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ORIGINAL ARTICLE

Effectiveness assessment and simulation of a wearable guiding device for ship evacuation

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Abstract
The evacuation of a modern passenger ship is a challenging task which might be hindered by a complex ship's internal layout and/or the blocking of escape routes due to fire/flooding. In this work, the application of mobile technology to reduce travel time is investigated. A pilot system has been developed and tested on the RoPax ship GNV Bridge. It is composed of a server and a mobile application running on wearable smartbands. The guidance and localisation of devices have been carried out through Bluetooth beacons. A test area has been identified on GNV Bridge including 2 cabins corridors on deck 6 and the main lounge on deck 5. The corridors and the lounge are connected by three staircases, defining three alternative escape routes starting from cabins and arriving at the muster station in the main lounge. In the trials, the escape routes have been randomly blocked to assess the reduction of travel time achieved providing guidance through wearable devices to a sample population. It resulted in a 16.9% reduction in travel time. Besides, a strategy to simulate with a certified tool the effect of a guiding system has been defined. This is essential to make trials' results transferable in different environments (e.g., other RoPax or cruise ships). In particular, experimental data coming from the trials have been used to assess agents' speed reduction rate due to mobile device consultation. Although available experimental data were limited by the pandemic, the 2.5% agent's speed reduction applicable to simulations has been assessed as most probable.

Keywords Ship Evacuation · Experimental trials · Wearable device · Mobile technology · Evacuation simulation

1 Introduction

As a consequence of an emergency situation, such as fire or flooding, ship abandonment can be required. Ship evacuation is a very challenging task, especially on modern passenger ships carrying thousands of persons that may have different ages and behaviors [1–4]. Modern passenger ships are usually designed to mask their primary extension towards the longitudinal direction, thus, often public areas have very complex layouts which might disorient passengers in case of emergency [5–7]. Furthermore, during an emergency, escape routes might be blocked due to fire or flooding, forcing persons who are following routes marked by fixed signaling to turn back and search for alternative paths toward muster stations or safe areas. Another crucial factor to consider is the increase of both passenger ships average size and the number of passengers onboard, caused by the growth in cruise demands. To handle evacuation procedures in a proper and safe way, novel ideas and solutions must be applied [8, 9]. In particular, great benefits come from any kind of dynamic signaling onboard, which adapts to the current situation helping passengers to deal with blocked routes as demonstrated in eVACUATE project [10].

In this framework, the application of mobile technology is an option worthy of investigation [11], since it can help in reducing the time required for ship evacuation and abandonment procedures. A mobile application, guiding passengers through the proper direction updated in real-time on the basis of the current status of escape routes might prevent passengers to move towards dead ends or congestions [12]. Such a technology shall be based on the localisation

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of passengers' mobile devices (smartphone, smartwatch, smartbands, ecc.) based on an infrastructure connected to the ship's emergency switchboard and/or an independent source of power to assure operations in any condition.

Localisation data onboard are very useful not only to provide guidance. They can be also transmitted to the bridge to ease monitoring and coordination of the evacuation procedure. Such a system might also help the crew to localize lost passengers and rapidly rescue them. In general, a better situational awareness can be achieved. Besides, localisation can be useful to improve safety/security or passenger experience during normal ship operations too. It can be used to early detect unauthorized access to restricted areas, allowing fast reaction of the onboard security team [13]. Moreover, in case of onboard infections, the localisation records, normally not accessible to protect passengers' privacy, could be put at disposal of medical officers. The movements of infected passengers can be analyzed to identify the passengers that came in contact with them [14]. Then, through the adoption of tests and quarantine, it will be easier to contain the infection growth onboard [15, 16]. Finally, localisation can be useful also for commercial purposes, such as allowing big data analysis, providing push notifications related to the passenger position and providing guidance onboard to reach desired destinations.

Mobile technology is already widely adopted to provide localisation services onshore. For instance, Bluetooth-based systems have been lately developed and tested in civil environments [17, 18]. In this context, localisation has been also used to aid building evacuation [19, 20] or to perform occupancy detection [21] in emergencies. However, despite the similar appearance, a passenger ship is a far more challenging environment compared to a building since ships are made of steel. The material can generate issues such as signal shielding or signal reflection [22, 23] making more difficult the development of localisation services onboard. To solve this set of problems, several international research programs have addressed the topic in the last years. The EU H2020 program SafePASS proposed a solution in which Augmented Reality and the Location-based Dynamic Evacuation Route (LDER) are combined [24], whereas the EU H2020 project Palaemon (https://palaemonproject.eu/) and the 2010-EU-21109-S project Monalisa 2.0 [25] aimed at implementing evacuation solutions that include a tracking and monitoring system able to perform an indoor positioning of passengers and to communicate them evacuation procedures and paths in case of emergency.

In this context, the aims of the present work are threefold:

- Reinforcing the basis for the exploitation of mobile technology during ship evacuation;
- Presenting the results of real-environment tests, to highlight pros and cons of the analyzed solution;
- Laying down a methodology to reproduce the experimental results with evacuation simulations.

A system based on Bluetooth beacons has been chosen since this technology has been already introduced on recent passenger ships for commercial purposes only [26]. The first objective of this study is to prove the technical feasibility of a system based on Bluetooth beacons on a ship along with its effectiveness in achieving a reduction of the travel time. To this end, in the framework of the INTERREG Italy-Croatia 2014–2020 DigLogs (Digitalising Logistics Processes) project a pilot system has been developed. Then, a set of trials on the RoPax GNV Bridge involving a test population has been carried out to compare the baseline travel time with the one related to the adoption of mobile technology. Attention has been given especially to scenarios where one or more escape routes are blocked, i.e., scenarios where the conventional fixed signs might guide passengers to a dead end.

Besides, here a methodology has been developed to simulate the effect of a guidance system in other contexts with no need for specific experimental campaigns. To this end, the experimental data collected in trials have been exploited to properly tune evacuation simulations carried out with a certified tool to reproduce the behavior of passengers using the guiding system. The outcomes can ease the transferability of the results of the trials opening the possibility to design and predicting the effect of the introduction of an emergency guidance system based on mobile technology on any passenger ship.

2 Materials and methods

In the present section, after a description of the rule framework governing the evacuation of ships, the methodology to simulate ship evacuation is presented using an Agent-Based Model(ABM) approach following international rule requirements. Then, the pilot system developed to assess the effectiveness of mobile technology to guide passengers during evacuation is described focusing on its hardware components and their scope. Finally, the methodology adopted to assess the pilot system's effectiveness and to enable results reproduction and transferability in other contexts is described.

2.1 Rule framework

The theme of passenger ships evacuation is regulated from the IMO MSC/Circ. 1533 [27], which made evacuation analyses mandatory for all the passenger ships whose construction started after 1 January 2020. As specified in the Circular, both a simplified and an advanced method is eligible; however, for highly detailed and populated ships, the advanced method is to be preferred due to the increased accuracy of the results [28].

