Modern Trends in Ship Evacuation

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SUMMARY

Accidents such as the Costa Concordia and more recently the Viking Sky incident cause a societal pressure for improving safety and emergency response in passenger ships. Finding realistic solutions for improvement requires first and foremost an understanding of the current regulatory landscape and the corresponding performance assessment standards. The first part of this paper is dedicated to the provision of a comprehensive outline of the regulatory framework that will ensure compliance of any new system and model developed. The second part is dedicated on the state-of-art projects and novel ideas on ship evacuation analyses and Life Saving Appliances (LSAs) for the purpose of unveiling areas for improvement. Finally, having identified the gaps in the aforementioned topics, suggestions are made on how future work can address the challenges of marine accident response.

1. INTRODUCTION

1.1 PASSENGER SHIP SIZE TRENDS

During the last decade, the tourist industry has shown a rapid growth in the demand of cruises that has led to an increase of the average cruise ship size by 30% [1-3]. This was driven mainly by the effort to make the most of the profit opportunities that come with the economies of scale [4] while trying to meet the market demand which continuously exceeded supply [5, 6].

This increase in passenger capacity is in line with a transformation on the cruise ship companies' business models that, in the same decade, have seen their ticket prices dropping due to the price elastic demand and competition [2]. Hence, companies focus on increasing their on-board revenue to make their reliance on ticket revenue smaller. This has changed the cruising experience over the years making the cruise ship itself the destination.

Financial drivers such as the ones above, together with port accessibility limitations have led to vessels with increased deck numbers and large entertainment areas spanning over many ship fire zones. This kind of design changes have brought safety related issues to the spotlight of technical challenges. Forming the "last resort" in case of an emergency onboard and its time-bound nature, ship evacuation and its corresponding procedures, modelling techniques and regulations should be constantly reviewed and updated.

1.2 PASSENGER SHIP SAFETY

Maritime Safety has been the cornerstone for the establishment of the International Maritime Organisation (IMO) and the introduction of its Safety of Life at Sea Convention (SOLAS). Both, passenger ships under operation and new builds, should guarantee the safety of the passengers and crew and that sometimes means going beyond the regulatory safety requirements. Unfortunately, accidents such as the fire on MS Norman Atlantic [7], the grounding of Costa Concordia and more recently the Viking Sky incident underpin gaps in our existing level of safety and emergency response. The societal pressure after incidents like these is forcing the regulatory bodies to act. IMO has introduced the Formal Safety Assessment [8] as a yardstick to quantify risks and gaps in the existing regulatory framework and select cost-effective risk control options (RCOs).

Safety is a life-cycle risk management endeavour, covering design, operation and emergencies [9]. Regretfully, safety had been perceived in the past as a constrain when it would be more beneficial to be treated as an objective [10]. This approach started gaining more and more ground at the end of 90s under the concept of Risk-Based Design (RBD). In the regulatory framework this was reflected by the introduction of the Goal Based Standards (GBS) and the Alternative Design and Arrangements (AD&A) [11]. Both are provisions to allow innovative designs to overcome bottlenecks emerging from the, frequently conflicting, design objectives of performance, functionality and safety. For the emergencies, we have seen the introduction of evacuation simulations and the introduction of the Safe Return to Port (SRtP, MSC.216(82)).

This kind of proactive risk management thinking should be overarching, from the design stage to the operation and emergency stage. In other words, there should be systems in place that can quantitatively assess the safety level of the vessel in real time and provide the decision makers with comprehensive situation awareness and a support for decision-making. The use of properly and real-time sensor-fused Decision Support Systems, able to provide feedback and guidance to all levels of actors during an emergency, can really revolutionize the evacuation process and create a step change in emergency response.

During the last decade, key enablers were the technological advancements, especially in the field of wireless communications and smart devices and the development of very accurate ship evacuation analysis models. Furthermore, the innovation achieved by a number of projects funded by the European Commission targeting tangible improvements to maritime safety have made brought us closer to the development of a Decision Support System (DSS) with unprecedented capabilities.

