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Identification of measures to contain the outbreaks on passenger ships using pedestrian simulations

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Abstract

The SARS-CoV-2 pandemic, since the beginning of 2020, has had a strong effect on many industry sectors including maritime transport. In this context, the passenger transport industry was the most affected and it is still in a very critical situation. Starting from the "No Sail Order" issued in March 2020, cruise companies stopped their operations. Besides the international regulatory bodies issued several guidelines for the prevention and management of pandemics onboard in order to safely resume cruises. The present work addresses this topic, aiming to discuss procedures and best practices to reduce the risk of uncontrolled spreading of SARS-CoV-2 infection on large cruise vessels. Starting from the lessons learned from the representative case of Diamond Princess, here the tools developed in the framework of Industry 4.0 have been used to highlight and handle the criticalities risen on the internal layout of passenger vessels, opening new opportunities to operate existing vessels and improve the design new buildings for outbreaks prevention and control.

Keywords: Pedestrian simulations; pandemic control; cruise industry; onboard application.

1. Introduction

The SARS-CoV-2 pandemic first notified in December 2019 in Wuhan (Hubei, China) had and still has a strong impact on the world economy. Considering the maritime sector, the cruise ship industry is widely the most impacted [1] with an estimated loss of over 50 billion dollars in the period March-September 2020. Cruise ships are high-density isolated communities, where often public spaces are overcrowded and many services are shared onboard by passengers or crew members. Such a scenario make ships prone to outbreaks and hinder their control. These critical issues were visibly highlighted by the Diamond Princess case, smashed by an outbreak of SARS-CoV-2 between January and February 2020. The infection started from a passenger disembarked in Hong Kong [2,3] and, despite the quarantine measures put in place, involved 3711 persons with 14 casualties. Onboard, the virus mainly was transmitted by direct contact among persons [4,5], infected surfaces [6,7], and Heating, Ventilation and Air Conditioning (HVAC) systems [8] although the latter has been questioned [9]. The Diamond Princess outbreak forced the US government to issue the "No Sail Order" that stopped all cruise operations in the USA, while other governments issued similar directives worldwide.

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This scenario opened the need to define procedures and guidelines to assure safety on passenger vessels relating to the SARS-CoV-2 pandemic as a necessary condition to resume cruise operations. However, currently, no rules or guidelines are applied during ship design and manufacturing to prevent or contain an outbreak onboard. Hence, the existing fleet, and in particular the internal layout of current passenger ships, is not suitable from this point of view requiring the definition of special measures. First, the internal spaces shall be classified according to their infection risk level [10]. Then, considering all the applicable guidelines issued in the last year by national and international regulatory bodies, a ship-specific plan to prevent and contain a SARS-CoV-2 outbreak shall be put in place [11].

Considering the large cruise vessels, one of the most critical issues is the density of persons within the public spaces, where easily infection can spread. The effect of people traffic patterns on virus transmission has been already explored for buildings [12]. Therefore, a detailed analysis of the movements of passengers and crew onboard can be very helpful to mitigate the infection risk. In such a context, Industry 4.0 and Shipping 4.0 tools can be applied. In particular, this work explores the application of pedestrian simulations to detect the critical issues in ship public spaces and assess countermeasures on existing ships. Besides, alternative designs to make new ships less prone to outbreaks can be proposed too. In the first section, the current guidelines regarding SARS-CoV-2 prevention and control measures are reviewed providing the context for the application of pedestrian simulations. Then, the risk evaluation and mitigation procedures are described and the application of pedestrian simulation is proposed. Finally, the procedure is applied to a critical area on an existing passenger vessel.

2. Rules framework

After the "No Sail Order" issued on March 14th 2020 by American Centers for Disease Control and Prevention (CDC) in agreement with Cruise Lines International Association (CLIA), the development of new guidelines started to enable safe recovery of cruise operation. In this section, the most important recommendations provided by the regulatory bodies are reviewed with special attention to cruise ships. The main reference is the Internationale Maritime Organisation (IMO) Circular Letter No.4204 [13] and its annexes. Besides, also guidances issued by CDC [14], CLIA [15], European Maritime Safety Agency (EMSA) [16] and World Health Organisation (WHO) [17] are here considered. The guidelines regarding SARS-CoV-2 can be divided into two categories: the preventive measures applied before the voyage and the ones adopted during the voyage including both prevention and control of the outbreak onboard. It is worth noticing that currently all these requirements are not mandatory, but provide a useful framework to deal with the SARS-CoV-2 pandemic onboard.