2.1.1 Calculation of the total evacuation duration

The total evacuation duration t_{tot}, which corresponds to the total time necessary to abandon the ship, is calculated through the following equation (graphically described in Fig. 1):

$$t_{tot} = 1.25(R + T) + \frac{2(E + L)}{3} \tag{1}$$

where R is the response duration to danger, T is the total travel duration for all the persons to move from their initial location to the assigned muster stations, and $E + L$ is the lifeboats embarkation and launching duration necessary for all the persons to complete the abandonment of the ship. In particular, $E + L$ must be calculated through one of the following methods:

1. Based on the results of full-scale tests on ships similar to the one in question and with similar evacuation systems;
2. Based on the results of simulations regarding embarking analyses;
3. From data given by the providers of the rescue vehicles (calculation method and corrective factors values used must be documented).

If none of the previous methods for the calculation of $E + L$ is available, the Circular imposes to consider $E + L$ equal to 30 min.

The calculated total evacuation duration must be inferior than a set value n that depends on the dimensions of the ship, as follows:

- $n = 60$ min for ro-ro ships and passenger ships with at most 3 Main Vertical Zones (MVZ);
- $n = 80$ min for passenger ships with more than 3 MVZs.

The Circular 1533 requires the calculation of the total evacuation duration for four mandatory scenarios and two optional scenarios, presented in Fig. 2. In all the scenarios, the population is distributed in accordance with the FSS code [29].

2.1.2 Advanced method for evacuation analysis

The advanced evacuation analysis allows calculating the total evacuation duration and identifying possible congestion points onboard the ship, with the aim of removing them.

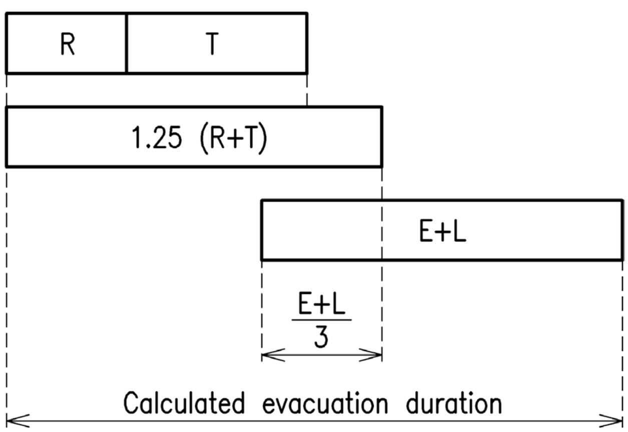


Fig. 1 Total evacuation duration calculation

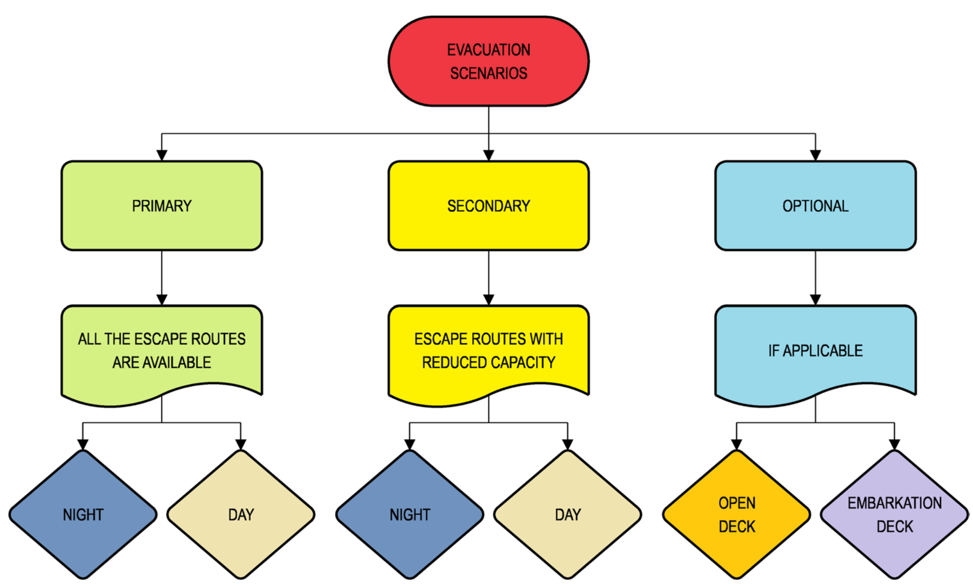


Fig. 2 MSC/Circ. 1533 evacuation scenarios

It is based on a microscopic approach, in which persons are analyzed as single well-defined entities with peculiar behaviors able to influence their escape [30, 31]. The method is based on the following specific assumptions:

1. Passengers and crew members are represented as unique individuals with specific individual skills and response time;
2. A safety factor of 1.25 is introduced in the calculation to take into account the omissions of the model, the assumptions and the limited number of reference scenarios considered. These model deficiencies can be:
   - The crew immediately positioned in the evacuation service station and ready to assist passengers;
   - Passengers who ideally follow the signage system and the crew's instructions. In other words, their selection of the path is not included in the analysis;
   - Smoke, heat, and toxic fire products present in the fire effluents are not considered to affect the performance of passengers and crew;
   - The behavior of family groups is not considered in the analysis;
   - The movement of the ship and the trim are also not considered.

The abilities of individuals are determined by a series of parameters, some of which are probabilistic in nature. The main parameters that influence the evacuation process are divided by the Circular into four categories, namely:

- Geometric: it considers the arrangement/layout of escape routes, their obstruction and availability and the initial conditions of distribution of passengers and crew members;
- Population: it considers the physical and demographic characteristics of the considered population. It describes the composition of the population in terms of age, gender and physical characteristics;
- Environmental: it considers static and dynamic conditions of the ship that may have a great influence on the speed of movement of people;
- Procedural: it considers the crew members assistance to support passengers.

The calculation of the total evacuation duration is performed through Eq 1. The response time R may be performed through the use of truncated logarithmic normal distributions [32], while the total travel duration T corresponds to the highest value of the four calculated travel times (t_I), one for each mandatory scenario. Specifically, the travel time is a random quantity due to the probabilistic nature of the evacuation process. Therefore, in total, at least 500 different simulations must be performed for each of the reference scenarios. This will produce, for each case, a total of at least 500 values of total assembly duration (t_A). These simulations must consist of at least 100 different randomly generated populations, within the range of demographic data of the population specified above. Simulations based on each of these different populations must be repeated at least 5 times. For each scenario, the times t_A are classified in ascending order from lowest to highest and t_I corresponds to the value below which 95% of the calculated values are located.

2.2 Advanced evacuation simulations

Advanced evacuation simulations require modeling the movement of a large number of passengers, who are essentially pedestrians [33, 34]. There are many different ways to approach this topic scientifically: regression models, queuing models, path choice models, gas-kinetic and macroscopic models, microscopic models [35–37]. One of the most predominant techniques is the ABM one. The ABM technique is a computational class model that simulates the interactions between agents for the evaluation of the effects on the system as a whole [38, 39]. The most common method uses virtual reality simulator-based software. These programs have the ability to reproduce all the main phases of a ship abandonment and to consider each person as a singular entity, with specific characteristics that affect the escape time. In particular, a three-dimensional model of the ship is developed and populated with individual agents that represent both passengers and crew members; within the analysis, the interaction between persons and the ship's structure is also taken into account.

