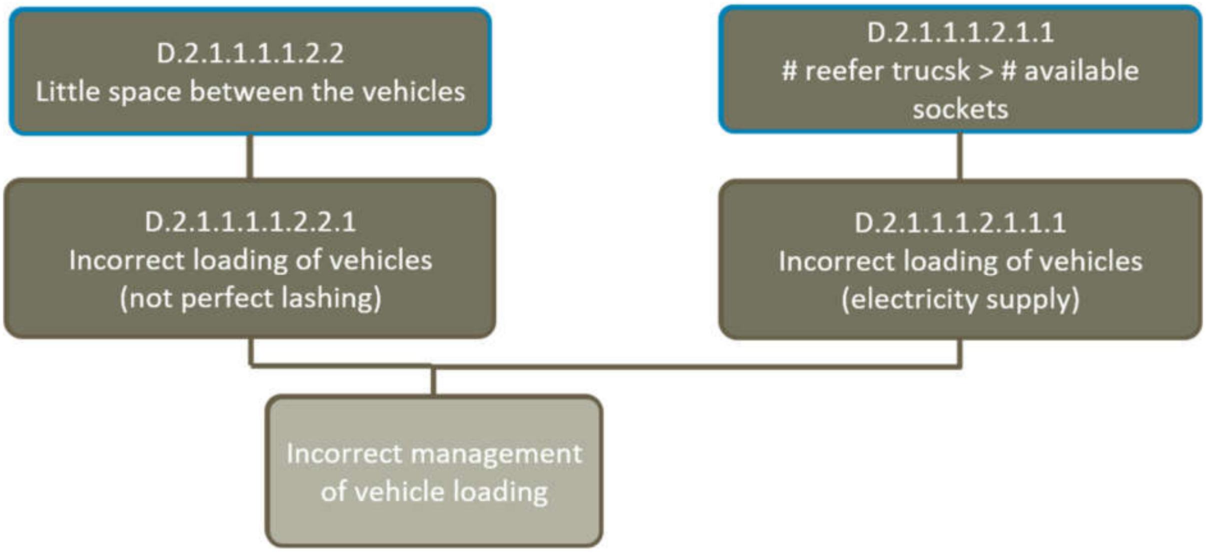


Figure 12: RCA scheme 6/8

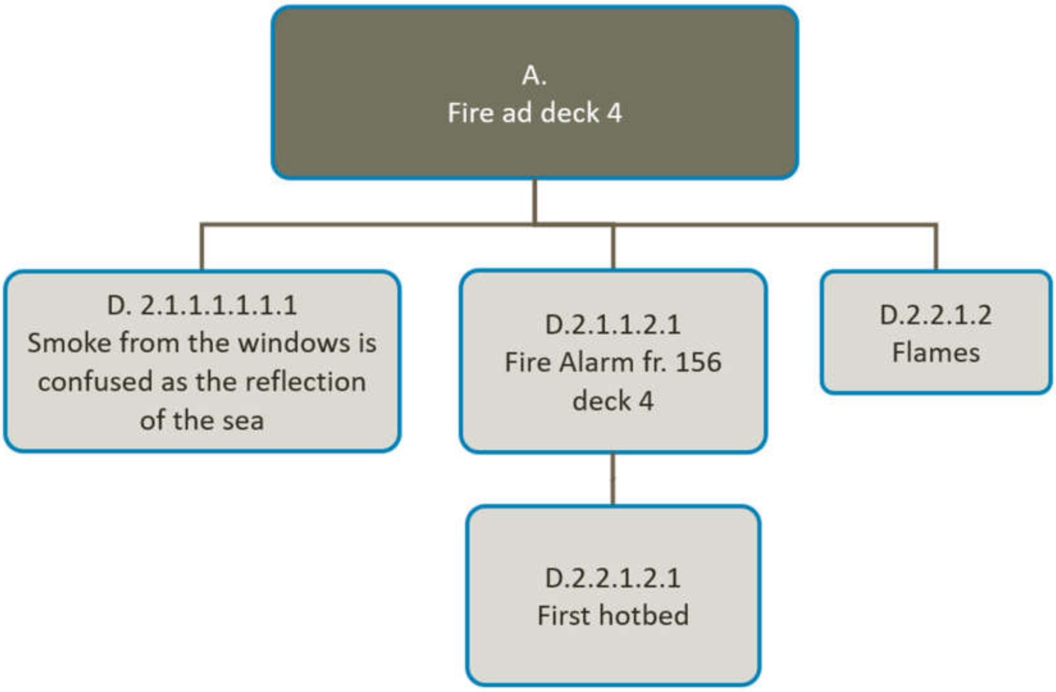


Figure 13: RCA scheme 7/8

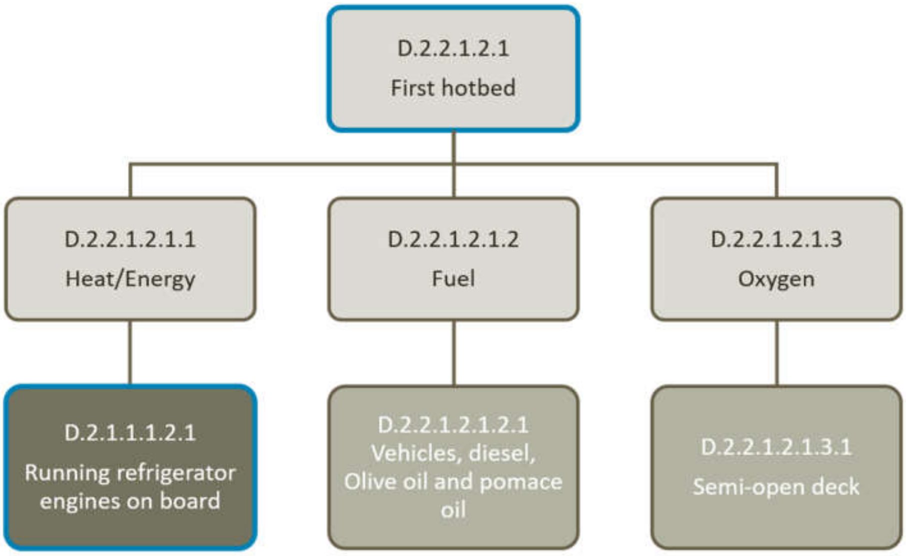


Figure 14: RCA scheme 8/8

RCA results

Root Cause Analysis led to a number of specific insights and, starting from identified immediate causes (Figure 15) it has been possible to select some important root causes (Figure 16).

