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Analysis of the impact of deploying thermal protective immersion suits on evacuation time for passenger ships operating in polar waters

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ABSTRACT

For passenger vessels operating in polar waters, the Polar Code requires that in case of possibility of immersion in polar waters, thermal protective immersion suits (TPIS) should be available for all passengers. Thus, international standards require that TPIS can be donned within 2 min and that walking speeds are reduced by no more than 25%. Clearlythese requirements are arbitrary and do not reflect their potential impact on evacuation performance. Other IMO requirements specify the maximum time permitted for assembly and abandonment times for passenger ships, which can be assessed using agent-based evacuation modelling (ABEM). However, these requirements currently ignore the impact of TPIS and employ a safety factor of 25% to represent all factors ignored when modelling evacuation. Here we explore the impact of TPIS on both the assembly and abandonment times of a hypothetical vessel using ABEM. The results demonstrate that requiring the donning of a TPIS can increase assembly times by as much as 65% and negatively impacts the abandonment process. It is thus essential that additional requirements associated with evacuation of vessels in polar waters are reflected within the IMO passenger ship evacuation certification guidelines. The paper suggests several ways in which this can be achieved.

1. Introduction

In recent years, there has been a growth in the popularity of adventure cruises involving large passenger ships sailing in polar waters (Misra, 2011; Maher, 2017). This inevitably results in increasing ship traffic and a higher probability of accidents or incidents involving these vessels in challenging polar conditions (Khan et al., 2020; Kum and Sahin, 2015). Under ideal conditions, the timely evacuation of hundreds of passengers from a cruise ship in distress is a very uncertain and challenging process (Vanem and Skjong, 2006; Norazahar et al., 2017) and this can be even more challenging when undertaken in the extreme conditions found in polar waters. Recognising these additional challenges the International Maritime Organization (IMO) introduced the Polar Code in 2017 (Polar Code, 2017) for passenger ships operating in polar waters. These requirements are in addition to the existing safety of life at sea provisions (LSA Code, 2017). A requirement of the Polar Code is that passenger ships operating within polar waters are required to provide thermal protective clothing or insulated immersion suits (referred here as Thermal Protective Immersion Suit (TPIS)), for each person on board.

The unpredictability and speed at which maritime emergencies may occur make time a critical factor (Andreassen et al., 2020), whether it be associated with the passenger response time (Brown et al., 2012), the time required to gather the passengers in the assembly stations (Galea et al., 2007), the time required by passengers to don their TPIS (Azizpour et al., 2022a), or the time available to move passengers from the assembly station to the Life-Saving Appliances (LSA) and subsequent abandonment of the vessel (MSC/Circ. 1533, 2016). While the TPIS is an essential item for emergencies in polar waters, the TPIS may also negatively impact the evacuation process. For example, the time required to don the TPIS could reduce the time available for safe evacuation, and wearing the TPIS may adversely impact passenger walking speeds, further delaying the evacuation process (Wang et al., 2020, 2021). Implicit within the intent of the IMO Polar Code (Polar Code, 2017) and the associated ISO standards (ISO 15027-3, 2012) is the requirement that the TPIS should not adversely impact passenger ship

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evacuation. This is reflected by the requirement that the TPIS can be donned within 120 s and that it does not adversely impact walking speeds of individuals by more than 25%, compared with the normal walking speed (ISO 15027-3, 2012). It is, however, of concern that the current requirements on walking speeds while wearing TPIS specified in the various codes and standards applies only to walking speeds on flat horizontal spaces, the impact on inclined surfaces (for example due to adverse vessel orientation) or stairs are ignored. Furthermore, the specified TPIS performance requirements appear to be arbitrary. Clearly, the acceptability of donning times and walking speed reduction factors must be assessed within the context of evacuation scenarios.

The evacuation of large passenger ships involves two distinct phases, the assembly (which comprises response and travel time) and abandonment phases. In the assembly phase, passengers and crew are gathered in their allocated assembly stations from where they can be sent directly to the LSA such as lifeboats. The abandonment phase involves dispatching the passengers and crew from their assembly station to their allocated LSA from where they can abandon the vessel. In some situations, it is possible for the assembly and abandonment phases to overlap, as the abandonment process can commence prior to the completion of the assembly phase.