2. REGULATORY FRAMEWORK

Understanding the sequence of events from Alarm to Rescue onboard a vessel is important for the identification of the area of application of the different regulations that are presented herein. The timeline illustration of Figure 1, depicts the phases of an emergency situation from Alarm to Abandonment and then Rescue.

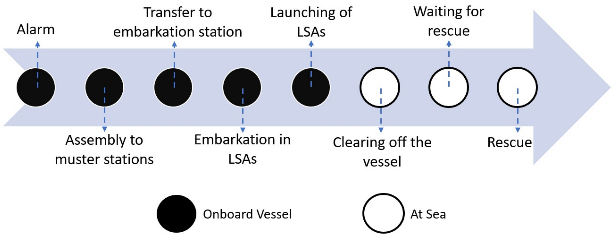

Figure 1: Alarm to Rescue Timeline (adapted from [12])

2.1 EVACUATION

Currently passenger ship evacuation regulatory conformity requires compliance with the IMO MSC.1/ Circ. 1533 [13] which constitute the revised guidelines for evacuation analysis for both new and existing passenger ships. Before Circ.1533, the MSC.1/Circ.1238 [14] required evacuation analysis to be conducted only on the escape routes of ro-ro ships, whereas for the rest of passenger ships, the guidelines where applied voluntarily or for the purpose of demonstrating 'equal level of safety' for approval under the AD&A provisions. Accidents in cruise ships though, and experience gained via evacuation analyses brought to light the fact that voluntary compliance is inadequate and hence the Resolution MSC.404 (96) [15] was adopted that proposes amendments to SOLAS Regulation II-2/13 'Means of escape' [16]. These amendments will make the evacuation analysis compulsory not only to ro-ro ships but also to any other new passenger ships constructed on and after 1st of January 2020. This analysis is of paramount importance, especially for the state-of-the-art passenger ships where passenger capacity, practical challenges and large communal entertainment areas give rise to congestion points and critical areas, thus requiring a revision of the operational counter-measures for a timely evacuation.

The regulations for ship evacuation are based, at the moment, both on SOLAS Chapter III and on the FSS code [17] and set the performance standard to 60 minutes for ro-ro vessels and passenger ships with less than three main vertical zones whereas for vessels with more than three vertical zones the limit is 80 minutes. In any case, the Embarkation and Launching time is considered to take up to 30 minutes. Those time limits should be checked with regard to some benchmark scenarios. In addition, the regulations provide a step-by-step procedure for a simplified evacuation analysis that models the problem as a hydraulic network, with the corridors and staircases being the pipes, the doors being treated as valves and the public spaces acting as tanks [13]. The assumptions of the simplified method are very limiting and, although it might provide an approximation on the expected evacuation time, it is unreliable and not so easy to use as the passenger demographics become more diverse, the accommodation more complex and the number of stairways and decks increases.

Fortunately, the regulations also provide sets of characteristics and parameters that an advanced evacuation method should take into account. An advanced model must calculate the individual time to evacuate in mixed passenger demographics in which the abilities of the passengers are distributed probabilistically [18], their movements are recorded and there is a universal algorithm that defines the rules of personal decision amongst the passengers. Finally, the same parameters that are used for the evacuation modelling in other fields, i.e. Geometrical, Population, Environmental and Procedural, should also be considered in advanced modelling. In the case of a vessel, that translates as the capability of the analysis to account for the different escape routes and their availability, initial passenger and crew distribution and their corresponding moving speed abilities and response time. More specifically though, the condition of the vessel (static and dynamic) and the effect of crew assistance in the case of emergency.

ISM Code Sec. 7&8 and Resolution A.1072(28) cover the evacuation procedures, drills and exercises whereas the officers' training and responsibilities in crisis management and emergency cases are outlined in the STCW Code Sec. AII & AV [19, 20]. In addition, SOLAS Ch. III also includes information regarding the safety instructions to passengers and the characteristics of the DSS that should be in place.

2.2 LSAs

The regulatory framework for Life Saving Appliances (LSAs) is being shaped initially by SOLAS Ch. III and the LSA Code which assess the design of the LSA against the requirements, identify potential deviations [16, 21]. Physical tests are then performed to ensure compliance of the non-deviating characteristics according to Resolution MSC.81 (70) [22]. As for the deviating characteristics of the LSAs, the proof of design equivalence falls under the regulations of SOLAS III-Reg.38 and the corresponding guidelines from AD&A provisions [11, 16], whereas the physical testing requirements of the deviating characteristics are prescribed by the Resolutions A.520(13) and A.689(17) [23, 24].