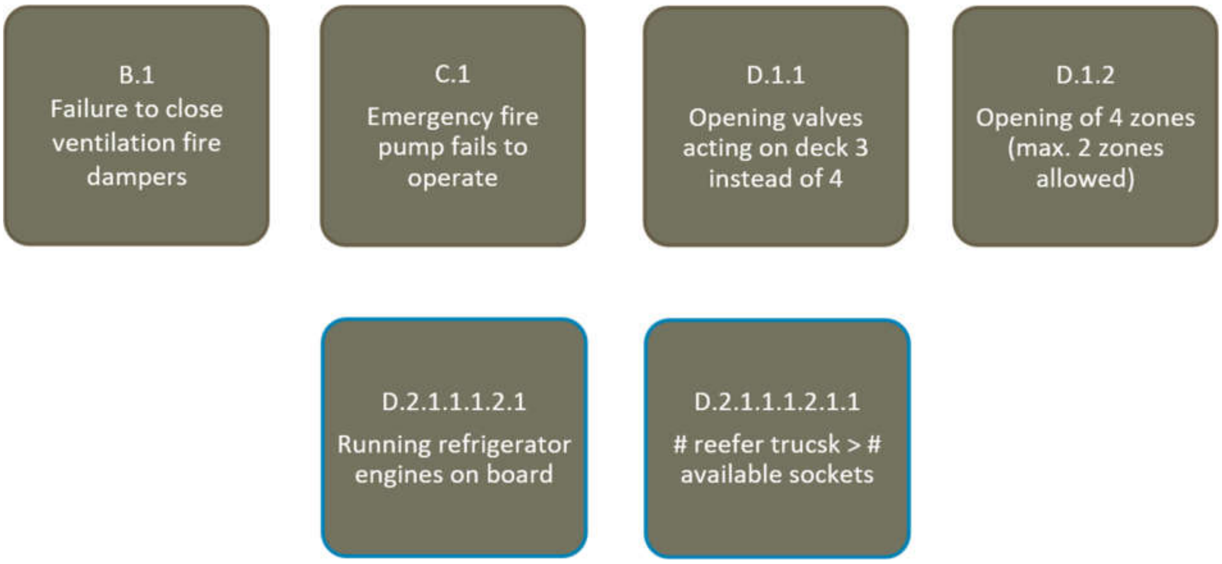


Figure 15: RCA - Immediate Causes

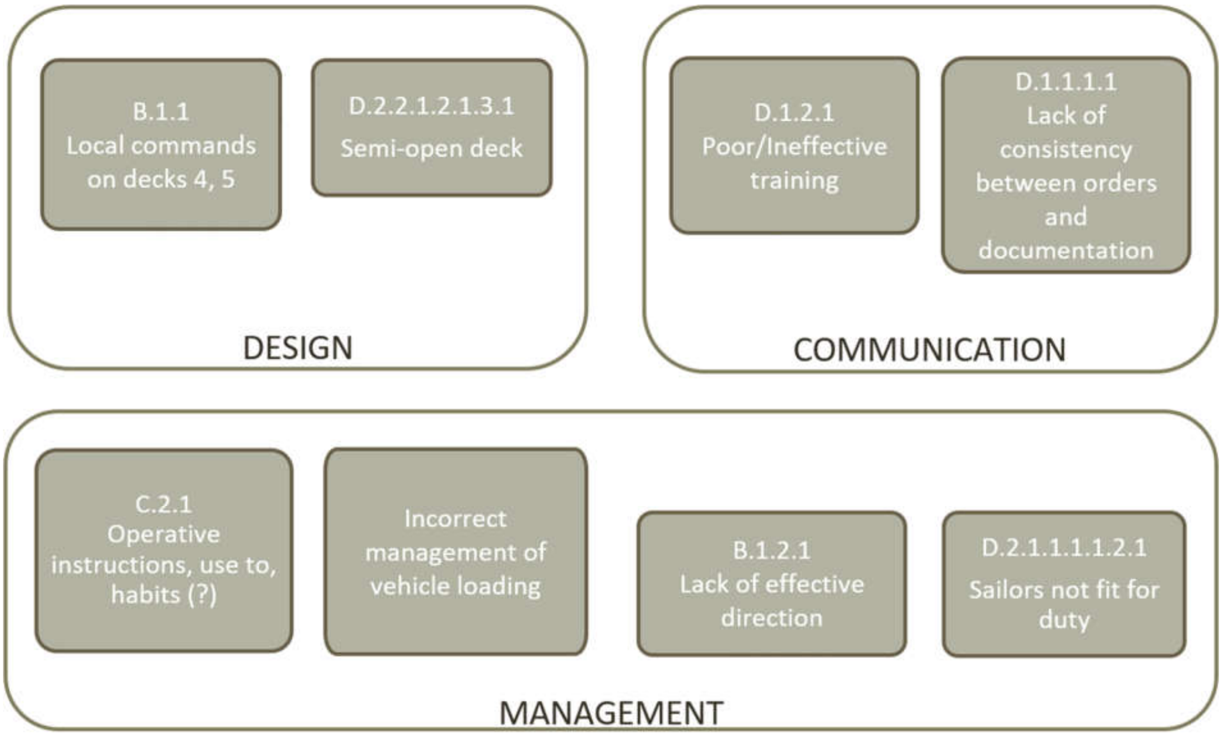


Figure 16: RCA - Root causes

The complexity of the Root Cause Analysis underlines the applicability of the Reason's Swiss Cheese Model: safeguards are not reliable 100% and when their ineffectiveness (i.e. their probability of failure on demand) align, then a hazard situation may become an incident.
It happened with the embarkation, the inspection, the drencher, the emergency pump, the emergency generator and the dampers, but, as the root cause analysis reveals, they are all attributable to an inherently weak fire safety management system.

The root cause analysis identified some significant and intrinsic engineering weaknesses, also related to the high probability of human error, even if the drencher system, by the law, is compliant with the applicable regulations and technical requirements.

Several root causes have been identified and they can be related to design and technical aspects but also to communication and management aspects that belong to behavior, competency and culture. Those aspects played a fundamental role both in the origin and in the escalation (with resulting severity) of the incident. The effects of the fire and its dynamic have been verified, as anticipated, with physical effects modelling conducted with the use of Fire Dynamics Simulator supported by Pyrosim.

Numerical simulations in CFD and developed recommendations

The limited arc of time between the first alarm at deck 4 and the other decks is very short (e.g. 3 minutes between deck 4 and 5) but not incompatible with the extensive technical literature available. Moreover, this rapidity also emerged from the numerical simulations, that have been carried out to validate the hypothesis advanced during the first stages of the investigation.

Four different simulations have been performed, after having created the simulation domain (Figure 17) on the basis of the ship design and of the evidences collected about the cargo load during the forensic operations (Figure 18)

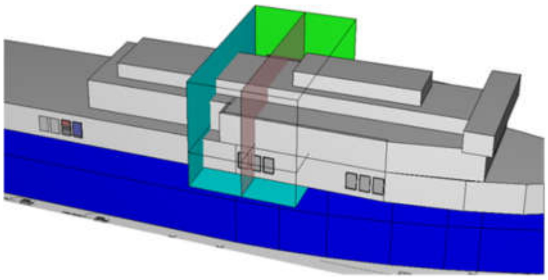
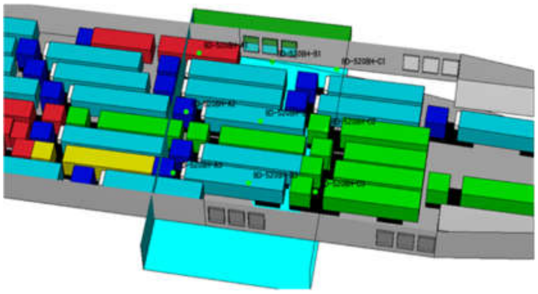


Figure 17: Simulation domain



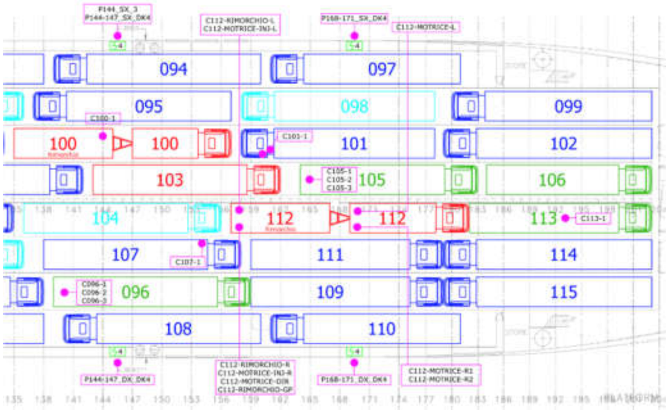


Figure 18: Cargo load

A view of the garage area, as an example, in the fire CFD simulation is given in Figure 15.

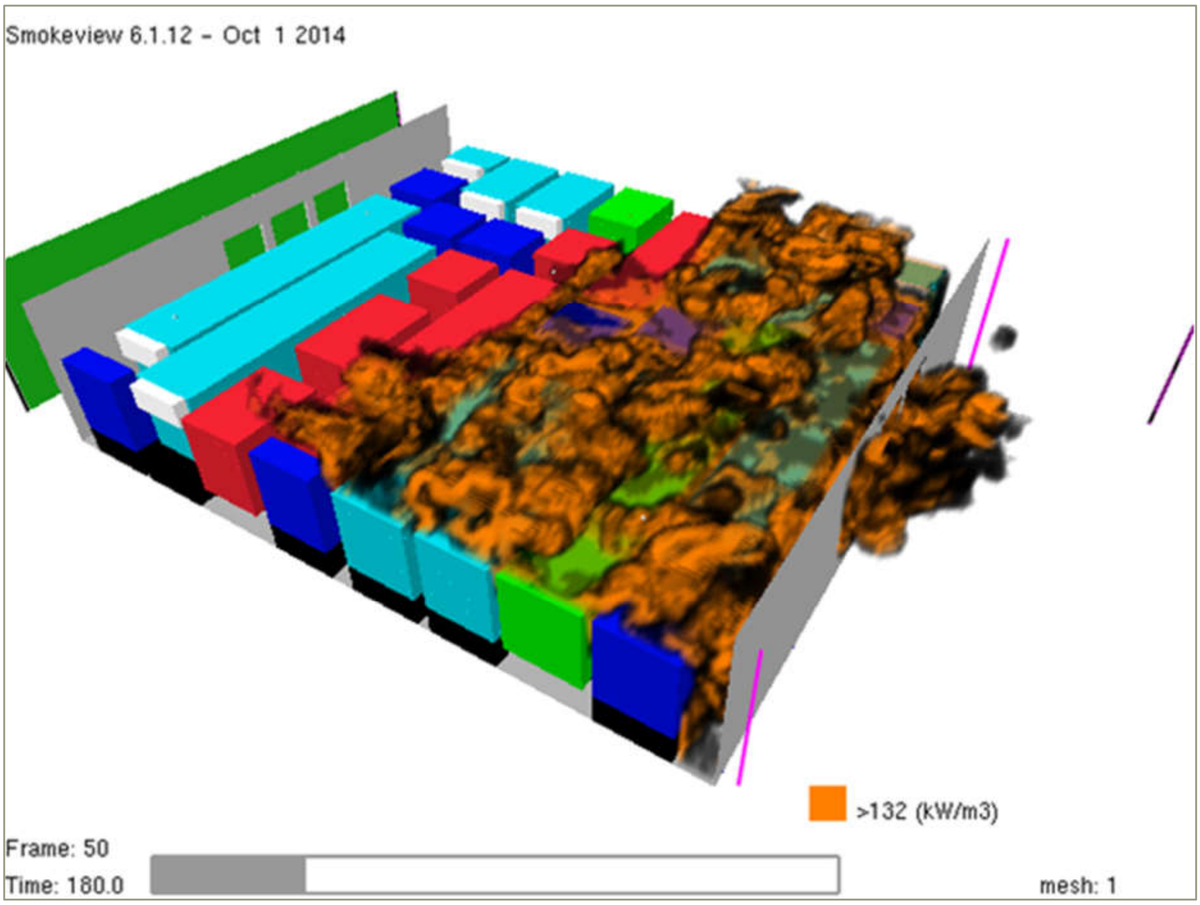


Figure 19: CFD simulation

The first one was used to calibrate the Heat Release Rate of a single isolated heavy vehicle, with a load comparable to what found on average during the census and unloading activities.

The other three simulations, confined in a domain over the frame 156, have been addressed to: study the expected outcome of the Fire Detection System, through its smoke and heat detectors; simulate the real fire on deck 4, taking into account the relative wind and all the vehicles inside the simulation domain; study the propagation of fire at deck 3. The simulations allowed to verify, together with the physical, digital and documental collected evidence, the thermal stress propagation hypothesis, the timeline sequences of the main events, the capability of the drencher system and the time of activation of the fire alarms.