Among the various software dedicated to evacuation analyses, EVI [31, 40] represents one of the most interesting as it is the only software specifically developed for the marine environment and is certified by the IMO. Such a tool consists in a multi-agent evacuation simulation software package that uses the mesoscopic approach and is based on semi-continuous space modeling [41]; therefore, the exact definition of the ship layout is enabled and the necessity of spatial approximation is avoided. EVI allows performing the simulation of an entire evacuation process by tracking the location of each single agent at each single instant. Furthermore, it enables the execution of multiple simulations to calculate the 95th percentile solution for the total travel duration.

In accordance with the Circular 1533, in EVI the speed of the different agents varies according to their role and their characteristics in terms of gender, age, mobility, as derived from the data in [42]. Specifically, the unhindered travel speeds on flat terrain (e.g., corridors) should be statistically modeled as a continuous uniform distribution having minimum and maximum values as shown in Table 1.

Table 1 Passengers speed according to IMO

Population groups ? passengers	Walking speed (m/s)					
	flat terrain		Stairs down		Stairs up	
	Min	Max	Min	Max	Min	Max
Females younger than 30 years	0.93	1.55	0.56	0.94	0.47	0.79
Females 30–50 years old	0.71	1.19	0.49	0.81	0.44	0.74
Females older than 50 years	0.56	0.94	0.45	0.75	0.37	0.61
Females older than 50, mobility impaired (1)	0.43	0.71	0.34	0.56	0.28	0.46
Females older than 50, mobility impaired (2)	0.37	0.61	0.29	0.49	0.23	0.39
Males younger than 30 years	1.11	1.85	0.76	1.26	0.5	0.84
Males 30–50 years old	0.97	1.62	0.64	1.07	0.47	0.79
Males older than 50 years	0.84	1.4	0.5	0.84	0.38	0.64
Males older than 50, mobility impaired (1)	0.64	1.06	0.38	0.64	0.29	0.49
Males older than 50, mobility impaired (2)	0.55	0.91	0.33	0.55	0.25	0.41

Furthermore, the Circular provides also the unhindered walking speeds on inclined stairs (for both up and down directions), derived from the data in [43] and shown in Table 1.

The evacuation simulation tool is designed to simulate the normal behavior of passengers during an evacuation procedure. Hence, if they are not provided with any guidance and one or more escape routes are not available, the agents in the simulation will reach the position where the route is blocked (e.g., a closed door or a dead-end) and then will turn back and search for an alternative path. Therefore, the simulation tool can properly simulate experimental runs without guidance assuming as agents speeds the values provided by IMO.

Moreover, the simulation tool can also make agents moving along predefined paths: for each room of the ship model, a predefined exit can be selected forcing the agents to follow an escape route. Although, considering the guided scenarios, delays connected to wrong directions can be avoided but persons need to consult the wearable device. Therefore, their mean speed is expected to be somehow reduced by the need to check and apply guidances. Thus, this reduction shall be assessed using experimental data to be applied in evacuation simulations.

2.3 Pilot system for emergency guidance

To prove the feasibility and effectiveness of mobile technology to improve onboard safety and security during ship evacuation, a pilot system has been developed to be tested in a real ship environment. The architecture of the pilot system is shown in Fig. 3. The system has been designed to validate the technology and, thus, it is not ready for deployment in operative environment.

The pilot system is composed by a backend application and a mobile application, which run using the five physical components having the functionalities defined hereinafter:

- Server: A Raspberry PI 4 (Ubuntu OS) where the Backend application runs. The backend application allows to control the pilot system and collect/record positioning data. In detail, the backend application receives the user commands (switching on/off guidance system, selection of an active escape Scenario from a collection of predefined options) through a web interface (Fig. 4). Once an escape route is selected, the application retrieves from a MySQL database and provides the sending beacons with the information to be exposed in the active scenario. Furthermore, the backend application stores in the database the log coming from receiving beacons related to the connected Bluetooth devices. Finally, the recorded evacuation trials can be visualized through the web interface;
- Sending Beacons: A network of WEMS TTGO OLED ESP-32 beacons are installed on the ship to cover all the areas with their Bluetooth signal. They are responsible to receive from the server through WiFi connection (MQTT protocol) the specific information that shall be exposed to passengers in their covered area according to the active evacuation scenario. They transmit the information through Bluetooth to all the devices in the area covered by the beacon signal. For each message and each sending beacon, the signal strength can be customized to configure the system for the specific operative environment and evacuation scenario;
- Receiving beacons: A second network of WEMS TTGO OLED ESP-32 beacons are installed onboard to search for Bluetooth devices in their covered area. Using WiFi network (MQTT protool), they transmit to the server the MAC address and signal strength of all the detected devices. Hence, it is possible to track the position and number of persons that are receiving information from the system;

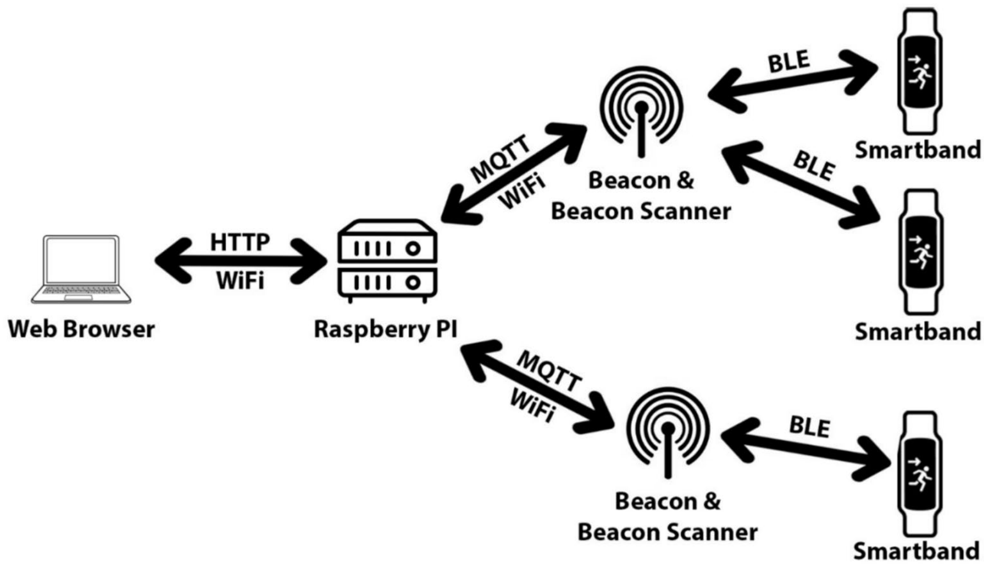


Fig. 3 System architecture

Fig. 4 Backend application web interface

- Wearable Smartbands: LILYGO TTGO T-Wristband has been selected for the pilot system as mobile wearable device to be given to users. Smartbands are by default in a standby mode checking with a 10-second time interval the emergency signal exposed by sending beacons. Once an emergency signal is received (i.e., after the selection of an escape through the backend application), the smartbands switch to the emergency mode while vibrating. Then they show on the screen the information associated with the nearest sending beacon. If multiple signals are received by the smartband, the one coming from the beacon having higher signal strength is shown. To be straightforward and effective for every possible user, information is conveyed using simple images derived from fixed signs marking escape routes accompanied by a short text in user's language. Two information types are available (Fig. 5):

  – Direction: an arrow indicating a fixed direction rotating accordingly as the user moves the smartband;

Fig. 5 A LILYGO TTGO T-Wristband and the list of the information that can be provided to pilot system users

– Instruction: composed by an icon and a text.