The IMO requires new passenger ship designs to be assessed for their evacuation performance, to determine the time required to evacuate the vessel. The assessment is undertaken using computer simulation following IMO specified guidelines (MSC/Circ.1533, 2016). These specify a series of minimum four benchmark scenarios that must be simulated using the proposed vessel layout and full passenger and crew complement. The scenarios involve two primary and two secondary cases. The primary scenarios consist of a day and night case. In the day scenario, passengers are assumed to be initially dispersed in the communal spaces of the vessel, while in the night scenario passengers are assumed to be initially located in their cabins. The two secondary cases are intended to represent the situation when the ship is damaged and some of the evacuation routes are unavailable in both day and night cases. The secondary evacuation scenarios utilise the main vertical zone that generates the longest individual assembly time duration for further investigation. These are intended to be benchmark scenarios and so make a number of simplifications such as assuming the vessel is at 0° heel and trim, the impact of smoke, heat and toxic gases from a fire are ignored, there are no dynamic motions, passengers know the procedures, crew are available to direct passengers, etc. To take into account the limited number of scenarios considered (i.e., four scenarios), software deficiencies (i.e., modelling human behaviour accurately is difficult), data deficiencies (e.g., passenger response time data is limited) and the simplifying modelling assumptions (e.g., 0° heel and trim), the IMO require that an arbitrary 25% safety factor is included in the predicted assembly times (MSC/Circ.1533, 2016).

Within the IMO evacuation guidelines, the passenger ship evacuation time (ET) is made up of essentially two components, the assembly time (ASST) and the abandonment time (ABT) where,

$$\mathrm{ET} = 1.25 * \mathrm{ASST} + \left(\frac{2}{3}\right) * (\mathrm{ABT}) \tag{1}$$

The ASST is multiplied by 1.25 to represent the 25% safety factor associated with omissions in the determination of the assembly time while the ABT is multiplied by 2/3 to represent that the abandonment process may start prior to the completion of the assembly process, i.e., passengers can be dispatched to their assigned LSA prior to the completion of the assembly process.

The ABT is also made up of two components, the embarkation time (EMT) and the launch time (LT). The EMT is itself made up of two components, the time required for the passengers and crew to walk from the assembly station to the assigned LSA (WT) and the time required for the passengers to complete the boarding process (BT), i.e., enter the lifeboats and take a seat. The LT is the time required to lower the loaded lifeboats into the water and push off. Thus, the ET is given by,

$$ET = 1.25 * ASST + \left(\frac{2}{3}\right) * (EMT + LT) = 1.25 * ASST + \left(\frac{2}{3}\right) * (WT + BT + LT) \tag{2}$$

For passenger ships other than Ro-Ro ferries with no more than three main vertical zones, to satisfy IMO requirements requires ET $\leq$ 60 min for each of the four specified benchmark scenarios (MSC/Circ.1533, 2016). If the vessel has more than three vertical zones, to comply with IMO requirements, ET $\leq$ 80 min (MSC/Circ.1533, 2016). Furthermore, the IMO guidelines requires that ABT $\leq$ 30 min. Thus:

$$WT + BT + LT \leq 30 \tag{3}$$

In practice, agent-based passenger ship evacuation models (see Sec. 2.1) are used to determine ASST while if data is not available to support the modelling of BT and LT, ABT is assumed to take its maximum allowed value of 30 min.

As there is no specific justification for the magnitude of the safety factor, it is assumed that for polar waters evacuation applications, the long list of omissions that the 25% safety factor is intended to compensate for, is expanded to include omissions relating to the use of TPIS. However, for this to be justified, it is essential to first determine the size of the likely impact the TPIS will have on evacuation times.

Quantification of behaviour, response, and walking performance of individuals under different environmental conditions in emergencies are amongst the key factors that are required for the development of reliable evacuation models (Galea, 2002; Deere et al., 2009). From the mid-1990s, the first evacuation models for passenger ship applications began to appear in the literature (Galea and Owen, 1994; Galea et al., 1998; Galea, 2000; Vassalos et al., 2002; Glen and Galea, 2001). These publications highlighted the need for the collection of maritime specific human performance data, such as walking rates in maritime environments involving adverse vessel orientation, the impact of life safety equipment, such as lifejackets on walking speeds and passenger response times (Galea et al., 2002; Yue et al., 2021; Kim et al., 2019, 2020; Arshad et al., 2022). Addressing these requirements, several studies have quantified passenger response times in specific conditions (Galea et al., 2013, 2014) and demonstrated the impact of environmental hazards such as fire on evacuation times (Galea et al., 2003). Furthermore, interest in quantifying the walking performance of people in maritime specific environments resulted in two significant land-based studies, one in the Netherlands at the Dutch Research Institute (TNO) (Bles et al., 2002) and the other at an industrial research facility in Canada (Glen et al., 2003). While these studies have provided useful insight into how angle of heel may impact walking speed of individuals, all have involved test subjects walking over relatively short distances and none of them shed light on the potential impact of TPIS on walking speeds of individuals at different angles of heel. Similarly, while some studies have explored the time required to don TPIS (Mallam et al., 2012, 2014) these studies have not provided a detailed quantification of the factors that impact donning times.