The simulations revealed that only a prompt and correct activation of the drencher system over the area of the first hotbed would have allowed to control the fire and avoid its propagation. The missed prompt activation of the drencher system determined a serious spoiling because the thermal regimes that tended to arise are capable of involving a significant part of the flammable material present in the area into the fire. It also caused critical damages to the structures, both for thermal radiation and for flame engulfment, with temperatures higher than the critical ones distinctive of the used materials.

The state of the areas and the timing of the investigation respect to the event did not allow to find certainly the origin of the flames. The fire dynamics, extremely rapid, could be however compared to a typical dynamic in heavy vehicle fleets.

Given the insights gained with the structured investigation conducted using the RCA it has been possible to verify alternative conditions of fire and its physical effects through the development of different scenarios that the actual scenario shown recorded in the incident. In particular it has been verified the variation, from the incident recorded fire dynamic, in terms of Heat Release Rate given different conditions (single and combined):

- fire protection deluge system (drencher) activation in 120 s;
- absence of severe meteo conditions (no wind across the decks openings);
- increase fire water density discharge (up to 90 l/min).

Some tested cases showed up to a 60% mean reduction of the HRR curve (Figure 20).

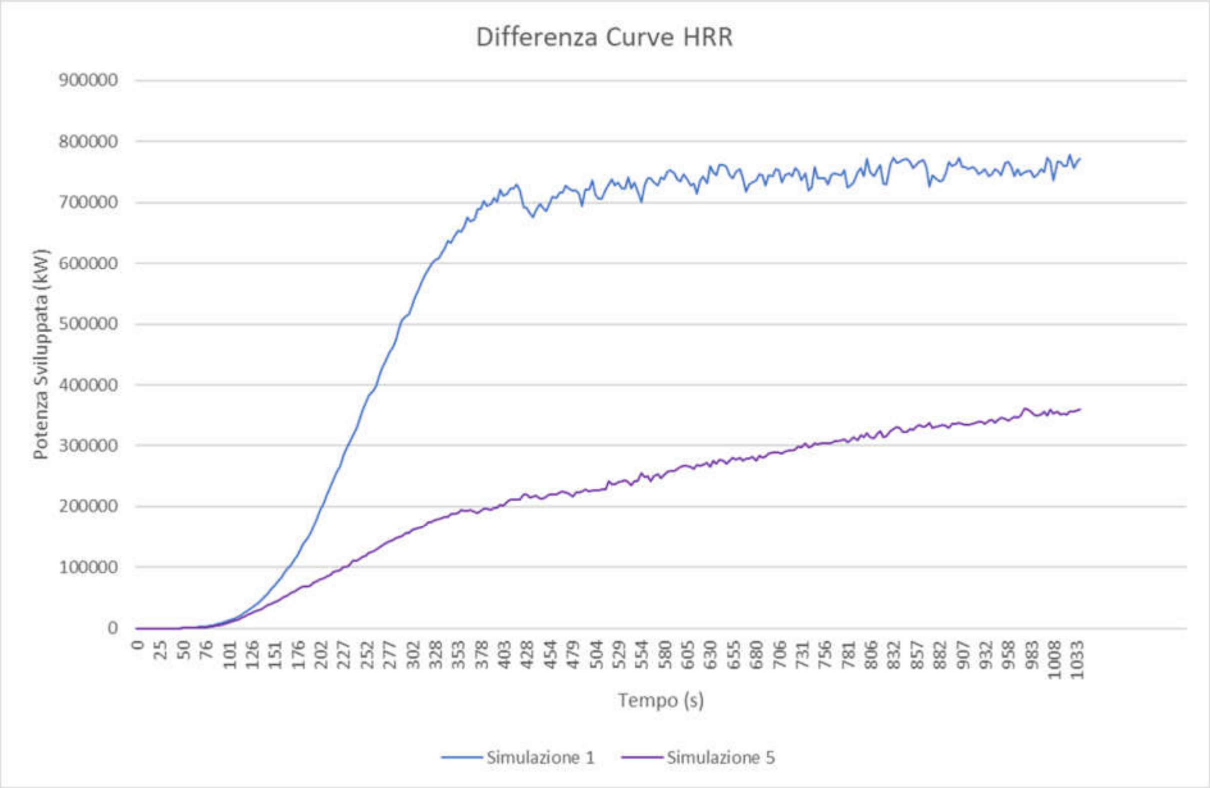


Figure 20: Example of comparison of the actual HRR curve with the alternatives considered

This activity allowed to identify, given different conditions, variations in the fire scenario and to make an estimation of the weight of the single factors that played a fundamental role considering the RCA results.

Apart from the activity conducted on behalf of the Court it has been possible to identify some recommendations to improve fire safety, as automatic activation of the deluge system, closure of the decks opening (done later on in a similar ship), installation of a ventilation system to guarantee air exchange rates as per regulation requirements. It is useful to say that from the first information coming from the recent fire event of Stena Scandica, a ship similar to Norman Atlantic, the recent closure of the decks opening helped in reducing the severity and speed of the event: *"Fortunately, there were no injuries or worse, but for many, the mind went to the Norman Atlantic, twin sister of the Stena, which burnt down along the Apulian coast in 2014 causing 32 deaths. After the tragedy, the Stena was refurbished and large windows were closed on the car deck because this type of ferry had already been the subject of several accidents in the past linked precisely to the development of flames on board, which always started from the car decks. The large windows in the event of a fire in fact let in air and wind, fanning the flames"* (Svezia: traghetto prende fuoco con 300 persone a bordo, la situazione » Scienze Notizie, 2022).

Similar approaches have been applied to other accidents in order to derive information about fire dynamics or passenger evacuations, e.g. the insights developed for Costa Concordia (Kvamme, 2017).

Further details

More details about the incident and the investigation conducted by the Court experts can be found in the official investigation documentation and in (Fiorentini and Marmo, 2021).

FULL SCALE FIRE EVACUATION DRILL

A fire event on a similar ship, a full-scale drill, organized on the 17th of February 2022 in Messina by the Fire Brigade and carried out involving all the local authorities. The evacuation simulation specifically concerned a fire on the car deck. The aim of the exercise was to test evacuation procedures for all passengers, with particular regard to people with special needs. In order to better coordinate the simulated emergency operations, the Prefecture of Messina also activated the regional center for emergency and the area emergency plan. All emergency services, including voluntary associations, took part in the drill. Scope of the drill was not to test emergency fire management technical capabilities by the crew or the external agencies, while the full-scale drill focused on the importance of coordination, synergetic approach and identification of passengers with special needs. It is fundamental having rescuer's knowledge of special needs for better emergency management and effectiveness in rescue.

Ro-Pax vessel

Ro-Pax vessel “Trinacria” (Blueferries) has been used for the drill (Figure 21). This ferry operates in the Messina strait among Calabria and Sicilia.

Figure 21: Ro-Pax "Trinacria"

Operation of this lane is conducted all the year with different meteo conditions (Figure 22).

Figure 22: Different meteo conditions in the Messina strait

Ro-Pax (Figures 23 and 24) has a length of 210 m, it is 17,20 m high with 4 different decks, a width of 18 m. It has been supposed a gasoline fire from a leakage from a tank truck onboard (in red the loss of containment point in Figure 23).

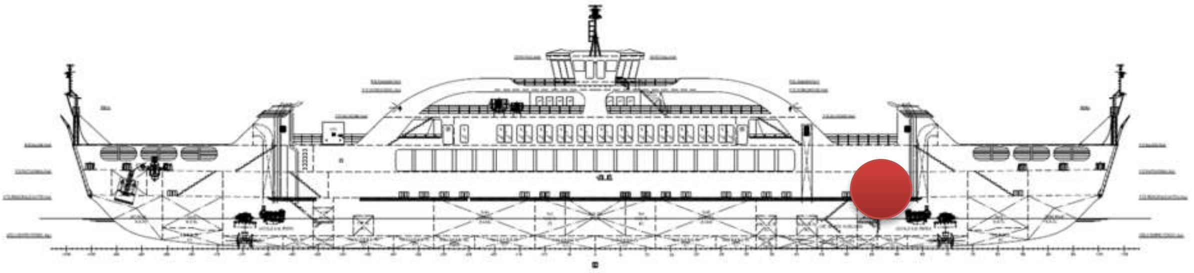


Figure 23: Ro-Pax View 1

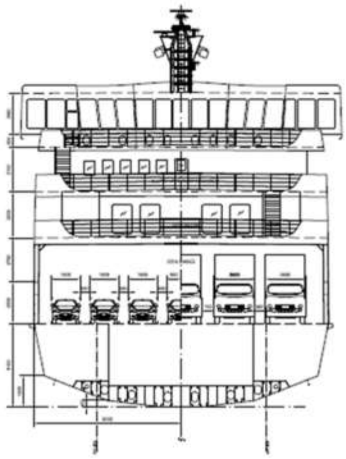


Figure 24: Ro-Pax View 2

Timeline of the drill and goals

Timeline of the event is given in Figure 25.

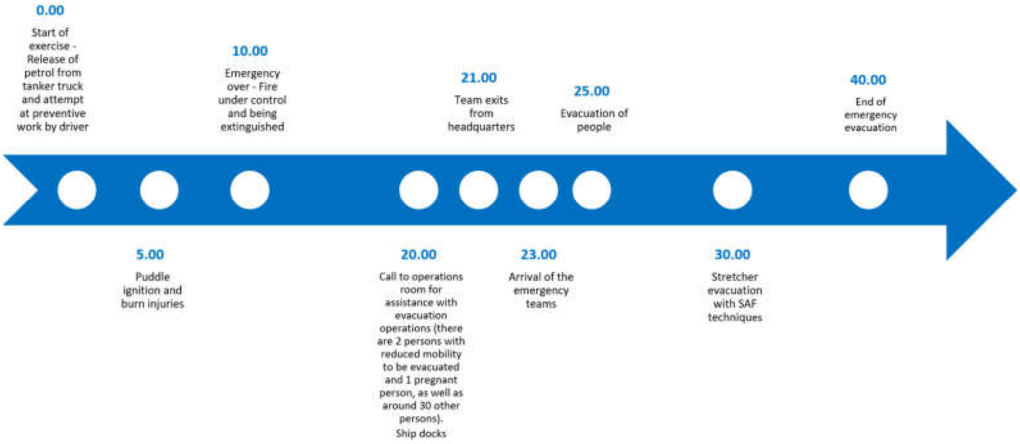


Figure 25: Drill timeline

Goals of the drill:

- synergy/coordination in a multi-agency emergency context;
- overall assessment of people evacuation;
- rescuer's approach evacuation procedures for people with special needs.