2.1. Pre-Cruise Preventive Measures

Before starting a voyage, the cruise company is required to monitor the global status of the SARS-CoV-2 pandemic, focusing on passengers origin. Based on screening data, a risk assessment should be carried out and the preventive measures should be customized according to the current situation. Besides, the passengers and crew members shall receive all the information about the current status of the pandemic as prescribed by WHO and are required to fill a form to collect their data relating to the 14 days before embarkment [18]. Moreover, persons engaged in international voyages shall be informed about the preventive measures put in place onboard and consent to the monitoring of their health status. Finally, all the persons shall be aware that they cannot embark in case of contact with a suspect or positive case of SARS-CoV-2 as defined by WHO [19].

Furthermore, the following preventive measures shall be considered before departure:

- Reduce the ship occupation to arrange a segregated quarantine area;
- Train the crew considering the new procedures and regulations applied onboard;
- Divide the crew according to their mansion and according to the risk level of exposure to SARS-CoV-2;
- Require crew members coming from high-risk regions to be tested and to limit their contacts 72 hours before the embarkment;
- Limit the access onboard for onshore personnel (only authorized persons in a restricted area).

2.2. Onboard Preventive Measures and Outbreak Control

During the voyage, the ship health safety shall be safeguarded by infection prevention and outbreak control. Both the measures are addressed by the so-called Outbreak Prevention and Management Plan (OPMP) introduced by the WHO [17]. The OPMP shall be carried onboard and a team shall be identified to assure its implementation and application. The OPMP deals with:

- *Social distancing and public space management*: the public spaces shall be ranked according to risk. Information regarding social distancing shall be implemented onboard including the maximum capacities of public spaces, routes to prevent congestions and overcrowding usage of protective equipment and hand sanitizing spots. A minimum distance of 1.83 m shall be assured between persons not coming from the same family unit [14]. Overcrowding shall be avoided as far as possible, including the removal of unnecessary furniture/obstacles. Fixed spots where crew may come in contact with passengers shall be arranged with protective barriers;
- *Cleaning and sanitizing*: the OPMP shall specify the frequency and the type of treatment of all the spaces onboard according to their usage, daily occupation level and material composing furniture surfaces. Specific spaces shall be allocated for storing

cleaning and sanitizing products. Procedures shall be defined to clean cabins housing suspected or positive cases of SARS-CoV-2 including the instruction to handle their objects;

- *Management of HVAC systems*: special measures to prevent the spreading of SARS-CoV-2 regarding the HVAC systems shall be considered by the cruise company together with the manufacturer [16]. In detail, the frequency of cleaning of HVAC systems parts, replacing filters and/or the number of air exchanges per hour should be reconsidered.
- *Management, preparation and serving of food and beverage*: preparation and serving shall be segregated. If a sufficient degree of safety cannot be assured, buffet areas shall be removed. Hand sanitizing spots and personal protective equipment shall be available in each area devoted to preparation and serving of food and beverage;
- *Use of Personal Protective Equipment* (PPE): the plan shall specify the areas of the ship where PPE are mandatory and define the proper PPE type for each area. According to WHO, the medical mask is mandatory in all the internal spaces and shall be required also in open spaces if social distancing might not be respected [19];
- *Managing a suspected case*: proper protocols shall be defined for the continuous monitoring of crew and passengers health [17]. A clinical centre shall be arranged onboard to carry out tests. The crew should be daily tested to assure their service onboard and thermo-scanners might be installed in public spaces. When possible, the crew members and the passengers should be provided with individual thermometers. If a suspected case as defined by WHO [20] is identified onboard the outbreak plan shall be activated. The suspected case shall be instructed to the procedures to follow and segregated from other passengers and crew. Infection control measures should be applied [20,21]. Contact tracing should begin immediately without waiting for laboratory results. All suspected cases and contacts with SARS-CoV-2 patients shall be quarantined for 14 days from the last exposition;
- *Segregated quarantine area arrangement*: a segregated area for quarantine shall be arranged onboard, reducing the total capacity of the ship. It might extend over multiple decks in a single Main Vertical Zone (MVZ). Only medical personnel devoted to patient cure shall be authorized to enter the area provided that they wear proper PPE. The HVAC systems of the area shall be independent. It is recommended to include in the quarantine area cabins with balconies to ease the natural air exchange and to lower the psychological stress coming from isolation. All the objects used by patients (e.g. garbage, sheets, clothes, etc.) shall be treated separately and considered infected. Food and beverage should be packed and delivered outside the cabins to avoid unnecessary contacts. The capacity of the quarantine area shall be assessed according to the ship characteristics and the planned voyage.
- *Disembarkment of positive cases*: in accordance with port authorities and if it is possible, positive cases of SARS-CoV-2 should be disembarked. Dedicated routes shall be arranged onboard for disembarkment to minimize the risk of infection and contact. These passages shall be cleaned and sanitized after usage. Personnel involved in disembarkment shall use proper PPE and follow the WHO guidelines [21,22].