In the emergency mode, smartbands search for sending beacons with a 1-second interval. Besides, smartbands are detected by the nearest receiving beacon. The ID of the next beacons along the escape route can be added to the direction or instruction exposed by a sending beacon. Hence, if the smartband receives a new signal from a beacon not included in the foreseen escape route, the smartband vibrates and shows the wrong direction instruction. Once the final destination beacon is reached, the smartband shows the related instruction and, if no other sending beacon is detected within 10 s, switches to the standby mode.

- WiFi network: Router Tenda 4G09 and Repeaters TP-Link TL-WA850RE assuring the communication between server and beacons. The system can also rely on the ship WiFi network, but an independent removable network has been planned to carry out the pilot tests even if the ship WiFi network was under completion.

The pilot system architecture has been designed to be easily scaled and to be as far as possible resilient to failures. Most of the communication traffic between mobile devices and the system is delegated to sending beacons that serve a specific area and does not give any feedback to the server. The communication between server and sending beacons via WiFi network is limited to a single message that specifies the information to be shown. Hence, in case of WiFi/power drop during the emergency, the sending beacons will continue to show the local information to passengers on their battery. Nevertheless, the WiFi or alternatively a cabled connection is needed to change the shown information and to provide the server with the estimated position of mobile devices collected by receiving beacons, which is the most important information to the crew to monitor the current status of evacuation procedure. Beacons are predisposed to be connected and powered by wires. However, in the pilot system all the beacons have been powered by batteries to ease the installation, set up and removal after trials.

2.4 Effectiveness assessment and guidance system simulation

System effectiveness can be tested with multiple experimental runs (i.e., ship evacuation procedures) comparing the travel times obtained with and without guidance. Furthermore, in the following the strategy to tune evacuation simulations to reproduce the effect of a guiding system is described. Given n different evacuation scenarios in a test area, using the previously presented advanced simulation methodology, for each i-th evacuation scenario two probability density functions of the travel time t can be computed:

- pdf_{b_i} related to a baseline scenario where agents are not guided;
- pdf_{g_i} where agents are guided (i.e., a scenario where agents follow a predefined escape route).

Defining a normalized travel time as:

$$t' = \frac{t}{\bar{t}_b} \tag{2}$$

where $\bar{t}_b$ is the mean of travel time according to pdf_b, the probability density function of t' can be evaluated as:

$$pdf'_{b_i} = pdf_{b_i} \cdot \bar{t}_{b_i} \tag{3a}$$

$$pdf'_{g_i} = pdf_{g_i} \cdot \bar{t}_{b_i} \tag{3b}$$

Defining a normalized difference of travel time as:

$$Dt' = t'_b - t'_g \tag{4}$$

its probability density function is obtained as:

$$pdf'_{d_i}(Dt') = \int_{-\infty}^{\infty} pdf'_{b_i}(t') \cdot pdf'_{g_i}(Dt' + t')\,dt' \tag{5}$$

Considering n evacuation scenarios, the overall probability density function of Dt' can be evaluated as:

$$pdf'_d(Dt') = \frac{\sum_{i=1}^{n} pdf'_{d_i}(Dt')}{n} \tag{6}$$

As mentioned, the agents' speed is usually defined according to IMO in simulations but it might be slightly reduced if passengers are consulting guidances. Therefore, to accurately simulate the adoption of smartwatches in a maritime environment, the agents' speed V_a shall be reduced by a factor tuned through experimental data.

For this purpose, several pdf_{g_i} can be computed applying different V_a reduction factors. Then, the resulting cumulative density function $cdf'_d(Dt')$ can be compared to the empirical one obtained from the experimental data related to the considered n evacuation scenarios tested with and without guidance. The effectiveness assessment can be carried out by means of a statistical goodness-of-fit tests. In detail, considering the limited number of experimental runs that can be carried out onboard, here the Cramer-Von Mises test has been adopted [44]. The tests is based on the null-hypothesis that the two compared distributions are from the same sample [45]. Therefore, the most probable reduction factor for agents' speed is the one for which the null-hypothesis shall be retained with the higher significance level expressed by the *p-value*.

3 Application

To prove the effectiveness of mobile technology providing guidance during ship evacuation, the pilot system has been configured and tested in a real environment. In the following the test ship, the selected area for tests and the system set-up is described. Then, the planned escape scenarios to test the system effectiveness are described along with the population that participated to the evacuation trials.

3.1 Experimental set-up

The ship selected as the test case is a medium-size RoPax ship, whose main dimensions and properties are reported in Table 2. For the purposes of calculations, a restricted area of the ship was identified [11]. Specifically, such area is spread on two decks and arranged as follows:

- Deck 6 (Passenger deck), where the passengers' cabins are located;
- Deck 5 (Restaurant deck), where both the muster station and the lifeboat embarkation stations are located.

The test environment was limited to two cabin corridors on Deck 6 and to the main lounge assigned as muster station on Deck 5, as shown in Fig. 6. The corridors and the lounge are connected through three staircases, which define three alternative escape routes from Passenger Deck to the muster station.

The system was set up in the test environment by taking into account the steel-made structures, which initially raised some issues due to signal shielding and reflection. In general, the installation in the ceiling was not authorized by the shipyard, hence the beacons have been temporarily fixed to handrails. Hence, signal emission was not directed downward but could be reflected by steel bulkheads causing unexpected connections to wrong beacons in some evacuation scenarios, especially in long corridors. The problem was handled by keeping sending beacons signal strength as low as possible and limiting the number of active sending beacons in corridors. The configured system was considered suitable for trials with a sample population and its final configuration for the test area is provided in Fig. 7.

Table 2 Test ship main dimensions and properties

Main particular	Symb	Value	
Length overall	LOA	203.28	m
Length between perpendiculars	LBP	194.20	m
Molded Breadth	B	25.60	m
Max Draught	T	6.50	m
Depth at DK 3 (main deck)	D	9.15	m
Depth at DK 4 (weather deck)	D	15.00	m
Deadweight	DWT	abt 8500	t
Sea trial speed	V	23.70	kn
People onboard (long international voyages)	–	400	
People onboard (short international voyages)	–	1000	