Drill

Images of the drill are given in Figure 26.

Figure 26: Drill phases (©Vigili del Fuoco)

Lessons learnt

The full-scale emergency drill allowed to identify some specific lessons in different areas, concerning the emergency management activities: those conducted by the onboard crew and those conducted by the authorities having jurisdiction. It has been important to identify, in a full-scale exercise, the main components of the human behavior in emergency situations, a topic very well known to Vigili del Fuoco agency that should become a point of discussion to raise the awareness in other supporting agencies for large and complex situations: occupants characteristics, fire and combustion products effects, movement, decision processes, human response to communication and signals.

Main lessons, in the field of "culture, behavior and competency" can be summarized in:

- dangerous goods pose a severe threat to occupants and to the vessel, a prompt response is fundamental, especially in all those cases external emergency services may not be readily available;
- importance of initial and prompt emergency management onboard due to the serious risk of fast escalation of an incipient fire also due to external conditions (e.g., meteo);
- crowding of passengers in specific areas of the ship can modify in a substantial way the evacuation to safe location, therefore specific training of the crew to manage high density areas is needed;
- triage activities in port are fundamental in order to have passengers needs priority, an initial level of priority should be defined onboard, before the arrival of external emergency services in order to speed up the unloading process;
- specific needs (eventually connected with disabilities) should be known in advance;
- crew should be trained to understand physical and mental disabilities in order to assist passengers effectively before the arrival of specialized teams;
- layout of the traditional ships may pose a severe threat to people having disabilities: those limitations, if not eliminated, should be known in order to guarantee a more effective emergency management;
- it is strictly advisable that several emergency scenarios are considered in order to guarantee that variations will cover the majority of the possibilities (including the location of the ship, the meteo condition, the partial availability of egress means, the late arrival of external emergency services due to meteo conditions);
- even if in port or taken to the port the ship evacuation due to a fire should be considered a large and complex emergency to be managed by a synergetic approach by authorities having jurisdiction with the coordination of all available resources; therefore specific drills, including table-top exercise should be planned at periodic intervals involving all the stakeholders;
- large scale experiments may provide meaningful elements to improve ship evacuation models conducted using simulation, also taking advantage by collection evacuation data. This is fundamental to understand how people behave in marine emergencies since still nowadays little data relating to passengers response time or full scale validation data in this environment exists. This data could integrate the IMO recommendations, as anticipated in (Galea, Brown, Filippidis and Deere, 2010) and later on confirmed in (Park, Ham and Ha, 2015);
- these experiments may help to understand actual evacuation times that, in a number of cases, such as in the Norman Atlantic fire, showed a large number of hours (Pospolicki, 2017);
- they can also raise the awareness about the importance of a multi-agency approach, as well as over national cooperation (for Norman Atlantic SAR activities three countries cooperated with a total number of 15 helicopters, 4 aircrafts, 5 patron vessels, 1 ship, 13 merchant vessels and 5 tugboats).

EMERGENCY EVACUATION SIMULATION

The study of accidents that have occurred has shown how the adoption of increasingly efficient and advanced technologies as well as crew training and the application of procedures are key aspects in safeguarding human life and property. Another crucial aspect is the use of technology and specialized software, which allow for multiple simulations in advance that can highlight any critical issues and/or opportunities. The use of software allows, for example, to simulate the evacuation of people in the presence of fire and/or in different conditions in which passengers and crew may find themselves (e.g., day or night) or analyze possible unavailability of escape routes.

The guideline (IMO, 2016) regulates evacuation analysis on ships through two distinct methods: simplified and advanced. The simplified method has its merits due to its relative simplicity and ability to provide an approximation to expected evacuation performance. However, as the complexity of the ships increases (number of decks, number of stairs, mix of passengers, and/or presence of accommodations), it is preferable to use an advanced method, through specific modeling software, which allows the limitations of the simplified methods to be overcome.

In the present case, the advanced methodology (IMO, 2016) was applied using Pathfinder software vers. 2022.1.0422, developed by software house Thunderhead Engineering Ltd. (USA) which uses an agent-based model (ABM) that allows capturing complex behaviors and interactions between occupants under the assumed emergency conditions.

The simulations were conducted by analyzing a two-way ferry ship used to transport people (399 passengers including 7 crew) and wheeled vehicles (150 cars or alternatively 23 TIRs). The Ro-Ro passenger ship has two access routes for vehicles and passengers located forward and aft, respectively, via a crew-operated hatch.

Passenger-usable spaces are distributed on 3 main decks: deck no. 3 for passenger and wheeled vehicle access, deck No. 4 where there are both outdoor and indoor spaces (dining area, toilet etc.), and deck No. 5 where there are both outdoor spaces usable by passengers and areas for the exclusive use of the crew (locker rooms, toilets and technical rooms). Decks no. 6 and 7 are for the exclusive use of the crew, specifically on deck No. 7 is the bridge. The graphical representation of the command bridge was omitted in the simulation, as it was not significant for the evaluation.

The geometric characteristics of the bow and stern are equal to each other in terms of both surface area and escape routes, both areas have no. 3 stairs connecting decks 3, 4 and 5. In case of an emergency, the ferry is equipped with a Marine Evacuation System (MES) located on deck No. 4. The system is simple and is so efficient that only one crew member is needed during deployment; the device complete with chutes and life rafts is ready for boarding in very few minutes. In the simulations, 180 seconds (3 minutes) were considered to make the evacuation system available.

The ro-ro passenger ship is equipped with No. 2 MESs equally distributed on each side of the ship placed on deck No. 4. In the model, the location of the MES is graphically highlighted with two red-colored "doors," which only after the system is in operation allow the passengers to evacuate. An outflow speed of people of 0,2 m/s was assumed in the model.

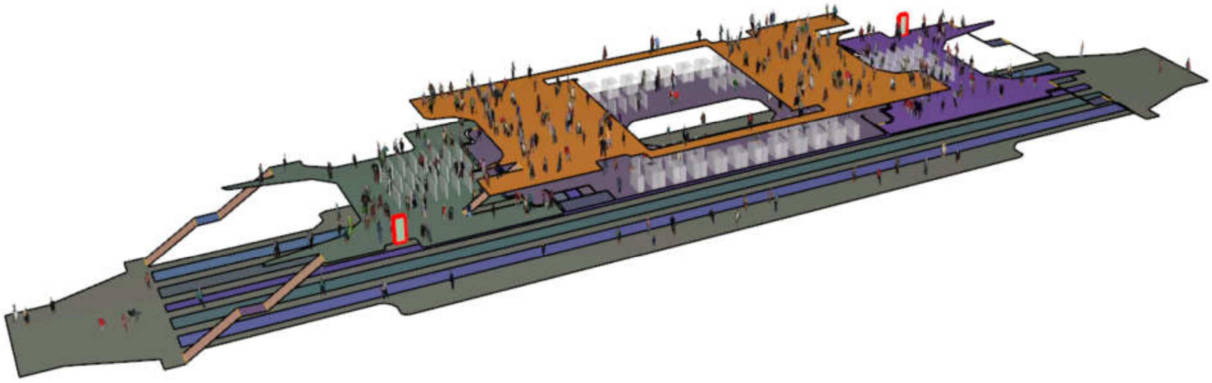


Figure 27: Model of the ship in Pathfinder

The analysis considers four scenarios, corresponding to the primary evacuation cases (cases 1 and 2, in which all escape routes are assumed to be in operation) and the secondary evacuation cases (cases 3 and 4, in which some of the escape routes are assumed to be unavailable).

In primary evacuation cases (cases 1 and 2): it is assumed that passengers and crew proceed along the escape routes and know the routes to the muster points; for this purpose, it is assumed that signage, lighting, crew training, and other relevant aspects related to the design and operation of the evacuation system comply with the requirements set out in IMO instruments.

In cases of secondary evacuation (cases 3 and 4): passengers and crew faced with an unavailable escape route are assumed to modify their behaviors by using all remaining available escape routes.
The guideline (IMO, 2016) states that at least 4 scenarios should be considered for the analysis: two in daytime condition and two in nighttime condition. In the specific case, the ferry ship only performs daytime service and has no cabins as the route in which it operates is limited to about 20 minutes of travel time. Therefore, in the present case, the significant variable that can affect an emergency situation is the distribution of people according to the season. In the summer period people are inclined to stay outside distributed on the various decks unlike the winter period which induces passengers to travel either inside their vehicles or in deck #4 where there is a refreshment area. The escape routes (ESMs) are located on Deck No. 4, an area where there is the greatest crowding of people.

