A CRITICAL REVIEW OF THE EVACUATION PROCESS DUE TO FIRE OR FLOODING FROM CRUISE VESSELS AND LARGE ROPAX CESSELS AND THE FUTURE CHALLENGES AND DEVELOPMENTS

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Ship evacuation in response to fire or flooding hazards involves two phases: mustering, that is the reallocation of passengers from a designated area to a safer area or to the muster stations and abandoning the ship (embarkation and launching lifeboats). Evacuating a dynamic and complex environment such as a cruise vessel is a safety-critical and strictly time-bound task, which typically involves thousands of people moving within parts of the ship, assisted by a significant number of crew personnel, and a complicated decision-making process based on the evolving situation on-board and the information available to the decision makers. Timely and safe mustering and abandonment require accurate evaluation of ship's conditions as well as estimation of remaining time. A critical review of the evacuation process due to fire or flooding from Cruise Vessels and large RoPax Vessels in terms of the existing regulatory framework, the installed life-saving appliances and the smart environment elements are presented. This paper is concluded with the future challenges and developments concerning the evacuation process.

Keywords: Maritime Safety, Ship Evacuation, Smart environment elements, Life-Saving Appliances (LSA), legislation

1. INTRODUCTION

During the last decades, size and capacity of Cruise and RoPax vessels have significantly increased. In two short decades (1988-2009), the largest class cruise ships have grown a third longer (268 m to 360 m), almost doubled their widths (32.2 m to 60.5 m), doubled the total passengers (2,744 to 5,400), and tripled in volume (73,000 GT to 225,000 GT). Also, the "megaships" went from a single deck with verandas to all decks with verandas [1]. This increase in capacity and complexity has raised concern on the safety and viability of evacuation, considering the thousands of people in distress during an emergency.

Ship evacuation in response to fire or flooding hazards involves two phases: mustering and abandoning the vessel. Mustering refers to the assembly of passengers into designated areas, while abandoning involves the embarkation and launching of Life-Saving Appliances (LSA). Each phase has its unique characteristics and limitations, while both involve managing large crowds of passengers. Thus, clear instructions and guidance for passengers are significant for large passenger ships in emergency scenarios [2].

SOLAS Reg. III/38 and Maritime Safety Committee's (MSC) MSC.1/Circ.1212 were implemented in 2007 to allow the use alternative LSA designs, as long as they are proven -through risk-based safety assessment methods- at least as safe as SOLAS complying appliances [3]. The regulations also act as a guideline to conduct the safety required assessment and since then, LSA manufacturers have been continuously improving the equipment they produce. Along these lines, the -relatively- recent and rapid advancements in information and communications technologies enable smart environment elements to be developed and integrated into the ship design to facilitate the evacuation procedure [4].

The goal of this paper is to contribute to the ongoing efforts for increasing the level of maritime safety on Cruise Vessels and RoPax Vessels. To achieve this, a critical review of the evacuation process due to fire or flooding in terms of 1) regulatory framework, 2) installed LSAs and 3) smart environment elements is conducted. This review aims to highlight both the recent developments as well as the future challenges concerning the evacuation process. This is followed by a discussion on the most promising proposed solutions -that are currently under development- and their anticipated impacts.

2. SHIP EVACUATION REGULATORY FRAMEWORK

The first organized attempt to set the minimum safety standards in ships, the International Convention for the Safety of Life at Sea (SOLAS) was adopted in 1914, in response to the Titanic disaster in 1912 [5]. SOLAS was based on internationally agreed standards, establishing detailed technical requirements on ship construction, fire protections, stability and life-saving equipment. SOLAS is under the auspices of the United Nations International

Maritime Organization (IMO), and during the past years has been revised and updated many times [6].

Following the adoption of SOLAS, several conventions have developed regulations in order to follow the technological advances, such as International Fire Safety Systems (FSS) [7] Code, the High Speed Craft (HSC) Code [8], the International Life-saving Appliances (LSA) Code [9], the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [10] and other MSC Circulations.

The LSA are covered by SOLAS Chapter III and the LSA Code [9]. The LSA code describes the requirements for lifeboats, rescue boats, lifejackets etc. considering each specific ship type. To avoid limitations and remove innovation constraints, the IMO opened the Alternative Design and Arrangements (AD&A) path for additional measures to be introduced - given that they provide, at least, equal level of safety. Acknowledging the constraints created by the existing prescriptive requirements, regarding, in particular, large cruise ships, in 2009 IMO opened the Alternative Design and Arrangements (AD&A) [11] path for novel solutions that offer the same level of safety and performance with the prescribed ones. Currently, IMO is developing functional requirements for life-saving appliances in compliance with MSC.1/Circ.1394/Rev.1. Therefore, the IMO has agreed on a new work item on the revision of SOLAS chapter III and LSA Code (MSC 98) [12] based on the Goal-Based Standards-Safety Level Approach (GBS-SLA) [13].