2.3 SAR

There also regulations in place for the procedures of alerting the Search and Rescue authorities [25] in case of an emergency as well as daily reports to the ship company informing them about the vessel's position [26]. The helicopter landing areas and the co-operation plans between SAR and Passenger ships are also subjects of IMO legislation [27-30].

Table 1: Regulatory reference by subject

Subject	Regulatory Reference	
Evacuation Modelling/ Procedures	MSC.1/Circ.1533	[13]
	MSC. 404(96)	[15]
	SOLAS 2009	[16]
	FSS Code	[17]
	ISM Code	[19]
	A.1072(28)	[20]
Life Saving Appliances	*SOLAS 2009*	[16]
	LSA Code	[21]
	MSC.81(70)	[22]
	A 689(17)	[23]
	A.520(13)	[24]
Search and Rescue	MSC/Circ.892	[25]
	MSC/Circ.1043	[26]
	MSC/Circ.895	[27]
	MSC.1/Circ.1079/Rev.1	[28]
	COMSAR/Circ.31	[29]
	IAMSAR	[30]

3. STATE OF THE ART LSAs

3.1 LIFEBOATS

It is worth mentioning, that although LSA Code 4.4.2.1 explicitly states that there cannot be a lifeboat of capacity greater than 150 people, the AD&A provisions have allowed the creation of 'mega- lifeboats' that have received approval after demonstrating equivalent level of safety. European Commission funded projects such as SAFEDOR and SAFECRAFTS have played a crucial role in the realization and commercialization of such lifeboats [31, 32].

Most noticeable being the 370-person CRV55 lifeboats from Umoe Schat-Harding that are installed in Oasis of the Seas [33]. These catamaran hull shaped 'mega-lifeboats' are designed to serve the needs of the new 'mega-liners' where the exponential increase in passenger capacity and the available deck area for LSAs makes the use of conventional lifeboats impractical or even impossible. The launching system for these boats, the LS45 davit, is also considered novel since it is designed specifically for cruise vessels and allows for the lifeboats to be lowered to water directly without any outswing since the boats are kept outside the hull. Another example is the SEL-T 15.5 by Fassmer which was the first IMO certified lifeboat offering a capacity up to 267 persons while also being certified for usage as a tender for 233 passengers [34].

Innovation in lifeboats is now focused on creating different release mechanisms and davits with as few moving parts as possible so that less maintenance to be required. Another tendency driven by the cruise industry is the ability of the lifeboats to be used also as tenders, thus leading to designs with ample space, window view while maintaining the robustness and reliability expected from a lifeboats [34]. Also, efforts are made towards reducing the complexity in both the launching and operational phase of these boats so that no much training to be necessary. Further development, though, is still needed in making these boats available for launching and use even after extreme heeling angles or releases from considerable heights. Ensuring the maximum availability of all the boats and LSAs in general requires also a careful selection on their location at the vessel. Damage stability and fire analysis should indicate the most vulnerable areas on-board and the location of the lifeboats should be determined by taking these factors under consideration.

Lifeboats occupy approximately 0.05% of a passenger ship´s volume but they do represent a 1%-2% of the total ship building cost and therefore ensuring cost effective and safe alternatives to the conventional boats is essential [35]. What also adds a certain level of challenge to the design of the lifeboats is the pressure from ship owners of increasing the number of ocean view cabins, which generate more profit, while also not taking over much deck area and do not obstruct the view.

3.2 LIFE-RAFTS AND MES

Marine evacuation systems are used to ensure the evacuation of the maximum number of passengers in the minimum amount of time and securely place them to the already deployed life rafts. The most common types of Maritime Evacuation Systems (MES) for fast and easy evacuation in large passenger ships are the single or double chute systems such as the VEDC by VIKING and the Marin Ark 2 by Survitec (RFD) [36, 37]. The manufacturers claim that these systems are capable of evacuating more than 850 passengers in less than 30 minutes and inflated within approximately 90 seconds after deployment. Those systems are designed to securely transfer persons from deck heights up to 16.8 meters, via helical slide paths in fully enclosed chutes, into the life rafts. Designed to require minimal human element involvement but, more importantly, have a flexible design that allows installation in wide range of vessel configurations.