CASE 1 DAY WITH ALL AVAILABLE ESCAPE ROUTES (SUMMER)

Simulation parameters
Crew - 7 people distributed in the space
Passengers people distributed as follows:
DECK 3 - 50 passengers
DECK 4 INSIDE - 50 passengers
DECK 4 OUTDOOR - 146 passengers
DECK 5 OUTDOOR - 146 passengers

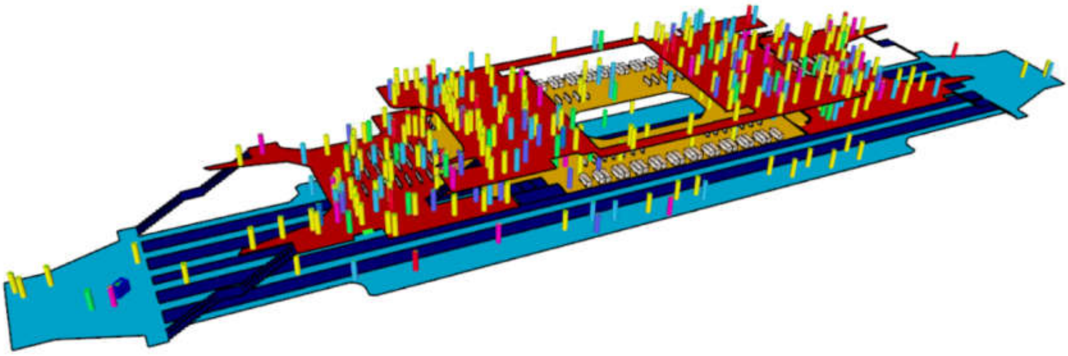


Figure 28: Model of the ferry ship case 1

Figure 28 represents one of the possible distributions of passengers. According to IMO 2016, a Monte Carlo approach has been adopted, running for each scenario 500 different simulations in which the distribution, speed, and of users vary according to algorithmic parameters that were set in the model.

In the second scenario analyzed (winter), people are more concentrated either in the ship access deck (garage) or inside in the bar/restaurant spaces.

CASE 2 DAY WITH ALL AVAILABLE ESCAPE ROUTES (WINTER)

Simulation parameters
Crew - 7 people distributed in the space
Passengers people distributed as follows:
DECK 3 - 150 passengers
DECK 4 INSIDE - 202 passengers
DECK 4 OUTSIDE - 20 passengers
DECK 5 OUTSIDE - 20 passengers

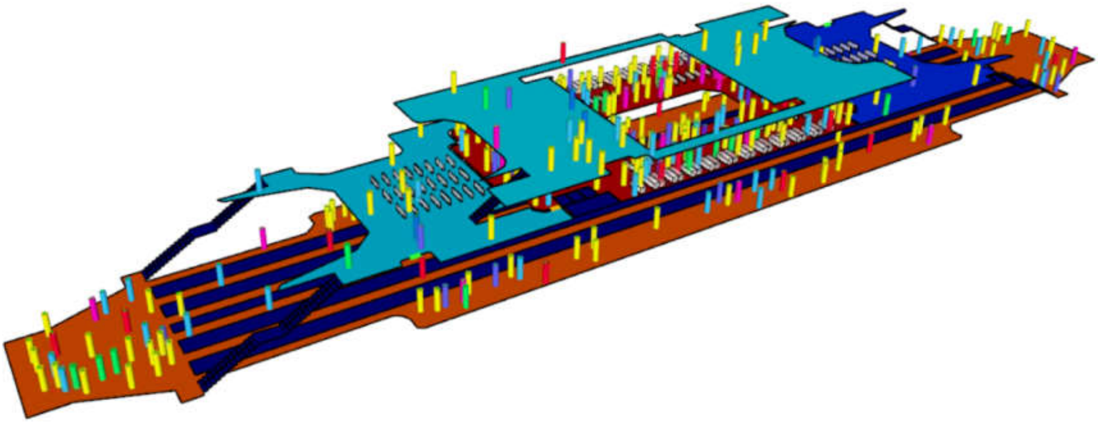


Figure 299: Model of the ferry ship case 2

The third case study, derived from the first scenario, analyzes the same situation (summer) by making an escape route unavailable. The simulation assumes that one of the connecting staircases between bridge 4 and 5 is temporarily out of service.

CASE 3 DAY WITH STERN ESCAPE ROUTE UNAVAILABLE (SUMMER)
Simulation parameters
Crew - 7 people distributed in the space
Passengers people distributed as follows:
DECK 3 - 50 passengers
DECK 4 INSIDE - 50 passengers
DECK 4 OUTDOOR - 146 passengers
DECK 5 OUTSIDE - 146 passengers

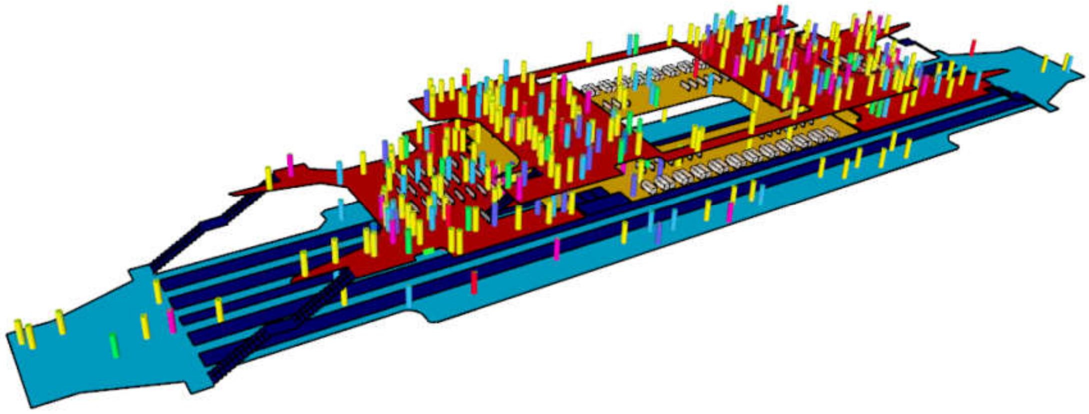


Figure 30: Model of the ferry ship case 3

CASE 4 DAY WITH THE FORWARD ESCAPE ROUTE UNAVAILABLE (WINTER)
Simulation parameters
Crew - 7 people distributed in the space
Passengers people distributed as follows:
DECK 3 - 150 passengers
DECK 4 INSIDE - 202 passengers
DECK 4 OUTSIDE - 20 passengers
DECK 5 OUTSIDE - 20 passengers

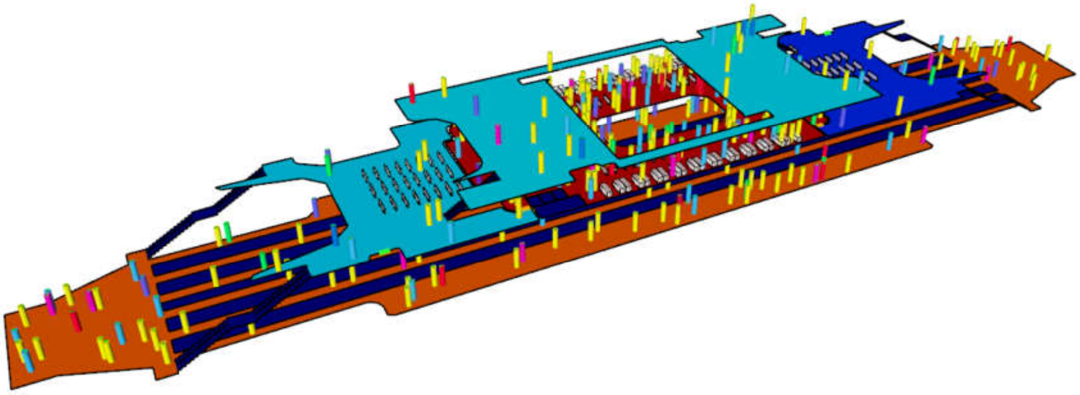


Figure 31: Model of the ferry ship case 4

To help readers to identify more easily the conditions applied to the four scenarios, these will be referenced as follows:
1-SA (Summer-Available);
2-WA (Winter-Available);
3-SU (Summer-Unavailable);
4-WU (Winter-Unavailable).

Characteristics of the model

The basic assumptions are the same in all scenarios inferred from the standard (IMO, 2016).

In each simulation, people are represented in the model individually, and personal decisions and movements are the same for all, described by a universal algorithm. The population is identical for all scenarios except for the response duration and initial positions of passengers that are randomly generated for each simulation according to specific distributions as explained below. The composition of the population is described in Table 1.

Table 1: Population groups – passengers (age and gender).

Population groups - passengers	Percentage of passengers (%)	Number passengers
FEMALES YOUNGER THAN 30 YEARS	7	27
FEMALES 30-50 YEARS OLD	7	27
FEMALES OLDER THAN 50 YEARS	16	63
FEMALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	10	39
FEMALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	10	39
MALES YOUNGER THAN 30 YEARS	7	27
MALES 30-50 YEARS OLD	7	27
MALES OLDER THAN 50 YEARS	16	63
MALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	10	39
MALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	10	39

Table 2: Population groups – crew (age and gender).

Population groups - passengers	Percentage of passengers (%)	Number passengers
CREW FEMALES	50	3
CREW MALES	50	4

The duration of occupant response time for the considered scenarios follows the logarithmic normal distribution described below:

For the all Cases (Day cases):

$$y = \frac{1.00808}{\sqrt{2\pi}0.94x}\exp\left[-\frac{(\ln(x)-3.44)^2}{2\times 0.94^2}\right]$$

$$0 < x < 300$$

where x is the response duration in seconds and y is the probability density at response duration x.

Regarding walking speed, a uniform statistical distribution with minimum and maximum values was considered for each sex and age group as shown in Table 3:

Table 3: Population groups – passengers (age and gender).