3. Risk evaluation and mitigation procedure

Passenger ships and, in particular, cruise vessels are a particular environment presenting some critical issues relating to outbreaks. As mentioned, SARS-CoV-2 infection can spread onboard in two main ways: direct contact with persons or contact with infected surfaces. In the first case, it can be vehicled by positive cases identified through testing or asymptomatic persons. While the formers are immediately segregated and their contacts tracked, the latter can still freely move inside the ship and come in contact with all the other persons. Hence, all the public spaces onboard having intrinsically a high density of persons and frequent contact can foster the outbreak. Therefore, it is very important to rationally identify the risk level of all the areas onboard to apply the proper mitigation strategies. Besides, the main critical parameters to assess the risk level shall be defined.

3.1. Critical Parameters

According to the recent experience and the recommendations issued by regulatory bodies, the most important parameters that can foster an outbreak onboard passenger vessels are the following:

- *Density of persons*: considering the infection risk within an internal space, the first critical issue is the number of persons. Considering the CDC minimal distance D = 1.83 m applicable to persons from different family units, the corresponding maximum density is 0.38 persons/m^2. Spaces having a higher density will be assigned to a higher level of infection risk compared with the ones having a lower density.
- *Proximity*: it takes into account the type of activity carried out within a specific internal space onboard. Some activities could not assure strict social distancing or cannot be carried out wearing the PPE. There are many situations where social distancing cannot be assured and are not all equally critical. Moreover, even when the density is kept under control, the type of activity might anyway imply higher risk (e.g. activities in medical areas).
- *Aggregation*: it accounts for the number of persons involved in an activity and the contact level expected among them. For instance, aggregation in cabins and small shops will be lower than the one in swimming pools or during a show. Then, aggregation shall be considered to assess the risk level.

- *Layout of internal spaces*: the arrangement of the internal spaces can affect the behaviour of persons and especially their movement between different areas of the ship. The ship design process defines the internal layout of the ship according to safety criteria (e.g. the ability to survive fire or flooding [23-25]) while fulfilling their functional requirement. Currently, no requirements dealing with the containment of an outbreak are applicable during ship design. Thus the ship internal layout might present several critical issues from this point of view.
- *HVAC*: Most of the public spaces onboard where crew and passengers come in contact are served by HVAC systems that are not capable to assure a sufficient air exchange and filtering required to prevent infections [7,26]. Usually, about 70% of air is recirculated and common HVAC systems serving multiple spaces might spread the infection among them, as already happened in passengers cabins having common air ducts [8].

3.2. Classification of Ship Internal Spaces

According to the identified parameters, a ship can be divided into areas with a different risk level of exposure to SARS-CoV-2. The exposure risk accounts for the probability of coming in contact with a source of infection during the specific activity carried out in a specific internal space of the ship. Following the guidelines provided by regulatory bodies [14,17], here a three-level classification is proposed including the related colour used hereinafter:

- *Low* (low exposure risk), colour: green;
- *Medium* (medium exposure risk), colour: yellow;
- *High* (high exposure risk), colour: red.

Table 1 provides an overview of the classification of internal spaces highlighting their characteristics and critical issues. It is worth noticing that most of the spaces of a ship are usually classified as low or medium risk areas since, according to the outbreak control measures, the positive cases shall be segregated and the main driver for high risk is the interaction with positive cases.

Table 1. Classification of ship internal spaces according to the exposure risk.