Smaller passenger vessels with low embarkation decks can make use of more compact lightweight MES such as Mini Chute Systems, Slide systems or direct boarding life rafts a few examples of which are VEMC, VEC Plus from VIKING and their equivalent Bruce Evacuation System Chute and Super Slide from Survitec.

The next generation of MES, similarly with the next generation of lifeboats should ensure the same or higher performance standards in trim and listing conditions and decrease the deck footprint. In addition, as arctic cruises become more and more popular, the heat insulation of these systems should also be reviewed.

3.3 LIFEJACKETS AND SMART DEVICES

Effective decision making for emergency depends upon the level of information that the ship officers have about the actual real time state of damage and passenger distribution within the vessel. Lack of sufficient and reliable information on these issues put on more strain to the decision makers [38] and directly affect the efficiency of the evacuation and SAR.
The research outputs of European Commission funded project LYNCEUS managed to demonstrate the benefits of using smart devices, such as wireless bracelets and lifejacket-embedded sensors, in ship evacuation. More specifically the project investigated how ultra-low power wireless area network technologies can be utilised for people localisation during emergencies [39]. This kind of localisation capabilities open new horizons for real-time emergency response management. These smart devices, lifejackets, the associated software and DSS are being brought to market via the second phase of the project 'Lynceus2Market' [40]. Lifejacket innovation can also come from technologies developed for sports [41] or military applications that can introduce more compact designs that also include survival kits.
Nevertheless, there are still many technical challenges to be addressed related to passenger health status monitoring, communication system protocols due to the large number of wireless sensors and bandwidth availability, all of which can play a key role in the evacuation. Especially for the matter of indoor localization, feedback from projects such as FP7 eVACUATE suggest the exploration of Ultra-Wide Band (UWB) technologies.

4. SHIP EVACUATION MODELLING

Ship evacuation modelling is significantly more complex than building evacuation because of, amongst other reasons, unique challenges arising from the fact that passengers cannot directly head towards the nearest escape exit but instead should be equipped with lifejackets, available on their cabins and/or elsewhere, and prepare themselves for embarkation in LSAs that are going to transfer them from one high risk area to another high risk environment, the sea. The complexity of modelling gets even harder when considering that most of the passenger ships have rambling layouts, identical corridors and confusing layout diagrams that make the passenger orientation problem worse in an already stressful environment [42]. Therefore, there are procedural, human behaviour and environmental factors that constitute conventional evacuation software, developed for other industries, unsuitable for marine emergency evacuation.
As of now, the most prominent ship evacuation modelling software are Evi [43], maritimeExodus [44, 45], IMEX [46], AENAS [47, 48], VELOS [49] each one developed to approximate the time to evacuate using different modelling methods, taking different factors under consideration and different assumptions.
Evi is a multi-agent based model capable of representing alignment and cohesion behaviours by adjusting the agent speed depending on the density of agents in a space [50, 51]. The multi-agent approach of the software places it amongst the most appropriate models for multi-level planning structure. In the case of fire accident, the maritimeEXODUS software can simulate the fire and smoke propagation together with the passenger evacuation using velocity-based fine network mode. AENAS and IMEX were created to solve problems arising from the consideration of ship motions in the evacuation modelling via velocity reduction coefficients for different deck inclinations [52, 53]. VELOS brought the Virtual Reality into the evacuation simulation with the purpose of creating a platform that would allow for design feedback at the early stages via the immersion of multiple users into hectic operational conditions.
Nevertheless, there is still room for improvement on not only the human behaviour under panic and the corresponding changes in the walking speed, but also the effect of disabled people on the evacuation flow. From the standpoint of environmental considerations, the effect of trim and heeling angles in the availability of the LSAs and the corresponding effects on passenger flow are still to be modelled. More importantly, though, there is not a dynamic enough model, yet, capable of assessing the total time to evacuate based on real time passenger localisation data. The real time coupling of passenger tracking and evacuation time calculation is a crucial gap, without which the ability of creating a DSS that will allow the optimal co-ordination of the evacuation process by assessing the most favourable escape route for each individual.