Population groups - passengers	Walking speed on flat terrain (e.g. corridors)	
	Minimum (m/s)	Maximum (m/s)
FEMALES YOUNGER THAN 30 YEARS	0,93	1,55
FEMALES 30-50 YEARS OLD	0,71	1,19
FEMALES OLDER THAN 50 YEARS	0,56	0,94
FEMALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	0,43	0,91
FEMALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	0,37	0,61
MALES YOUNGER THAN 30 YEARS	1,11	1,85
MALES 30-50 YEARS OLD	0,97	1,62
MALES OLDER THAN 50 YEARS	0,84	1,40
MALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	0,64	1,06
MALES OLDER THAN 50 YEARS, MOBILITY IMPAIRED	0,55	0,91

Table 4: Population groups – crew (age and gender).

Population groups - passengers	Walking speed on flat terrain (e.g. corridors)	
	Minimum (m/s)	Maximum (m/s)
CREW FEMALES	0,93	1,55
CREW MALES	1,11	1,85

The computational algorithm runs ever-changing simulations by changing the position of the occupants, emergency response time, and speed of movement.

Once the model was set up, simulations were started and were repeated 500 times for each case under consideration, for a total of 2000 simulations. The greater the number of simulations the more reliable the analysis performed.

Results

The most important type of data that we're interested in are evacuation times. These will be analyzed with the use of charts that compare the results obtained from the simulations.
Another important information is the level of congestion, because having areas congested with people for too long can cause people to panic, and is absolutely undesirable.

In the following paragraphs these two aspects will be investigated.

Evacuation time

The primary design evacuation scenarios (case 1-SA and 3-SU) are set in summer; in the first case all escape routes were assumed to be available, while in the third case the escape route connecting decks 4 and 5 is assumed to be unavailable. The Fig. 32 diagram compares the maximum exodus times for both scenarios, showing that in a situation where passengers are mostly located outside the decks, having only 50 % of the doors available (1 out of 2) has an appreciable impact on the exodus times.

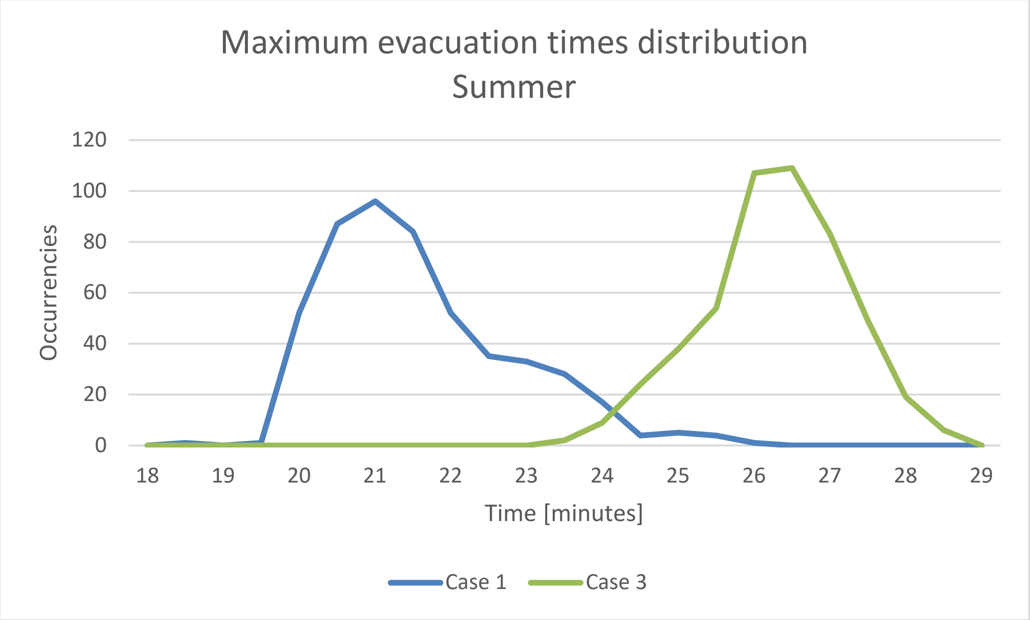


Figure 32: Diagram maximum evacuation time scenarios 1-SA and 3-SU compared.

As can be seen from the comparison of scenarios 1-SA and 3-SU, the unavailability of one escape route (1 out of 6), increases the total time for exodus by 5 to 6 minutes on average. The simulations for cases 2 and 4 are set in winter, so the concentration of people occurs mainly at decks 3 and 4 with relative occupancy of outer decks no. 5. This causes the impact of having one of the two escape routes connecting decks 4 and 5 unavailable to be lower than in cases 1-SA and 3-SU (summer).

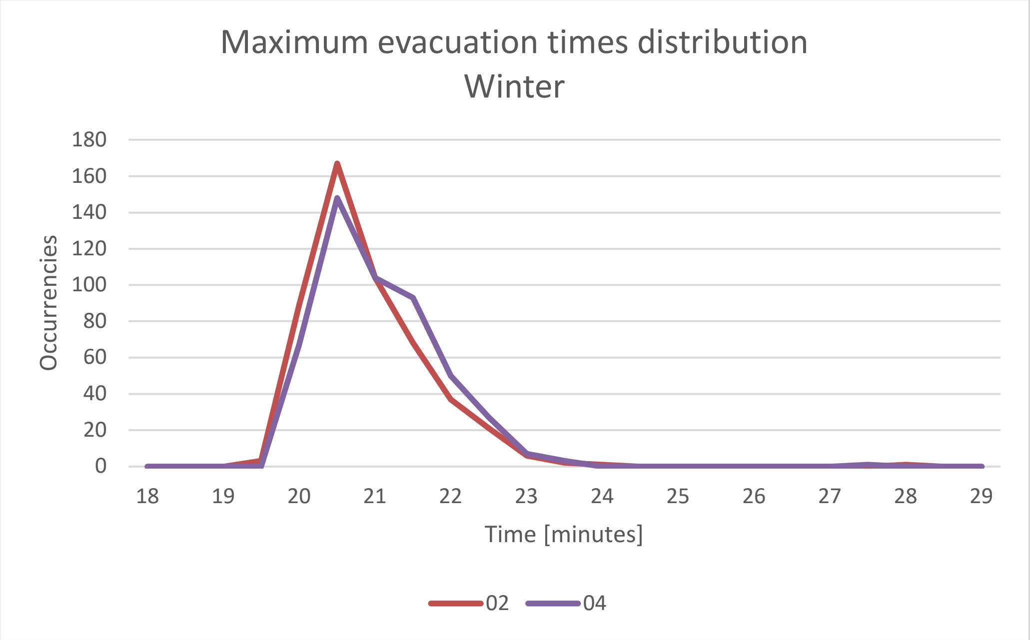


Figure 33: Diagram maximum evacuation time scenarios 2-WA and 4-WU compared.

Another interesting insight into the analysis is provided by comparing scenarios 3-SU and 4-WU both with at least one of the exodus routes unavailable. The diagram shows how the timing of exodus can vary significantly, depending on the season and thus the distribution of users.

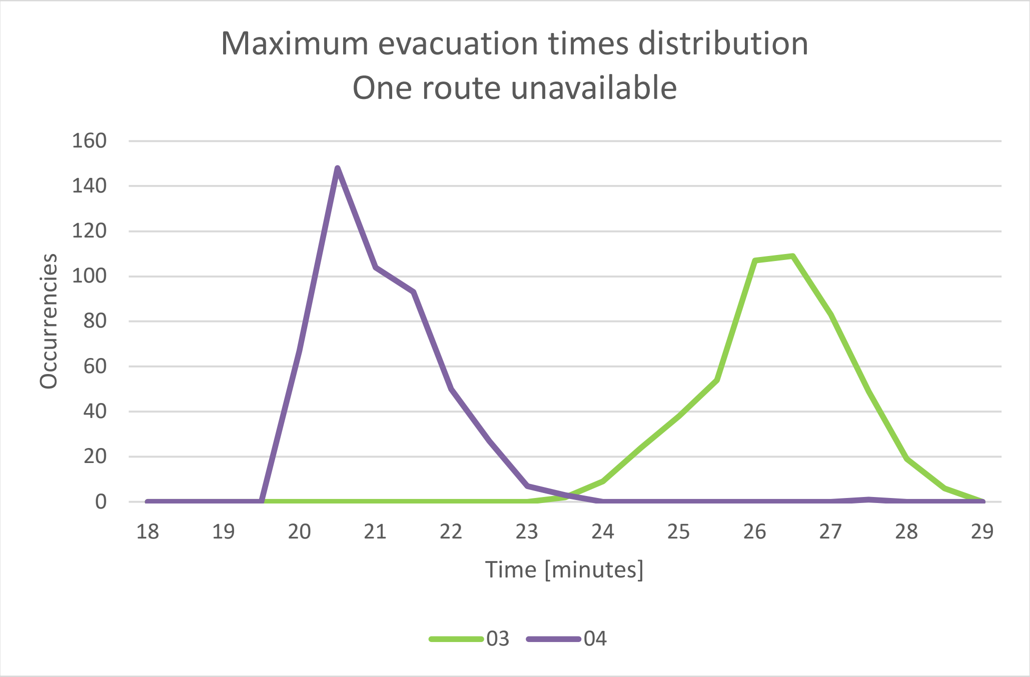


Figure 34: Diagram maximum evacuation time scenarios 3-SU and 4-WU compared.

In case 4-WU (winter) the average exodus time of the 500 simulations conducted is about 21 minutes, while in case 3-SU the average evacuation time rises to 26/27 minutes with a significant time delta.

According to IMO, 2016, the exodus time is verified when the total evacuation time, calculated with the formula below, is less than or equal to n minutes.

$1.25(R+T) + 2/3\ (E+L) \leq n$
For ro-ro passenger ship, n=60 minutes

The normative value of R is 5 minutes (day) or 10 minutes (night)
In the present case where the simulations were done in daytime, the value of R is assumed to be 5 minutes in all cases (1 to 4)

The value of T is assumed to be equal to the 95th percentile of the most severe scenario.
In the case under study, the T value of scenario 3-SU was taken as the most severe of the 4 scenarios under investigation. T= 27.5 minutes.