Classification	Characteristics	Limited ventilation and air exchange	Direct contact with infected surfaces and objects	Possible overcrowding/insufficient capacity	Direct contact between passengers and crew	Difficult cleaning/sanitizing of surfaces/objects	High density of persons (social distancing issues)	Congestions at entrance/exit	No secondary entrance/exit	Direct contact with suspected or positive cases	Example
Low exposure risk	Areas with no direct contacts with persons, or where contacts are limited in time or to the members of a family unit; Areas with no direct contact with a suspect or positive case.	✓	✓	✓	✗	✗	✗	✗	✗	✗	Corridors, Stairs, Cabins
Medium exposure risk	Areas with no direct contact with a suspect or positive case; Areas used as an aggregation point by passengers/crew; Areas where social distancing cannot be kept or PPE cannot be used for limited periods due to proximity; Internal spaces with limited air exchange capability.	✓	✓	✓	✓	✓	✓	✓	✓	✗	Restaurants, Bars, Cinemas, Theatres, Casinos, Elevators,
High exposure risk	Areas with direct contact with a suspect or positive case.	✓	✓	✓	✓	✓	✗	✗	✗	✓	Medical zone, Quarantine areas

In the proposed classification, a low-risk area is not intended as a safe one (null probability of exposure) but an area where there is not frequent interaction among passengers and between passengers and crew. Therefore, low-risk areas can be mainly identified as stairs, corridors and cabins. Stairs and corridors serve only as a passage to move from a place to another. Hence, interactions among passengers/crew are just limited in time and it is quite easy to keep the social distancing. Inside cabins, contacts are mainly limited to the family unit, although the risk might be increased by several causes: imposing restrictions is difficult and many contact surfaces are present [27].

Medium-risk areas differ from low-risk ones mainly due to the high density, proximity and/or aggregation. The main medium-risk areas onboard are public spaces, service spaces, lobbies, restrooms and elevators. Public spaces (e.g. restaurants, cinemas, theatres, casinos, etc.) are very critical since they are usually used by a large number of persons having frequent contact with each other. Usually, in public spaces, seats and tables layout is not designed to ensure the minimum distance (Fig. 1). Besides, due to the high density of people and the nature of activities (e.g. eating, attending a spectacle, etc.) entrances and exits might create temporary overcrowding. Besides, contact surfaces can also vehicle infection in public and service spaces (e.g. galleys, pantries, laundries, etc.). The virus can deposit on surfaces during ordinary activities and then be transmitted to the persons touching the infected surface/object [28]. From this point of view, buffet areas are the most critical spots. Considering crew during normal operations, it is very likely that crew members carrying out different activities in service and public spaces come in contact with other crew members inside their common or accommodation spaces. The lobbies have been also considered here as medium-risk areas. Encompassing three or more decks, they connect multiple public spaces favouring the air interchange as well as the natural interaction among passengers. Finally, the elevators have been classified as medium-risk areas due to the high density (about 3 persons/m^2) that is not compliant with social distancing. Additionally, the pushbutton panel is a critical surface that can easily vehicle the infection among users.

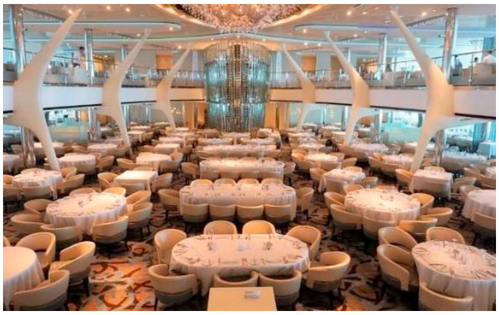
a)  b) 

Fig. 1. Sample of public spaces on a cruise vessel: (a) restaurant; (b) theatre.

High-risk areas are the ones where interaction with suspected or positive cases occurs. Hence, in normal operations, only the medical zone is classified this way. Considering existing ships, this area has usually limited extension. It is located within a single MVZ on a deck devoted to crew accommodation and service areas. Considering current designs the main critical issues are the lack of separation from other spaces and the insufficient capacity during outbreaks. Currently, the crew might be expected to cross the medical area while carrying out their normal tasks. Besides, the systems serving the onboard hospital (including HVAC) are not usually dedicated. Finally, accommodations are fitted for about ten patients assisted by a very basic medical staff. Hence, the capacity, system and staff are currently not sufficient to deal with a wide outbreak such as a SARS-CoV-2 one. This is why a wider quarantine area is required classified as a high-risk area too and assuring segregation from the rest of the ship.