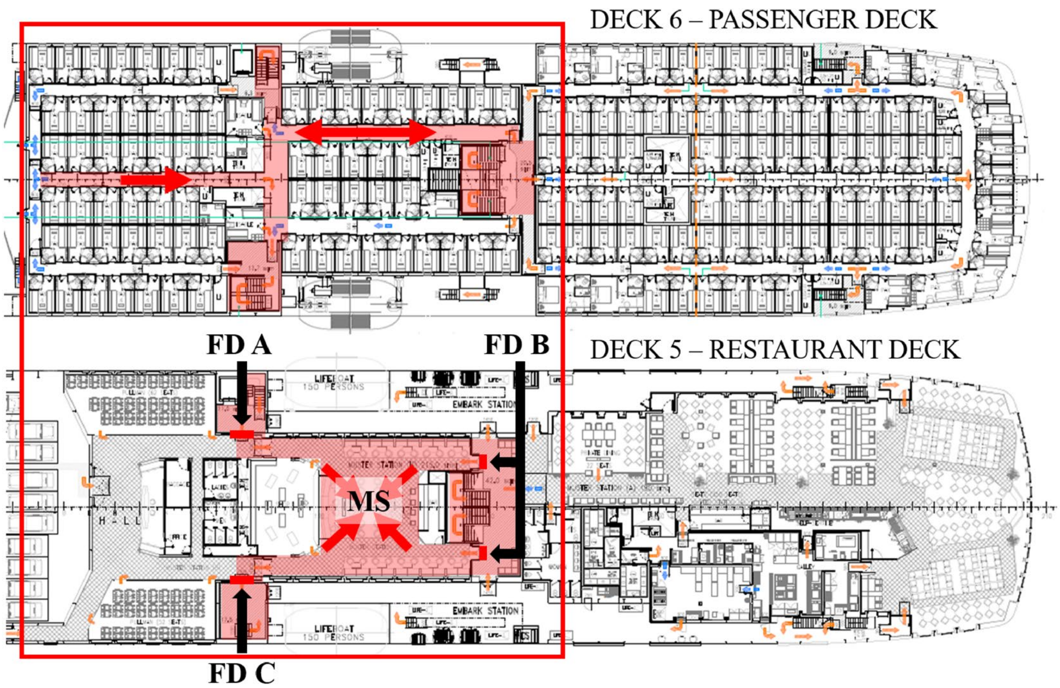


Fig. 6 General arrangement of decks 5 and 5 highlighting the selected test environment

3.2 Evacuation scenarios

The selected test area enables the definition of three main escape routes from Deck 6 to the muster station at Deck 5 passing through the three staircases. Hence, acting on four fire doors on Deck 5 (FD A, 2xFD B, FD C as identified in Fig. 6) seven different evacuation scenarios can be realized. Table 3 provides a list of such evacuation scenarios specifying which doors are available or blocked and which information among those defined in Fig. 5 is shown by each sending beacon located as for Fig. 7. In Fig. 8, an example of information shown by beacons in the test area is provided in the scenario 02. During the evacuation trials, when a person reaches a blocked fire door, he shall climb up again to Deck 6 and search for an alternative escape route with a considerable waste of time. Therefore, the proposed experimental layout is particularly suitable to study the effects of the introduction of guidance provided by mobile devices, that can prevent the person to take a path leading towards a blocked door. For each evacuation scenario in Table 3, two trials have been carried out with a sample population, initially located inside cabins:

- Baseline: persons are required to reach the muster station without any guidance other than fixed signs installed according to international regulations;
- Guided: persons are required to reach the muster station following the instructions provided by smartbands; if a wrong direction is identified by the system, persons are required to turn back and wait for the next instruction.

All the trials (baseline and guided) have been performed in random order. Evacuation runs starts with evacuation alarm ringing in all the test area and with contemporary activation of the emergency mode of the pilot system for the guided scenarios. Travel time is computed from the alarm to the instant in which the last person reaches the muster station.

3.3 Test population

The sample population during the trials was composed of 37 persons as shown in Fig. 9. Most of the sample population was composed of university students since the SARS-CoV-2 pandemic situation (lockdown was into force in Italy at the time) dramatically reduced the willingness to participate from other stakeholders and private citizens and limited the sample population recruitment. The trials have been carried out according to a safety protocol specifically developed to prevent infection from spreading.

3.4 Evacuation simulation model

To perform the advanced evacuation simulation, the selected ship was modeled within EVI (Fig. 10). However, the simulation was limited to the restricted area selected as test environment; therefore, the authors focused on the model of the

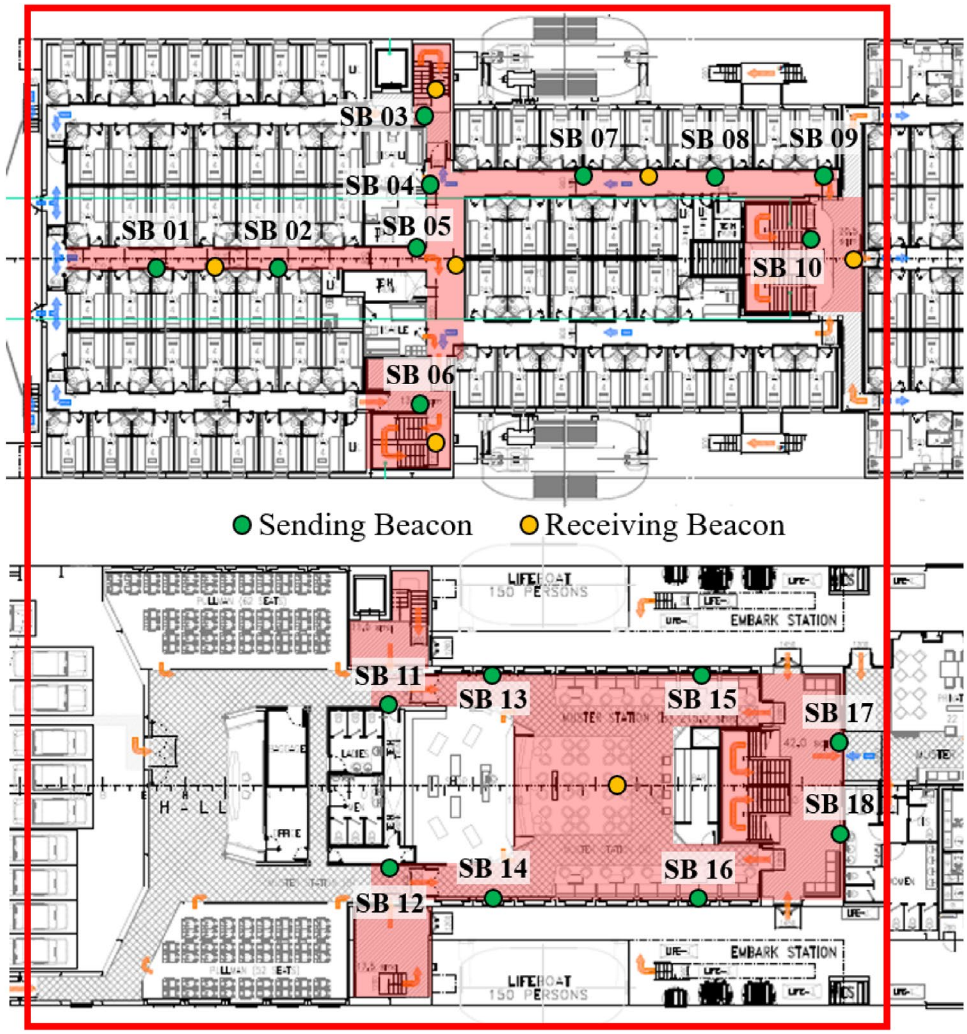


Fig. 7 Position of sending and receiving beacons in the test environment

portions of Decks 5 and 6 shown in Fig. 11, in which the corridors of passengers' cabins, the staircases, and the muster station are visible.

The population selected for the experimental tests was reproduced within the software, by inputting their characteristics in terms of gender and age. The agents were randomly distributed in their initial cabins on Deck 6 and assigned to the muster station on Deck 5. For each scenario, the correspondent fire doors were put unavailable and blocked. Since all persons during trials were waiting for the evacuation alarm, null response duration R is assumed in all the simulations. In the runs aimed at simulating the evacuation process without the guidance device, the agents were left free to roam without an assigned path and had to find the correct route to the muster station by themselves.