The value of (E+L) must be ≤ 30 minutes.
In evaluating the exodus, the value of (E+L) was assumed to be 20 minutes. This value represents the time it takes for users to head to the gathering places and put on life jackets. The simulations showed that passengers have plenty of time to put on the PPE, so the value of 20 was assumed as a precautionary measure.

Putting the values into the equation, we obtain:

1.25(5+27.5) + 2/3 (20)≤ 60 minutes

53.95 ≤ 60 minutes

This result is in accordance with IMO 2016, anyway just considering the maximum exodus time doesn't provide any information about how the exodus times are distributed. For example, we could have two situations, one in which the great part of people escapes in a short time and very few people (to the limit, just 1 person) take a long time, and another one in which the great part of people escapes in a significantly longer time than the previous case, but with a lower maximum time.
Looking at the maximum time only, the second case is obviously better than the first one, but if we also look at the average times, we could conclude that case one is better than case two.
To investigate in this sense, charts with the comparison of average escape times are provided below.

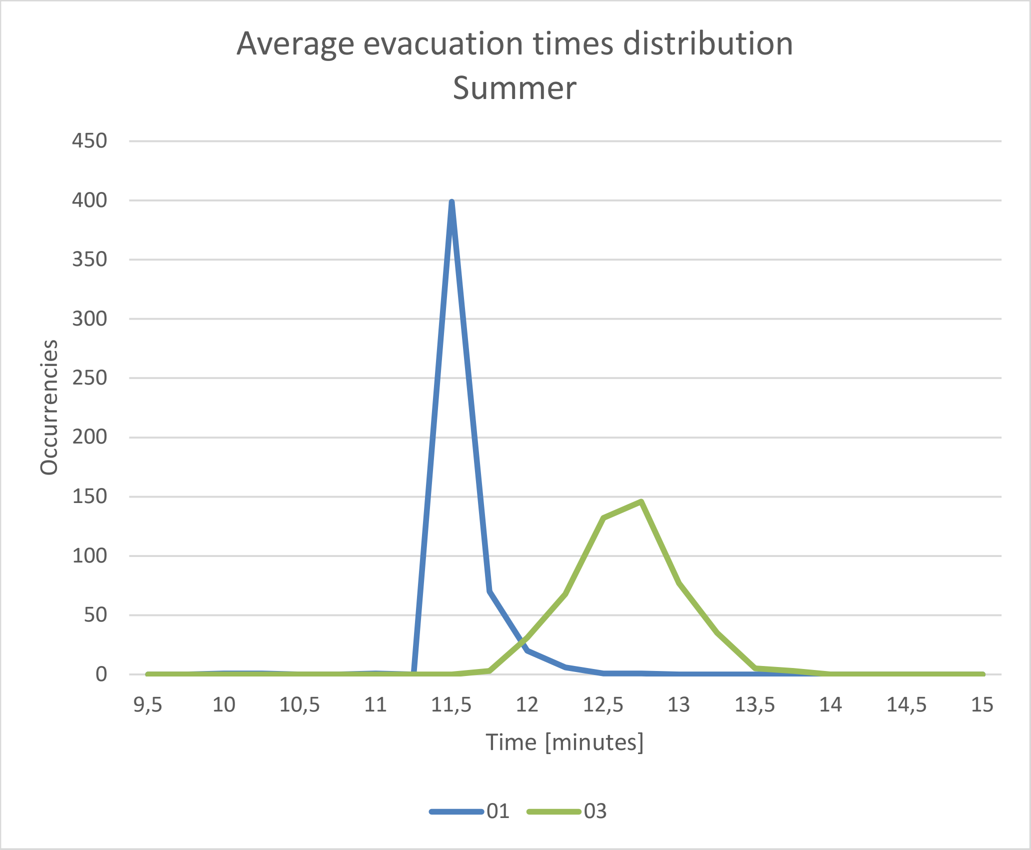


Figure 35: Diagram maximum evacuation time scenarios 1-SA and 3-SU compared.

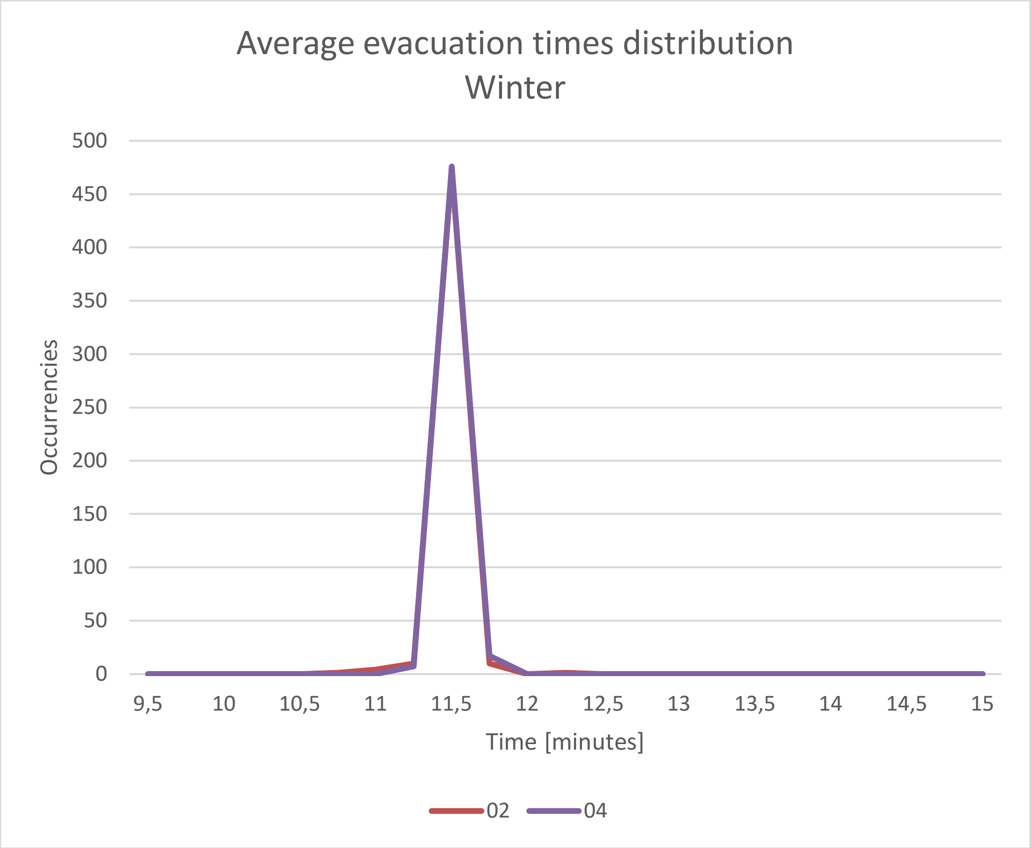


Figure 36: Diagram maximum evacuation time scenarios 1-WA and 4-WU compared.

Looking at the two charts, we see that average times confirm the findings coming from maximum times, with case 3-SU having the highest average escape time followed by case 01-SA.
The two Winter cases, 2 and 4, are quite similar, so that they curves overlap almost totally.

Level of congestion

The regulations (IMO, 2016) specify that if the calculated total evacuation time is longer than the total allowed evacuation time, the evacuation procedures on board must be revised with the aim of taking appropriate action to reduce congestion. As seen before, in the simulations under consideration, the evacuation time is always fulfilled as the total value measured in the worst case condition 3-SU is less than the 60 minutes for ro-ro ships.

However, the analysis of the quantity of data offered by the specialised software also makes it possible to highlight possible criticalities with regard to possible congestion along the escape routes, which can increase the discomfort of users during an emergency. An in-depth analysis of occupancy density carried out on the most unfavourable simulation of case 3-SU also made it possible to understand how, even if the maximum evacuation time fulfils its requirement, there is a problem related to the level of congestion in a specific area.

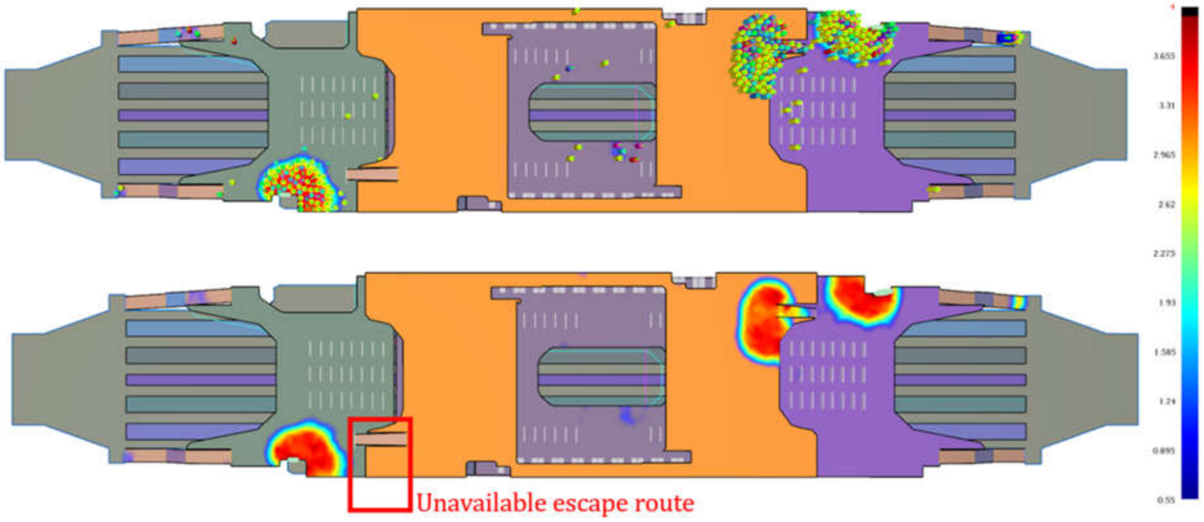


Figure 37: Model of the ferry ship case 3-SU – Occupancy density (software Pathfinder)

Figure 37 highlights how the unavailability of one escape route leads to congestion of the other escape route located in the opposite position, albeit limited to a few minutes.