Despite the extensive regulatory framework, evacuation of passenger ships and especially of very large vessels remain a complex task, in which multiple factors must be considered [14]. Current International Maritime Organisation (IMO) evacuation guidelines relate to daytime and night-time scenarios in calm water and in the absence of any additional hazards [15]. The construction of the ship, the proper use of the life-saving equipment, the safety plans that must be followed, the time restrictions and the necessary training are among others critical parameters in case of an evacuation announcement [16].

2.1 DESIGN AND CONSTRUCTION PHASE

Starting from the early design stage of a ship, certain technical requirements and regulations must be followed. These requirements are established to address both fire safety and ease of crowd movements during an emergency. Ship designers must comply with the regulations while flag states are responsible for proper enforcement. SOLAS Chapter II-2 covers all the topics of the fire protection, detection and extinction until the escape. Part D, Regulation 13 describe the means of escape so that persons onboard can safely escape to the lifeboat or/and life raft. According to the regulations, all spaces or group of spaces should provide at least two widely separated and ready means of escape (lifts not to be considered as mean of escape). Dead-end corridors or corridors with only one route are prohibited. Stairways also are specified by certain requirements and shall not be less than 800mm in clear width [17].

Fire containment in the space of origin is depending on the structural characteristics of the ship. Ship designers must create divided regions by thermal and structural boundaries in order to minimize the fire. In addition, fire integrity of the regions must be maintained at openings and penetrations (SOLAS Chapter-II, Reg. 9).

More technical requirements and calculations methods about the means of escape, are described in International Code For Fire Safety Systems (FSS Code) [7]. The code includes arrangement of means of escape and covers the specification requirements for the width of stairways, doorways, corridors and landing areas calculation methods.

The IMO guidelines [18] for evacuation analysis of ro-ro passenger ships published in May 1999. Two years after, in 2001, IMO published an interim guideline for SOLAS Regulations [19]. A year after, in 2002, IMO publish the “Guidelines for a simplified evacuation analysis for new and existing passenger ships.” [20] The basic concept was that passenger are not reacting immediately when the emergency announced. This delay between the announcement of the evacuation and passenger starting to move off to the assembly station is known as the response time and is of major importance for the evacuation analysis. In addressing the above need, IMO in 2007 publish the (IMO, 2007b) [21] in which an advance evacuation analysis is described.

Later, in 2016 IMO approve the “Revised Guidelines on evacuation analysis for new and existing passenger ships” [23], which supersedes the previous Circulation and establishes the evacuation analysis mandatory not only for ro-ro ships but also for other passenger ships which carry more than 36 passengers and are constructed on or after 1 January 2020.

2.2 SAFETY PLANS

Safety plans are of paramount importance during the evacuation procedure. The crew must follow established procedures to facilitate the movement of the passengers to their designated stations. These should include pants for locating and rescuing passengers, including those with impaired mobility or injured. SOLAS (Chapter III Regulation 37) describe the requirements of muster lists, including the emergency instructions that could need.

In addition, an emergency management system should be provided to the navigation bridge. Regulation 29 (SOLAS, Chapter III) highlights the importance of a decision support system to assist the master during the emergency. The decision support system can either be in physical form (such as printed emergency plans) or software based.

Additional details on means of escape from a vessel during an emergency are provided by Regulation 13 (SOLAS, Chapter II-2, Reg. 13) “Means of Escape”. Details include specifications and requirements such as: doors in escape routes must open in-way of the direction of escape; there must be at least two means of escape at every room in order to reduce risk; at least one of the two means must provide access to a stairway forming vertical escape; access from stairways to lifeboat and life raft embarkation areas shall be protected either directly or with internal fire integrity routes; and escape routes should be marked by lighting indicators that are placed not more that 300mm above the deck.

2.3 ESTIMATED AND REQUIRED TIME FOR EVACUATION

Another critical parameter in evacuation of passengers is the time. In 2002 IMO publish the “Interim Guidelines for evacuation analysis for the new and existing passenger ships” [23]. The regulatory framework relies upon data and parameters that are derived from civil engineering and are based on risk analysis of fires in buildings. The purpose of this regulation was to identify and mitigate the congestion during evacuation on certain routes onboard the vessel, while considering some escape routes may be unavailable due to extensive damage.