4. Pedestrian simulators

Simulation is one of the key enabling technologies in the framework of Industry 4.0. Considering the specific problem posed by onboard outbreaks this knowledge can be used to properly manage existing vessels and, besides, to modify the new designs and make them more resilient to outbreaks. In this section, a pedestrian simulation tool initially developed for terrestrial application is presented, along with its usage procedure in a ship environment to face pandemics.

4.1. Adopted Simulation Tool

Here, the Legion pedestrian simulation model has been used. It has been developed for infrastructure design to simulate the movements of persons inside a limited space and it is quite different from tools used to simulate ship evacuation [29]. Legion is based on an intelligent-agent approach to modelling pedestrian behaviour and event ingress and egress movements [30]. The model has been validated against empirical measurements of real people [31] being a reliable simulation tool for crowd behaviour simulation. In detail, the pedestrian simulations permit the analysis of the interaction between persons and the environment under test/design. Its typical applications are transport nodes (e.g. airports, train stations, underground stations [32,33]) or crowded environments (e.g. stadiums, squares, city centres, expos [34]).

Simulations are carried out in a microscopic model of the environment that can be modelled with CAD tools. In the model, all the spaces available to the crowd are delimited and the ingress and egress points are defined. The number of intelligent agents with their start and final points is defined for groups or single agents by the so-called Origin-Destination (OD) matrix. Intelligent agents move between start and final points following the “minimum effort” principle to reach their final destination. During the movements, agents interact with the environment, with the objects and with the other agents. Agents follow behavioural models defining their characteristics and their actions. In fact, besides principal movement from the start point to the destination, agents can do actions or follow specific paths inside the model controlled by direction modifiers, delay points, route guides and focal nodes. The pedestrian simulation model enables the evaluation of all the main variables describing the crowd status at each time instant during a simulation: examples are the cumulative mean density, the level of service, and mean velocity of persons, time of ingress/egress. A recent update introduced some additional features to deal with the current SARS-CoV-2 pandemic [35]. To deal with social distancing, the pedestrian model can evaluate the maximum capacity of a specific space and keep a defined distance between agents.

4.2. Simulations in Cruise Ship Environment

Figure 2 shows the proposed process to use pedestrian simulations to manage existing passenger vessels or to improve new designs. First, it is necessary to model the ship internal spaces under study. The model can be defined starting from ship general arrangement identifying all the areas available to the agents (e.g. stairs, elevators, doors, etc.) and all the obstacles that can affect the movements (e.g. walls, windows, bulwarks, furniture, etc.). Considering the complexity of the ship general arrangement, to assure an acceptable computational load, all the elements that are not useful during simulation shall be removed (e.g. the movable objects such as chairs in a restaurant).

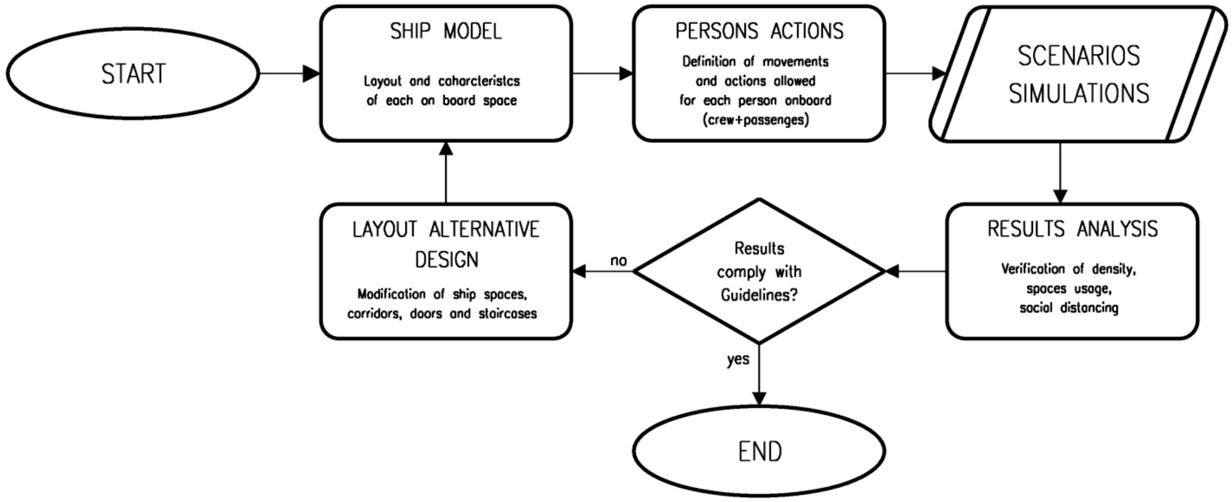


Fig. 2. The developed process for a cruise ship environment.