In such cases two different approaches should be adopted, according to the situation being analysed: if the analysis is done for the design phase, a solution by design should be investigated; if the analysis is being carried out for an existing ship, procedures should be put in place in order to address the criticalities emerged from the study.

CONCLUSIONS

Effective fire risk assessment and consequent management cannot be put in place with the support of a single approach or with a safety concern relegated to a single phase of the life-cycle (e.g. during design activities).

Proper fire safety level can be achieved if fire risk is managed also during operation phases, including the reaction to real recorded events.

Technical safety, especially during design, is not enough while, at the same time, technical safety insights, as seen in this document, may benefit from the availability and tools (as fire and pedestrian simulation) in order to understand specific threats and conditions, test different hypothesis, etc.

These tools, in a performance based and risk-based approach, will allow to consider specific aspects of the marine environment as the influence of ship motion, heel and trim on pedestrians movement during emergency as suggested in some important papers given the fact that these influencing factors affects the entire evacuation process ((Wang et al., 2021), (Sun et al., 2018), (Kim, Roh and Han, 2019)). But, in any case, advanced evacuation analysis, made mandatory not only for Ro-Ro and Ro-Pax ships, is not to be used alone since existing guidelines still do not take into account a number of effects that are peculiar of the maritime environment, given the buildings environment basis of the guidelines (Wang et al., 2020).

Among the peculiarities it is possible to quote: pre-movement time, path-finding, behaviour when the selected exit is congested, counter flow behaviour, competition and cooperation behaviour, group behaviour, impatient behaviour, carrying luggage, temporary leadership behaviour. All these aspects, exacerbated in maritime emergency environment, relate with the “human factor” aspect and may take advantage of other means of insights (*in primis* the structured study of real incidents).

Human factor is also a key element for the availability and the effectiveness of a number of different preventive and protective barriers, as well as the first cause of marine accidents involving ferries (Kvamme, 2017).

Human factors play a crucial role in accident causation and in emergency response (Khan, 2008); also, human failures whilst performing critical tasks may contribute to major accidents. Human factors methods can improve safety (Grattan, 2018).

“Human Factors” is the complex of disciplines, methods, tools that consider the individual and his characteristics part of a sociotechnical system, having the goal to ensure and increase safety, performance and well-being.

It considers the importance of the interaction of humans with systems and environment (Bridger, 2021), (Hollnagel, 2014), (Wilson, 2014), (Hancock, 2012), considering human capabilities and limitations.

Human factors are fundamental since human conditions (physical ergonomics, stress level, time available to perform a specific task, environmental conditions, interactions with other sociotechnical systems, ...) play a vital role on human performance and reliability.

This requires specific considerations, as suggested in (Kim, Park and Presley, 2021), (Di Pasquale, Miranda, Iannone and Riemma, 2015), (Liu et al., 2020) and (Golestani et al., 2020).

“Human factors” can be applied to various stages of consideration, from design to operation. This should be coupled with the concept that safety has a critical part since design (England and Painting, 2022).

Human factors consideration has implications for the operation in terms of operational procedures, staff training/competences, staffing levels, ... (Human factors considerations in the safety case for the Channel Tunnel project, 1990). The earlier it is used in a project the better the results are (Stanton and Young, 2003).

This is outmost true considering the fire risk associated to “Ro-Ro” and “Ro-Pax” ships due to their intrinsic vulnerabilities.

These ships and their operation should be considered *"complex socio-technical systems with many interfaces among technical components, physical equipment, operators (human) and organisation"*.

Given this, the fire safety kernel becomes the risk scenario and *"additional scenarios will develop as the system changes…through its life cycle. Therefore, additional scenarios must be learned from continuous or frequent system monitoring for unusual behaviour and near-misses".*

Studies of *"comprehensive systems"* through accident and organisational models, coupled with the studies on management factors based on the "man-machine-environment" system paradigm ((Li and Guldenmund, 2018) and (Léger et al., 2008)) is then recommended.

Taking advantage of an holistic approach may lead to the development of specialized and validated tool, built on top of RCA results, full-scale experiments and multiple scenarios simulation, as maritime safety on-board decision support systems to enhance emergency evacuation on ferryboats, as suggested in (Sarvari et al., 2019).

As shown in this document an integral approach based on lessons learnt, performance-based design supported by specific insights with modern methods and tools, real full-scale exercises allow the implementation of a fire risk management framework able to identify fire safety improvements and to link different stakeholders at different stages of the life-cycle of these specific marine assets that, in the future, are even more likely to play a fundamental role in maritime transportation.

REFERENCES

Baird, N. (2018) Fatal ferry accidents, their causes and how to prevent them. Doctor of Philosophy. University of Wollongong.

Bridger, R. (2021) Introduction to human factors and ergonomics. 1st ed.

Di Pasquale, V., Miranda, S., Iannone, R. and Riemma, S. (2015) A Simulator for Human Error Probability Analysis (SHERPA). Reliability Engineering and System Safety, **139**, pp.17-32.

England, D. and Painting, A. (2022) An Effective Strategy for Safe Design in Engineering and Construction. Newark: John Wiley & Sons, Incorporated.

Fiorentini, L. and Marmo, L. (2021) Principles of forensic engineering applied to industrial accidents. 1st ed. New York: Wiley.

Galea, E., Brown, R., Filippidis, L. and Deere, S. (2010)

Grattan, D. (2018) Improving barrier effectiveness using human factors methods. Journal of Loss Prevention in the Process Industries, **55**, pp.400-410.

Hancock, P. (2012) Human Factors/Ergonomics. In: V. Ramachandran, ed., Encyclopedia of Human Behavior, 2nd ed. London: Academic Press, pp.358-363.

Hollnagel, E. (2014) Human factors/ergonomics as a systems discipline? “The human use of human beings” revisited. Applied Ergonomics, **45**(1), pp.40-44.

IEC (2019) 31010 Risk management — Risk assessment techniques. Geneva: IEC.

IMO (2016) MSC.1/Circ. 1533: Revised guidelines on evacuation analysis for new and existing passenger ships. London: International Maritime Organization.

ISO (2018) ISO 31000 Risk management -- Principles and guidelines. Geneva: ISO.

Khan, F. (2008) Human factors special issue. Journal of Loss Prevention in the Process Industries, **21**(3), pp.225-226.

Kim, H., Roh, M. and Han, S. (2019) Passenger evacuation simulation considering the heeling angle change during sinking. International Journal of Naval Architecture and Ocean Engineering, **11**(1), pp.329-343.

Kim, Y., Park, J. and Presley, M. (2021) Selecting significant contextual factors and estimating their effects on operator reliability in computer-based control rooms. Reliability Engineering and System Safety, **213**, p.107679.

Kvamme, V. (2017) Use of behavioral theories for the interpretation of human behavior in the Costa Concordia disaster. Lund: Lund University.

Léger, A., Farret, R., Duval, C., Levrat, E., Weber, P. and Iung, B. (2008) A safety barriers-based approach for the risk analysis of socio-technical systems. IFAC Proceedings Volumes, **41**(2), pp.6938-6943.

Li, Y. and Guldenmund, F. (2018) Safety management systems: A broad overview of the literature. Safety Science, **103**, pp.94-123.

Liu, J., Schmid, F., Zheng, W. and Zhu, J. (2019) Understanding railway operational accidents using network theory. Reliability Engineering and System Safety, **189**, pp.218-231.

Norman Atlantic disaster [2022] Testimony given by F. R. (Bari Court).

Park, K., Ham, S. and Ha, S. (2015) Validation of advanced evacuation analysis on passenger ships using experimental scenario and data of full-scale evacuation. Computers in Industry, **71**, pp.103-115.

Pospolicki, M. (2017) A study on how to improve mass evacuation at sea with the use of survival crafts. Master Thesis. Lund University.

Sarvari, P., Cevikcan, E., Celik, M., Ustundag, A. and Ervural, B. (2019) A maritime safety on-board decision support system to enhance emergency evacuation on ferryboats. Maritime Policy and Management, **46**(4), pp.410-435.

Scienze Notizie (2022) Svezia: traghetto prende fuoco con 300 persone a bordo, la situazione » Scienze Notizie. [online] Available at: <https://www.scienzenotizie.it/2022/08/30/svezia-traghetto-prende-fuoco-con-300-persone-a-bordo-la-situazione-5259655/amp> [Accessed 2 September 2022].

Stanton, N. and Young, M. (2003) Giving ergonomics away? The application of ergonomics methods by novices. Applied Ergonomics, **34**(5), pp.479-490.

Sun, J., Guo, Y., Li, C., Lo, S. and Lu, S. (2018) An experimental study on individual walking speed during ship evacuation with the combined effect of heeling and trim. Ocean Engineering, **166**, pp.396-403.

Wang, X., Liu, Z., Wang, J., Loughney, S., Yang, Z. and Gao, X. (2021) Experimental study on individual walking speed during emergency evacuation with the influence of ship motion. Physica A: Statistical Mechanics and its Applications, **562**, p.125369.

Wang, X., Liu, Z., Zhao, Z., Wang, J., Loughney, S. and Wang, H. (2020) Passengers' likely behaviour based on demographic difference during an emergency evacuation in a Ro-Ro passenger ship. Safety Science, **129**, p.104803.

Wilson, J., Norris, B., Clarke, T. and Mills, A. (2007) People and rail systems. Human Factors at the Heart of the Railway.. Aldershot: CRC Press.