A few years later, in 2016, IMO publish the " Revised guidelines on the evacuation analysis for new and existing passenger ships” [24], which supersede the previous and includes more case studies and several scenarios.

The calculation of the total evacuation time is calculated by the sum of the Response duration (R), the Total travel duration (T), the Embarkation and Launching duration. Each duration is multiplied with a proper correction coefficient in order to be normalized. Response duration (R) is the duration it takes for people to react to the initial alarm. This duration begins when the initial notification (e.g. alarm) of an emergency sounds and ends when the passengers have total awareness of the situation and initiate their movement the assembly station. The maximum response duration is expected to be 10 min for the night-time scenarios and 5 min for the day-time scenarios. Total travel duration (T) is the duration it takes for all persons on board to move from where they are when the emergency notification sound to the assembly stations.

Moreover, Embarkation and Launching duration (E+L) is the time required for the total number of persons on board to abandon the vessel, initiating when the ship signal is given and after all persons have been assembled, with their lifejackets on. E+L duration should be calculated separately based upon the results of full-scale trials and drills on ships with similar characteristics and installed evacuation systems; the results of a simulation-based embarkation analysis; or data which are provided by the shipyards. However, in this case, the method of calculation should be documented, including the value of correction factor that has been used. The embarkation and launching duration (E+L) should be clearly documented to be available in case of changes on the installed LSA arsenal. For cases where neither of the three above methods can be used, E+L should be assumed equal to 30 min.

In general embarkation and launching duration should not exceed in total the 30min in order to comply with SOLAS Chapter III. Regulation 21 mentions that all survival craft shall be capable of being launched with their full complement of persons and equipment within a period of 30 min from the time the abandon ship signal is given. The survival crafts must be capable of accommodating the total number of passengers on board.

According to the above, the mathematical model for calculating the Total evacuation time is:

$$1{,}25\,(R+T) + 2/3(E+L) \le n$$

$$(E+L) \le 30\,min$$

Where n=60 for ro-ro passenger ships and for non ro-ro passenger ships, n=80 if the ship has more than three main vertical zones and n=60 if the ship has no more than three vertical zones.

Another quantity that is examined during the evacuation analysis is the Individual travel duration, which is the duration incurred by an individual in moving from its starting location to reach the assembly station. Additionally, individual assembly duration, which is the sum of the individual response and the individual travel duration and total assembly duration, which is the maximum individual assembly duration [24].

2.4 CREW TRAINING AND CERTIFICATES

The training to deal with emergencies at sea is crucial for effective evacuation. Passengers engaged on a voyage for more that 24h should be instructed on the use of lifejackets and on the necessary actions in an emergency situation [29]. In addition, crew members should participate in at least one abandon ship and on one fire drill every month. Moreover, since 1978 the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (IMO, 2010a) [25], sets the minimum qualification standards for masters, officers and watch personnel on seagoing merchant ships.

2.5 INSTALLED EQUIPMENT - LSA

For a passenger ship to be properly evacuated, the right equipment should be installed and used. SOLAS Chapter III describes the requirements of the LSA, the mustering and embarkation procedures and the equipment launching arrangements. Additional requirements are mentioned, especially for passenger ships. Every passenger ship engaged on international voyages, after 1 January 2020 must carry totally enclosed lifeboats on each side to accommodate not less than 50% of the total passengers. In other words, the sum of the lifeboats on both sides must equal at least to 100% of the passengers, while, in some cases, lifeboats may be substituted by life rafts. In addition, inflatable or rigid life rafts must accommodate at least 25% of the total number of persons on board. [17] [28]

Technical specifications of life-saving appliances are described in detail at International Life-saving Appliance Code [9], which includes a comprehensive set of minimum requirements for lifeboats to lifejackets. Life-saving appliances should follow certain requirements, such as certain marking in a permanently fixed plate. Moreover, lifeboats should be fully functional and operational under all conditions of trim up to 10° and list of up to 20° either way. The speed of a lifeboat when proceeding ahead in calm water fully loaded shall be at least 2 knots when towing the largest life raft. The maximum allowed persons onboard of a lifeboat should be 150. The arrangement of every lifeboat should be in a way that allow the boarding of all persons in less than 10 minutes from the time the instructions to board is given. Finally, the material of the hull and rigid covers should be fire-retardant or non-combustible.