On the other hand, in the runs aimed at simulating the process with the aid of the guidance device, the agents were assigned a specific route to the muster station, ito reproduce the instructions given by the device. In the guided scenarios, multiple simulation runs have been carried out while systematically reducing the speed of the agents from 0% up to 10% in steps of 2.5%. For each baseline or guided run 500 simulations have been carried out as required by IMO guidelines.

4 Results

The trials were carried out in April 2021 in "Arsenale San Marco" (Trieste) while the GNV Bridge was under hull maintenance with the sample population previously described.

Table 4 shows the experimental results obtained for the seven evacuation scenarios for both baseline and guided trials. The application of the pilot systems lead to a reduction of the travel time in all the scenarios involving at least one blocked escape route whereas, when all the escape routes are available (scenario 01), a moderate increase in travel time was observed. This result was expected, since the population does not know the execution order of the trials and thus

Table 3 Trials scenarios including available and unavailable fire doors and information shown by sending beacons

id	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05	Scenario 06	Scenario 07
FD A	Open	Open	Open	Open	Blocked	Blocked	Blocked
FD B	Open	Open	Blocked	Blocked	Open	Open	Blocked
FD C	Open	Blocked	Open	Blocked	Open	Blocked	Open
SB 01	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right
SB 02	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right	Arrow-right
SB 03	Stairs-down	Stairs-down	Stairs-down	Stairs-down	No info	no info	No info
SB 04	Arrow-up	Arrow-up	Arrow-up	Arrow-up	Arrow-down	Arrow-down	Arrow-down
SB 05	Arrow-down	Arrow-up	Arrow-down	Arrow-up	Arrow-down	Arrow-up	Arrow-down
SB 06	Stairs-down	No info	Stairs-down	no info	Stairs-down	No info	Stairs-down
SB 07	Arrow-left	Arrow-left	Arrow-left	Arrow-left	Arrow-right	Arrow-right	Arrow-left
SB 08	Arrow-right	Arrow-right	Disabled	Disabled	Arrow-right	Arrow-right	Disabled
SB 09	Turn right	Turn right	No info	No info	Turn right	Turn right	No info
SB 10	Stairs-down	Stairs-down	No info	No info	Stairs-down	Stairs-down	No info
SB 11	Turn left	Turn left	Turn left	Turn left	Disabled	Disabled	Disabled
SB 12	Turn right	Disabled	Turn right	Disabled	Turn right	Disabled	Turn right
SB 13	Dest reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac
SB 14	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac
SB 15	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac
SB 16	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac	Dest. reac
SB 17	Left or right	Left or right	No info	No info	Left or right	Left or right	No info
SB 18	Left or right	Left or right	No info	No info	Left or right	Left or right	No info

consulted the smartbands even in scenario 01. On the other hand, when some escape route is not available, the smartbands guidance had a positive effect being capable to prevent persons to move in the wrong direction and wasting time coming back when a blocked door was reached.

The results of the simulations are provided in Fig. 12 where the experimental results are also reported. It can be noted that the experimental records are quite aligned with the simulations. In some cases the experimental values are located in the tails of the probability distributions coming from simulations (e.g., Scenarios 01, 02, and 07).

Applying the previously presented methodology, the probability distribution of the normalized difference of travel time Dt' have been assessed using the simulated evacuation trials. At the same time the empirical cumulative density function of Dt' have been estimated from the experimental records. The resulting probability and cumulative density functions are shown in Fig. 13 and Fig. 14, respectively. It can be noted that, although only limited experimental data have been collected due to the pandemic situation, the kernel-fit of the experimental probability distributions of Dt' results in a multi-modal distribution that fits quite well the distributions coming from simulations carried out with different agents speed reduction factors.

Then, the Cramer-Von Mises test has been employed to assess which of the simulated agents speed V_a best fits the experimental data collected during evacuation trials. In Cramer-Von Mises test the null-hypothesis states that the compared distributions come from the same sample. Hence, the simulated probability distributions leading to retain the null-hypothesis with the higher significance level shall be chosen. In Table 5 the *p-value* associated with Cramer-Von Mises are provided. Hence, the most probable agent speed reduction factor is −2.5%, corresponding to 0.86% significance level related to null-hypothesis rejection.

Nevertheless, the experimental data are not sufficient to exclude that other values of speed reduction cannot be applied. In particular, for speed reduction within [0%, −7.5%] range the significant level to reject the null-hypothesis is still high. However, assuming a significance level of 0.1, the statistical test proved that the experimental data and the one related to the simulation based on $V_a = -10\%$ came from different samples. Hence, it can be excluded that the introduction of mobile technology to provide emergency guidance will not lead to passenger speed reduction exceeding 10%.

5 Discussion

The pilot system trials carried out in the test environment proved the technical feasibility of the application of mobile technology to provide guidance in a steel-made environment. However, steel-made environment was found very challenging for the tested technology, requiring careful installation and testing of the system before starting operation. To go

Fig. 8 Information shown by sending beacons in scenario 02 (FD C blocked)

beyond the current pilot system, installation of beacons in the ceiling to limit bulkhead reflection issues and avoid any compass-based signaling to make the guidance independent from ship course are recommended. Nevertheless, guidance provided by smartbands has been proved capable to reduce the travel time in case of blocked escape routes. In the experimental trials, 16.9% mean reduction of travel time has been achieved including scenario 01, where the travel time has been slightly increased. Besides the median of the evacuation experimental time reduction is 13.2%. These results are well aligned with ones coming from evacuation simulations assuming $V_a = -2.5\%$ (most probable value): the mean Dt' value is 18.3% whereas the median is 14.9%. These considerations, along with the statistical tests, proved that evacuation simulations are capable to reproduce the effect of the guiding system.

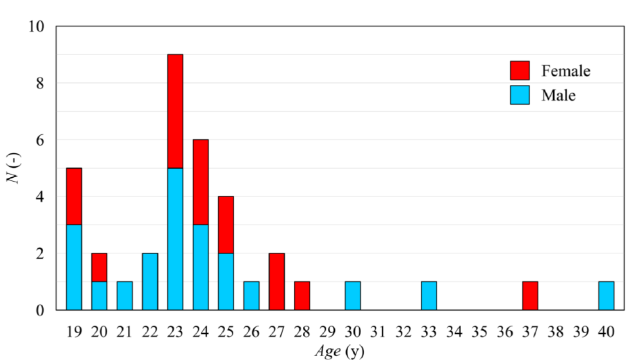


Fig. 9 Composition of the population who took part to the trials

Analysing Dt' probability distribution coming from simulations assuming $V_a = -2.5\%$ some additional considerations can be drawn. First, the introduction of mobile technology to guide passengers during an evacuation will result in a transit time reduction in 78.3% of cases in the studied environment. Moreover, the probability to cut by more than 50% the travel time is 9.5%. The same probability is associated with an increase in travel time higher than 8.5%. Such growth is mainly due to the scenario where all three escape routes are available (scenario 1), which is the only scenario having a negative mean and median of Dt' if considered alone. Thus,