Then, the persons' actions are defined according to the space type and purpose. The ingress/egress facilities shall be modelled as well as the points where specific activities are carried out. Preferred paths can be defined for a group of agents (e.g. crew movements in service spaces) and also delays can be introduced (e.g. at elevators, at a restaurant entrance, etc.). In detail the following data can be used:

- *Persons' profiles*: for the maritime environment, the standard population (age, gender, etc.) defined by IMO is used [36];
- *OD matrix*: the distribution of passengers and crew (origin) is defined according to the day case as specified in chapter 13 of Fire Safety Systems (FSS) Code [37]. Detailed data can be retrieved from the ship escape plan. The destination definition is more complex since data are not usually available especially in a design phase. Hence, case by case assumptions shall be done consulting shipping companies;
- *Simulation controls*: according to the agent/group of agents additional actions or specific paths can be defined to better reproduce the behaviour of crowd moving in the environment and to simulate outbreak preventive measures.

As model and persons behaviour have been defined, the simulation can be performed and, then, the result analysis can start. Considering the SARS-CoV-2 infection prevention, the most important parameters to monitor are the maximum cumulative density, the level of service and the maximum capacity of a space computed while complying with social distancing. If the current layout/capacity of the spaces turns out to be non-compliant with the international guidelines for the containment of SARS-CoV-2, a layout alternative design shall be proposed and tested. Considering an existing vessel, major changes in the current arrangement are not possible. However, acting on the simulation controls, the impact of the mitigation/prevention measures can be assessed (e.g. the definition of guided paths defined with movable signs/barriers, the removal of some seats/tables or more strict limitation of the space capacity). Considering a new design, the general arrangement can be modified too. For instance, boundaries can be moved or additional entrances/exits can be fitted. However, this higher freedom shall be handled with care since it might affect the overall commercial/technical performances of the passenger ship while improving the outbreak resilience only.

5. Case study

The pedestrian simulations for outbreaks prevention and controls have been applied on a recent large passenger ship operating on the west coast of the USA and Canada. The ship is 299.65 m long and has a breadth and draught of 35 m and 7.95 m respectively. Its maximum capacity is 4173 persons of which 1036 are crew members. Here, focus has been made on the restaurant located on decks 2 in the aft MVZ, i.e. the last zone at the rear of the ship. In the present section, the critical issues of the test environment are identified exploiting pedestrian simulations to define possible solutions for the current vessel as well as for a new design, modifying the current internal layout only.

5.1. Test Environment

Deck 2 on the test ship is fitted with large public spaces as shown in Figure 2 together with the classification according to the proposed risk scale. Most of Deck 2 is considered a medium-risk area. Only the large corridors connecting the main spaces are classified as low-risk areas. The restaurant located in the aft MVZ is one of the most critical medium-risk areas (Fig. 4a). This space has a maximum capacity of 700 passengers and 25 crew members. Thus, considering the day case the occupation in a normal condition is 525 passengers and 25 crew members [37]. Persons have access to the restaurant only through the main doors in the fore boundary of the space. It is worth noticing that the simulation of movements within a restaurant is quite critical due to the large number of tables and chairs. Since the pedestrian model considers only fixed obstacles, the chairs have been not modelled, but the tables' dimension has been increased by 50% to compensate for chairs removal (e.g. Fig. 6). This assumption can affect the simulation, however, the main objective of this work is to avoid congestions, hence it is more focused on what happens at the entrances/exits, which are the most critical points from this point of view.

Fig. 3. Classification of Deck 2 spaces according to the proposed risk scale.

a) b)