However, in some cases and due to rapid technological improvements, life-saving appliances may deviate from the existing standards. Regulation 38- AD&D [3] describes the methodology that should be followed in those cases, in order ensure equivalent -at least- safety standards. In addition, novel life-saving appliances are developed and installed on new cruise vessels, which meet the SOLAS requirements. In 1983, IMO publish the Resolution (IMO, 1983) [26] in order to evaluate, test and accept prototype novel life-saving appliances. The use of novel equipment created the need for a more organized evaluation system. In 1991, IMO publish the [27] "Testing of life-saving equipment" in which extensive tests are recommended based on SOLAS Chapter III requirements. Later, IMO publish the IMO [33] in order to standardize the life-saving appliances and test forms.

3. LIFE-SAVING APPLIANCES

As mentioned earlier in this paper, the increasing passenger capacity of vessels makes the evacuation procedure significantly more complex and challenging. During the evacuation, large masses of passengers flow between different areas of the vessel towards the LSA and their designated muster stations. Hence, each evacuation station may need to service up to 1000 people, putting the system under strain and, therefore, impairing its effectiveness. At this point, it is important for the reader to note that the calculations are conducted during ideal conditions. On the other end, real-life scenarios are highly likely to take place under various unfavourable conditions. The effect of significant list/trim angles and ship motions has been highlighted by recent accidents (Costa Concordia) and contemporary research in the field of ship evacuation [29, 30].

All life-saving appliances installed on cruise vessels shall comply with the requirements of the International Life-Saving Appliance (LSA) Code, adopted by IMO's Maritime Safety Committee (MSC) at its 66th session (June 1996) by resolution MSC.48 (66). It provides international standards for the life-saving appliances required by chapter III of the 1974 SOLAS Convention.

Life-saving appliances are classified to personal life-saving appliances like lifebuoys, lifejackets, immersion suits, anti-exposure suits and thermal protective aids; visual aids, such as parachute flares, hand flares and buoyant smoke signals; survival craft, such as life rafts and lifeboats; rescue boats; launching and embarkation appliances and marine evacuation systems (MES); and general alarm and public address systems.

Lifejackets shall be provided in three sizes - infant, child and adult - and shall be correctly donned by at least 75% of persons who are completely unfamiliar with them in less than a minute without assistance, guidance or prior demonstration. However, there is consideration for the development of a new standard for infant/child life jackets due to the significant failure rates across all the participants after an ergonomic evaluation, irrespective of age, gender, experience with children and experience with recreational marine equipment [31].

Immersion suits made of material with inherent insulation are certified to provide sufficient thermal insulation, to ensure that the wearer's body core temperature does not fall more than 2oC after a period of 6 hours immersion in calm circulating water at a temperature between 0oC and 2oC. Meanwhile, these suits are typically used in harsher environments where they often underperform. Therefore, it is recommended that when assessing the performance of immersion suits, tests should be conducted in conditions that are as representative as the range of conditions which are expected in the operational area for the immersion suit, or correction factors should be considered [32].

Vertical chute marine evacuation systems (MES) have been installed on large cruise vessels to serve the rapid evacuation of large numbers of passengers using large life rafts instead of lifeboats. However, it has been recorded that, during training, several major injuries and a fatality occurred to the participants. The results of a related study focused on two important factors which had an adverse impact on the efficiency of the chute and increased the risk of suffering an injury. These factors were momentary stops in the chute and the type of clothing material worn by evacuees [33].

4. SMART ENVIRONMENT ELEMENTS

Current evacuation processes that incorporate smart environment elements are based on exit signs (dynamic or not), customised lighting, vocal or visual instructions. They are generic and pre-defined aiming to lead the passengers safely to mustering stations through established routes along the ship. In case that a specific part of the ship is not suitable for passengers to access it, crew members are positioned and provide verbal instructions (usually in English). These situations can greatly exploit the latest advancements in smart environment technologies.

Maritime industry is aware of the possibilities offered by the Internet of Things (IoT) devices. There are some examples in the cruise industry such as the Ocean Medallion offered by the Carnival Princes Cruises ship to the passengers, and Pepper. The Ocean Medallion is a wearable device that holds the passenger's unique digital identity and communicates with thousands of readers on-board and in port [34]. The device helps the passenger to discover seamlessly everything around him, and is used for payments, for unlocking the stateroom door, and speeding up embarkation procedures. Pepper is a 47-inch-tall humanoid robot developed by Softbank Robotics for Costa Cruises (a branch of Carnival), which helps passengers during embarkation and answers general questions [35]. It is the first robot that interacts with vacationers in a broader way, providing directions, information about destinations, entertainment, and general assistance.