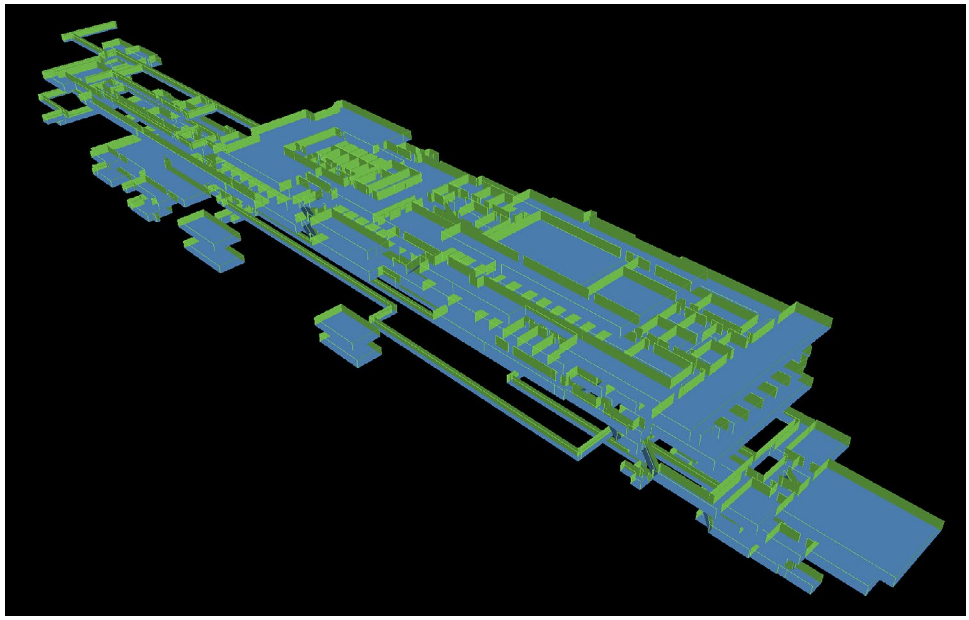
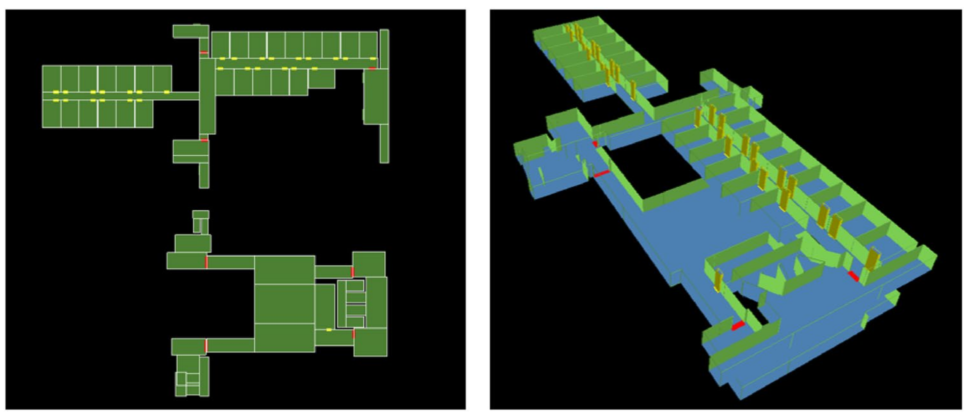


Fig. 10 Test ship model environment



a b

Fig. 11 Test environment model: **a** 2D view; **b** 3D view

Table 4 Experimental results for the tested scenarios

id	t (s) Baseline	Guide	Dt (s)	Dt (%)
01	100.0	105.0	−5.0	−5.00
02	114.5	81.0	33.5	29.26
03	87.0	78.0	9.0	10.34
04	124.0	104.0	20.0	16.13
05	96.0	75.0	21.0	21.88
06	106.0	103.0	3.0	2.83
07	130.0	74.0	56.0	43.08
Mean	108.2	88.6	19.6	16.93

the pilot system and the trials clearly show the benefits coming from passenger guidance even in a quite simple layout such as the one selected for the trials.

Finally, some limitations and issues with the pilot system, the test environment and the sample population shall be highlighted and discussed. First of all, the trials were carried out in a limited area of a medium-size RoPax vessel, which is far less complex than other passenger ships (e.g., large cruise ships). Although this was sufficient to reach the main goal of this work (i.e., check technical feasibility and reproduce the results with simulations) the travel time reductions obtained are case-specific and cannot be universally transferred to other contexts. In particular, it is expected that longer escape routes in more complex environments might lead to higher reductions in travel time.

Besides, the pilot system, although designed to be scaled, has been tested only in a limited area and with a limited number of users. Thus an upgrade might be still required to be applied to larger-scale environments. Moreover, the population that is mainly composed by young persons used to mobile technology might raise some concerns about the