5. EVACUATION ENHANCEMENT

Starting with the LSAs, a new generation of cost effective personal survival equipment must be developed together with innovative concepts in ship design layout that can accommodate novel lifeboat designs and increase the evacuation efficiency by considering the spatial constraints in place. Effectively this means more compact and ergonomic life-jackets, fitted with the necessary sensors for localisation and pairing abilities with health monitoring and information receiving devices such as smart hand bands and earplugs. Augmented Reality (AR) technology could also be employed for the secure guidance of the passenger throughout the evacuation stage. Alternative ship layouts should be examined based on their efficiency in reduction of the time for mustering and abandonment.
In terms of ship evacuation modelling, the new challenges and targets will be the incorporation of real time data [54], from the various sensors monitoring both the type and propagation of damage and human physiological factors, in an evacuation analysis model that can evaluate different route alternatives for individuals while taking the human behaviour under consideration [55]. Evacuation models can also be improved with regards to their accuracy in embodying the differences in walking speed as a function of the individuals' specific psychological and physical

characteristics, that means to include family and panic behaviour as well as the effect of disabled people in the evacuation flow [56]. Moreover, the recent acts of terrorism have added the security threat in the list of subjects that should be investigated with respect to evacuation [57, 58]. Another area of improvement is the calculation of the actual time for lifeboat embarkation. Most of the models calculate explicitly only the time to evacuate up until the assembly station and are not able to do the same for the lifeboat boarding stage due mainly to the lack of operational or experimental data that would allow verification.

Besides the aforementioned suggestions for evacuation enhancement, recent studies on the combined effect of trim and heeling angles on the walking speed [59] allow for refinements on the accuracy of existing models and pave the way for a truly more dynamic evacuation analyses. The continuous, non-static, effect of ship motions in walking speeds has also to be linked with real time flooding simulations so that the time-to-evacuate can be associated with the time-to-capsize, which is an important connection to be made in the next generation of evacuation modelling software.

The biggest challenge though, will be the integration of all the systems related to the evacuation and emergency response under one DSS that will broadly cover all the emergency cases and co-ordinate the evacuation process more efficiently. Data from flooding and fire sensors should quantify the risk of untenable propagation of damage in real time while also giving to the decision makers on the actual available time for evacuation based on passenger localisation data. In the meantime the risk of evacuation itself according to the available search and rescue options should be evaluated to lead the officers to a well informed decision and reduce the human errors. This task is particularly challenging in view of the technical difficulties that have to be overcome and the number of different stakeholders that have to work together to produce cost effective solutions that can be integrated with the software and hardware products of other companies or research groups.

6. CONCLUSIONS

Since ship evacuation is a dynamic multi-variable problem with parameters that are constantly changing and evolve as a function of time, environmental conditions, human behaviour, and type of emergency, it is essential to have a dynamic evacuation analysis model. Dynamic in the sense that can effectively calculate the available time to evacuate (ASET) and the required time to evacuate (RSET) based on the state and location of fire, flooding or security threat, for instructing accordingly the passengers on how to proceed. Improving ship evacuation is a problem that has to be approached simultaneously from all angles. Novelty in the LSAs, real time evacuation analysis and the creation of a DSS that will quantify in real time the risk of evacuation and weight it against the risk of ship loss and the number of potential fatalities are being the challenges of the upcoming decade.

The feasibility of the aforementioned system is a matter that requires the collaboration and co-ordination of academic research groups with passenger ship companies, LSA manufacturers and software and tele-communication engineering teams. This kind of initiatives become possible after the financial support and encouragement by regulatory and governmental bodies for research and innovation actions. For instance, European Commission funded projects under the call for marine accident response initiatives (MG-2-2-2018) are going to bring together academia and industry to develop and test systems and devices that will improve evacuation. An example of such a project is SafePASS that aims to design the next generation of life saving appliances and systems for a safer and more efficient evacuation of large passenger ships in extreme emergency and environmental conditions.

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