Data anonymization is essential, as some sensitive data (such as personal data and health-related data, biometrics and preferred services) are required to access the system's personalised services. [36]

This domain ontology also assigns each passenger to his/her cabin (i.e., the cabin he/she bought when he/she purchased the cruise); moreover, the passenger can decide whether to specify or not his/her special necessities. This can be done by resorting to the International Classification of Functioning, Disability and Health (ICF), a World Health Organization Standard that allows for describing the functioning of an individual. ICF is divided in four components (Body functions, Body structures, Activities and participation, Environmental factors), each of which is further deepened into Chapters, which identify the addressed domain; each component is identified by a letter (b for Body functions, s for Body structures, e for Environmental factors, d for Activities and participation) and can be deepened by adding digits. According to the number of digits following the letter, it is possible to get a code, whose length indicates the level of granularity—up to five digits. [37]

Through research, several emerging technological fields that are being incorporated into ship evacuation were identified. The below examples indicate the efforts, both from research and industrial stakeholders, to develop smart environment elements to facilitate the evacuation process.

Personalised evacuation route has been attempted before. In the eVACUATE project, Bluetooth Low Energy (BLE) and a smartphone application were combined to ease the mustering process.[38]

Indoor localisation is emerging technology that promises to disrupt the current state of the art. Indoor Positioning Systems on board ships are demanding [39]. Royal Caribbean's Oasis of the Seas utilises Real-Time Locating System (RLTS), combining WiFi-based RFID tags in badges or wristbands and a smartphone [40]. BLE beacon indoor positioning was used in the eVACUATE project. Both techniques have some disadvantages that inhibit their accuracy – reflections and dispersion of signals due to heavy metal structures having EM properties that bear resemblances to waveguides.

Augmented Reality (AR) and Virtual Reality (VR) applications are another tool that is being considered. AR has been used in maintenance to optimise task efficiency [41], but it is still facing some drawbacks. AR is more common in aviation industry, than maritime. VR and AR technologies for indoor visualisation are still under research [42].

5. CONCLUSIONS

This paper presents a critical literature review on the regulatory framework, installed LSA and smart environment elements that are either exist or are under development, regarding evacuation from a cruise or RoPax vessel during fire or flooding. The legislative framework has been analysed in order to describe its history and current trends. This paper also describes the existing LSA and promising smart environment elements that aim to further advance the level of safety during the evacuation procedure. Through the review, several challenges regarding the legislation and technological solutions were identified.

Currently SOLAS provides requirements for the quantity and types of the LSA. However, the effectiveness/efficiency of the LSA can become reduced under unfavourable list, trim and fire conditions or suffer from restricted access under critical conditions of operation, especially for specific demographic groups. Current evacuation procedures are prone to bottlenecks at different stages, as large numbers of passengers have to be assembled at predefined stations.

Moreover, there is strong convergence in literature that there is room for improvement regarding passengers' demographics. Demographic parameters such as age [43] need to be more adequately addressed in order to enhance crowd evacuation efficiency. The layout of each deck [44] and the overall ergonomics [45] of the ship also pose a challenge in terms of minimizing the evacuation time.

As with every innovative technology that is introduced in the maritime domain, widespread implementation of novel solutions regarding evacuation requires time. While new technologies are being developed, adequate testing to assess the level of safety of the solutions must be conducted. Then, with improvements upon the initial design the innovative solutions will eventually surpass the existing systems in terms of efficiency. Therefore, with the addition of new technologies, the required time for evacuation will minimize and, thus, keep up with technological advancements and increasing passenger capacity among the worldwide fleet. However, it is important to be aware of the potential complexity this may add to the overall system – equipment that allows for deskilled operation can greatly facilitate their widespread adoption and should be considered at all steps.

Through the study, several emerging technologies have been presented, including personalized evacuation routes; indoor localization techniques; and AR applications. The aforementioned applications aim to improve the passenger's comfort with personalised services. There are some basic elements, like sensors, collected data and the architecture, that could be used in an application that aims for the safety of the passengers. In addition, latest amendment in SOLAS (2020) cover the damage stability in case of flooding, a previously relatively neglected hazard with regards to the regulatory framework, as was observed during this research.

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