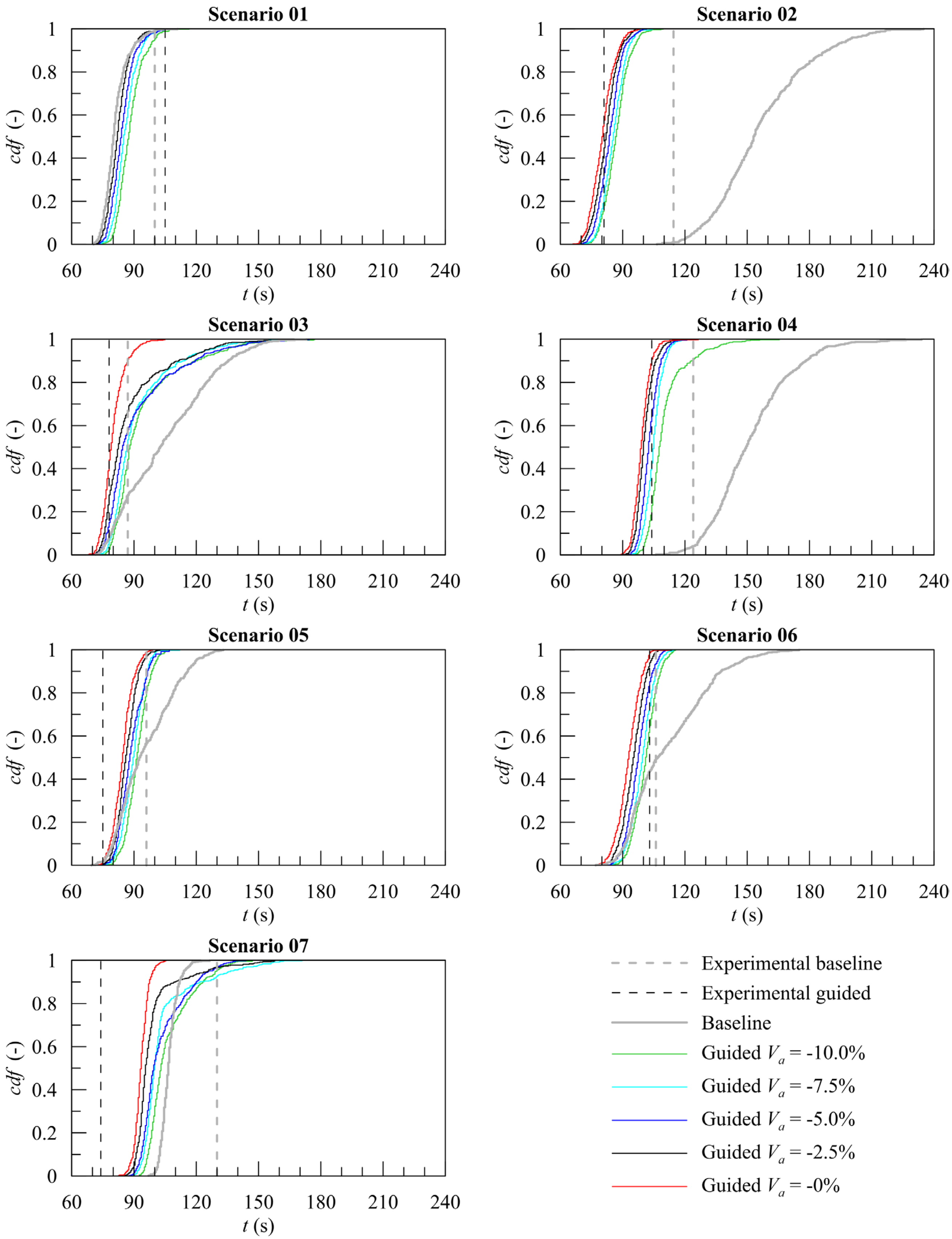


Fig. 12 Probability density functions of the normalized travel time reduction

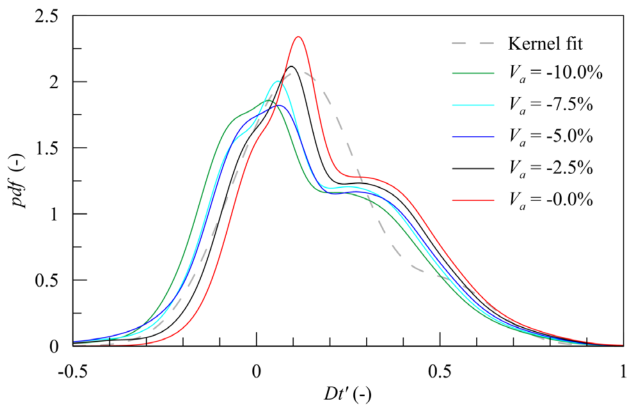


Fig. 13 Probability density functions of the normalized travel time reduction

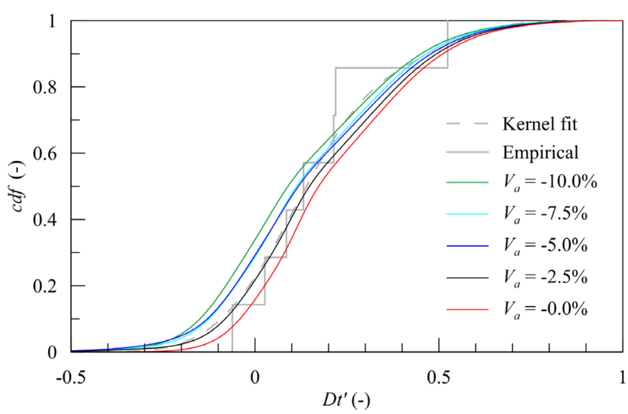


Fig. 14 Cumulative density functions of the normalized travel time reduction

applicability of determined agents' speed reduction factor to old people (that often can be found especially on cruise vessels). Further testing is advisable in the future using a more heterogeneous population.

Finally, during the trials, the ship WiFi has been adopted to enable the communication between the server and beacons. Currently, an onboard WiFi network is not explicitly required to be functional in an emergency situation since usually it is not used for the emergency communications defined in SOLAS Ch II Regulation 42. However, if an emergency guidance system is deployed, it will be subject to such a regulation. Hence, the solution tested in the trials would be viable provided that the WiFi network and beacons are powered by the emergency switchboard or an alternative emergency source of power. Otherwise, it would be necessary to adopt a wired connection to assure full functionality during an emergency.

Table 5 Experimental results comparing travel time with and without guidance

Agent's speed V_a (%)	p value
−0.0	0.53
−2.5	0.86
−5.0	0.54
−7.5	0.59
−10.0	0.09

6 Conclusions

The present work mainly aims at assessing the effectiveness of mobile technology to reduce travel time on a passenger ship and reproducing with a simulation tool the effects of guidance. The application of the proposed technology has been proved technically feasible in a real environment. Considering the selected test area and evacuation scenarios, persons have been safely guided by smartbands towards available escape routes, avoiding wasting time and removing the need to find out alternative routes when the main one (indicated by fixed onboard signaling) is unavailable for some reason. The achieved average reduction of travel time is 16.9% during trials. This is a remarkable result, considering that the test area was limited and the escape routes were quite short. Thus, it is expected to obtain even better results in more complex environments, such as cruise vessels.

To make data transferable to such different environments, the effects of a guidance system on the travel time shall be simulated. To this end, the scenarios investigated during trials have been reproduced through a simulation tool certified by IMO. The guidance effect can be simulated by combining a predefined path for the agents and a small reduction of their travel speed to account for the consultation of mobile devices. Despite the SARS-CoV2 pandemic limited the population recruitment and the number of experimental trials, through the proposed methodology based on the Cramer-Von Mises test, a good fit of experimental data has been achieved by applying a reduction of agent's speed ranging between 0% and 7.5%. In light of the available data, the recommended value is 2.5%, however, a further experimental study carried out with a larger population, in a larger environment with a larger number of runs per scenario is still advisable to improve the accuracy of these preliminary results. Besides, due to the young mean age of the population, some concerns might arise regarding the effectiveness of providing mobile guidance to elderly people. Again, further tests are advisable, but the straightforward design of information provided by the devices is expected to mitigate those issues. People not able to understand the information conceived by the device likely could not be able to read fixed signs as well, thus needing assistance from other passengers or crew anyhow. The future combination of visual and audible instructions from mobile devices might further mitigate issues related to elderly people's guiding effectiveness.

From a financial point of view, the proposed system does not require a significant initial investment; furthermore, it can be more easily amortized by adding commercial features to the system. In fact, indirect revenues might come from the enhanced corporate image gained with the safety improvement. Besides, other revenues can come from the analysis of the localisation data collected during normal operation or from providing additional services to passengers connected to smartbands (e.g., access to cabins, payments, guidance in normal conditions, etc.). The integration with commercial features/services is deemed very important by all the stakeholders inquired during the pilot system development to assure a financial return as well as to make passengers familiar with smartbands. Besides, the proposed technology can be useful for the detection, tracking and limiting the spread of pandemics onboard, since mobile devices might be equipped with biometric sensors and can communicate long proximity to the system's backend.

In conclusion, after the deployment of the pilot system, the trials carried out with the sample population and their successful reproduction with a simulation tool, the main goals of the present work can be considered achieved. These promising results are expected to foster further research in the field aimed at a widespread application of mobile technologies to improve the safety and security of ships.

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Author Contributions Luca Braidotti: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing– original draft, writing–review and editing, visualization. Serena Bertagna: conceptualization, methodology, validation, investigation, resources, writing–original draft, writing–review and editing, visualization. Vittorio Bucci: conceptualization, validation, investigation, resources, writing–review and editing, visualization, supervision, project administration, funding acquisition. Alberto Marino': conceptualization, validation, investigation, writing–review and editing, supervision, project administration, funding acquisition.

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Data availability Data available within the article.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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