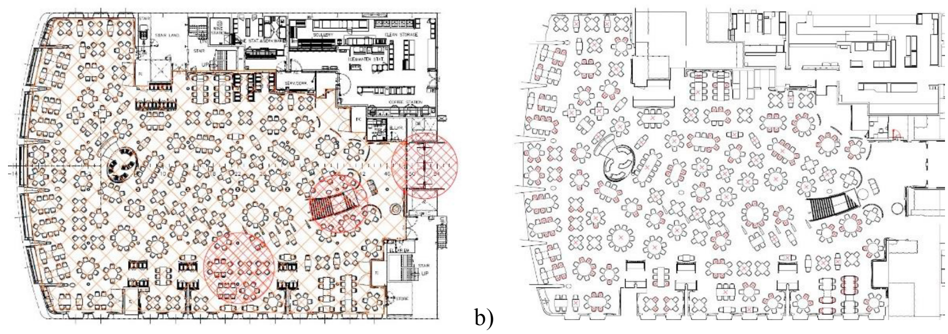
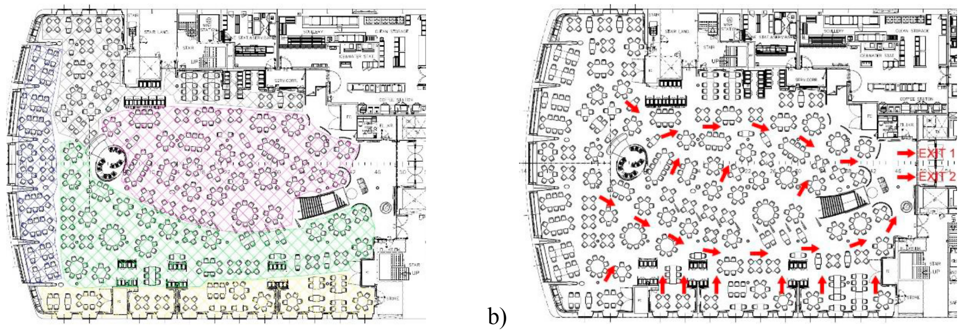


Fig. 4. (a) The considered test environment; (b) seats and tables removed to assure social distancing.

5.2. Critical Issues Identification

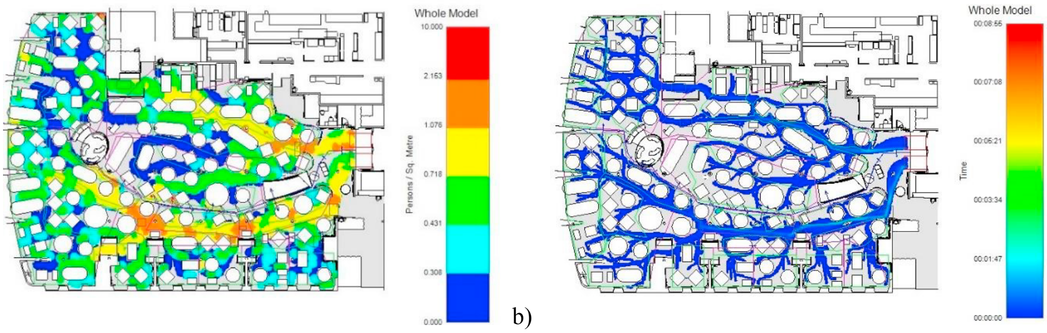
Considering the total surface of the space (highlighted in Figure 4a), the maximum number of passengers and the one according to the FSS code drive to a mean density equal to 0.67 and 0.49 persons/m^2, respectively. In both cases, it exceeds the maximum density related to social distancing (0.38 persons/m^2) and deeper analysis is then required. Since passengers are usually seated in restaurants, social distancing among seats and tables shall be checked. According to CDC [14], no more than 4 persons can stay at the same table and a 1.83 m minimum distance shall be kept between different tables (very large tables can be considered two tables, provided that the distance between seats is more than 1.83 m). To remove seats and tables, an initial pedestrian simulation carried out with 525 passengers (day case according to [37]) provided guidance, helping to select the ones that impede the main routes followed by passengers. This assessment resulted in a maximum number of seats equal to 287 arranged as in Figure 4b.

With such an occupation, simulations can help in checking the density during the critical phase of entrance and exit. Preliminary tests showed that free-to-move people create very critical congestions at the restaurant main entrance. Since the current layout cannot be changed without a costly retrofit, tan access scheduling has been proposed. To this end, the restaurant has been divided into sectors as shown in Figure 5a. Seats can be booked onboard to fill first the most distant ones from the entrance. Besides, also exit from the restaurant shall be strictly regulated. Specific paths (Fig. 5b) shall be defined and marked with proper signalling and the exit from sectors shall be carried out in reverse order compared to the entrance. The whole exit process has been planned to last no more than 10 minutes. With these measures, the congestion is much reduced resulting in the maximum cumulative density and level of service shown in Figure 6. It is worth noticing that some overcrowding exceeding the maximum density is still present at the exit and bottlenecks created by tables layout. However, their duration is very limited in time.



a) b)

Fig. 5. (a) Division in sectors of the aft restaurant; (b) exit routes of the aft restaurant.



a) b)

Fig. 6. (a) The maximum cumulative density in the test environment; (b) the level of service in the test environment.

These problems might be solved only by changing the current layout or further reducing the space capacity, although the first cannot be easily implemented on an existing ship and the latter is not feasible for commercial reasons.

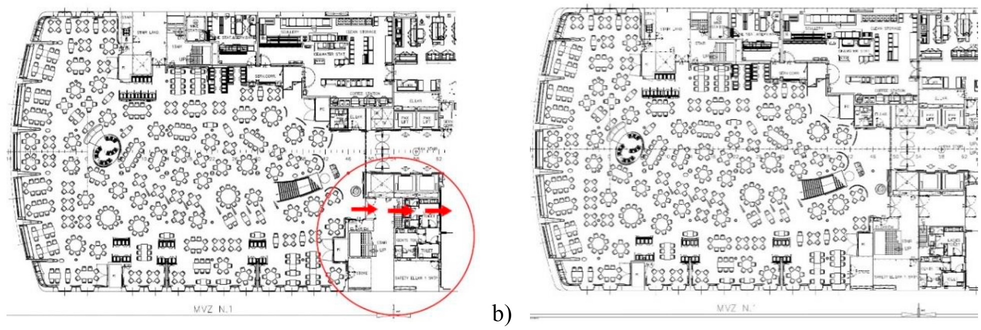
5.3. Guidelines for New Buildings

Considered the critical issues identified above, it is possible to propose some changes applicable to a new design to make it more resilient to outbreaks. Considering the aft restaurant, the main design issue is the single entrance which is insufficient to avoid overcrowding during the passenger exit at the end of a turn. In a new design, the issue can be solved by adding a new entrance/exit to the restaurant. The process requires the reallocation of the spaces or functions that now occupy the position of the new entrance.

For the specific case under study, the position identified for the new entrance is shown in Figure 7a. Hence, it is required to review the layout of three restrooms, a store and an electric cabinet. The proposed alternative layout is provided in Figure 7b. The restrooms have been slightly modified and moved towards the ship side while the store and the cabinet are located abaft. It is worth noticing that the modification affects the current capacity of the restaurant by removing 8 seats. This example shows how it is possible to rearrange spaces in a new design starting from the criticalities identified through pedestrian simulations. However, such modifications might be costly. Usually, arrangements to prevent outbreaks require more space compared to the current passenger vessel layout with a negative impact on ship capacity and thus on its economic/commercial performance.

6. Conclusions

Simulation, as a key tool within Shipping 4.0, has proved once again to be a powerful instrument applicable to very different contexts. This work showed how pedestrian simulations can be used to mitigate the risk related to outbreaks on a large passenger ship. Firstly, the assessment of the infection risk has been defined. Then a procedure to use pedestrian simulations on a passenger ship environment has been proposed and applied to the test ship.



a) b)

Fig. 7. (a) The area identified to add a restaurant exit; (b) the alternative layout of a new design.

The critical issues related to infection onboard have been identified by means of pedestrian simulations. In detail, simulations are capable to monitor the space occupation and density during critical movements of passengers and crew. Moreover, by using the simulation modifiers applied to groups of intelligent agents, measures to mitigate the infection risk in an existing ship have been tested. The results of these analyses can guide the ship design team to review the ship general arrangement when it might foster an outbreak onboard. This process can be applied for both new ships or old vessels refitting. As mentioned, the design procedure shall consider concurrently technical and commercial aspects too in order to assure the success of the new design and minimize the expenditure, especially in retrofit cases.

The present work explored a first example of the possible application of pedestrian simulations onboard, focusing on medium-risk spaces with tables and seats characterized by passenger long stay with limited use of PPE. However, future works should address the other medium risk spaces not intended for passenger long stay as well as corridors, stairs and passages where simulations can support the decision of unidirectional routes to limit contacts among passengers and crew. Besides, to improve the outbreak resilience of passenger ships, other actions are also mandatory: proper signalling or guidance shall be put in place, the HVAC systems shall be redesigned including proper filters and air exchange capability as well as the medical spaces and the ways to improve their capacity in case of outbreaks including a large and segregated quarantine area. In all these processes, pedestrian simulations are expected to play a key role to design and build more safe ships.

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