To address this gap in the evidence base, the ARCtic EVACuation (ARCEVAC) project undertook a series of experiments to assess the time

Fig. 1. Hansen and Viking (TPIS).

required for donning (Azizpour et al., 2022a) and the impact of TPIS on walking performance of individuals at different angles of inclination ($0^\circ, 10^\circ, 15^\circ$, and 20° degrees of heel) (Azizpour et al., 2022b). Two different types of TPIS (Hansen Protection (Sea Pass passenger suit) and Viking immersion suit (Yousafe Blizzard PS5002)) (see Fig. 1) were used in the trials. The results demonstrate that TPIS donning times, and walking speeds of individuals can be significantly influenced by a range of factors including type of TPIS, age, gender, and angle of heel.

This paper attempts to quantify the impact of TPIS on the time required to evacuate large passenger ships particularly with respect to the appropriateness of the 25% safety factor imposed by the guideline of evacuation analysis. The donning time data (Azizpour et al., 2022a) and walking speed data (Azizpour et al., 2022b) generated in the ARCEVAC trials are utilised (see Sec. 2.2) along with the agent-based evacuation simulation software maritimeEXODUS (mEX) (Galea et al., 2020) (see Sec. 2.1). The current release version of the mEX software (V6.0) was modified to incorporate both the donning time and walking speed data sets (see Sec. 3). A vessel layout based on the Hurtigruten vessel, MS Roald Amundsen, a passenger ship built and certified for sailing in polar regions, was used in the analysis (see Sec.4.1 and Supplementary Material Sec. S1) and a selection of evacuation scenarios, based on the primary IMO cases but suitably modified to represent the impact of heel and TPIS on assembly and abandonment times are defined (see Sec. 4.2) for analysis. A series of verification scenarios are first explored to demonstrate that the required software modifications are correctly implemented (see Sec. 5.1) and a further series of scenarios are investigated to explore the impact of TPIS on individual walking times over travel distances equivalent to that encountered when walking from the assembly stations to the LSA (see Sec. 5.2). Finally, the impact of heel and TPIS on assembly and abandonment times for a realistic vessel configuration is examined (see Sec. 5.3). The significance of the findings is then discussed in relation to the appropriateness of assuming that the impact of the TPIS can be accommodated within the existing 25% safety factor (see Sec. 6). Finally, analysis limitations are presented (see Sec. 7) along with the study conclusions and recommendations (see Sec. 8).

2. Modelling software and dataset

This section provides a brief overview of maritime evacuation simulation, introduces the evacuation software that was used in this study and the TPIS dataset.

2.1. Ship evacuation modelling

Advanced agent based (Gwynne et al., 1999; Kuligowski et al., 2010) ship evacuation models such as EVI (Vassalos et al., 2002, 2003), ODIGO (Vassalos et al., 2004; Pradillon, 2003) and maritimeEXODUS (Galea et al., 2007; Brown et al., 2013)can be used to determine the performance of passengers under conditions of emergency evacuation. Common to these types of models is the ability to represent; the ship population as a collection of unique interacting individuals (i.e., agents), the detail of the space in which the agents interact (i.e., the model can represent the details of the ship geometry) and to assign agents or groups of agents specific goals to achieve as part of the scenario definition, e.g., to move to an assigned assembly station or from an assembly station to an LSA. Some agent-based ship models also have the capability to represent the impact of adverse vessel orientation, such as heel and trim (e.g. (Brown et al., 2013)) on the evacuation process.

The maritimeEXODUS (mEX) agent-based ship evacuation software was used to perform the evacuation simulations presented in this paper. The software has been described in detail in many publications (Deere et al., 2006, 2009; Galea et al., 2002, 2013; Brown et al., 2013; Gwynne et al., 2003) and so only a brief description of the software will be presented here. EXODUS is a suite of software tools designed to simulate the evacuation and circulation of large numbers of people within a variety of complex enclosures. mEX is the ship version of the software. The software takes into consideration people-people, people-fire and people-structure interactions. It is rule-based and so the progressive motion and behaviour of each individual agent are determined by a set of heuristics or rules. Many of the rules are stochastic in nature and thus, if a simulation is repeated without any change in its parameters, a slightly different set of results will be generated. It is therefore necessary to run the software a number of times as part of any analysis. In addition to the representation of the geometry of the vessel, the abandonment system can also be explicitly represented within the model, enabling individual components of the abandonment system to be modelled individually.

The software has a number of features such as the ability to incorporate the effects of fire products (e.g., heat, smoke, toxic and irritant gases) on agents (Galea et al., 2013) and the ability to include the impact of heel and trim on the walking performance of agents on flat spaces and stairs (walking up and down) (Galea et al., 2002) using the TNO (Bles et al., 2002) and SHEBA (Glen et al., 2003) datasets. The software also has the capability to represent the performance of both naval personnel and civilians in the operation of watertight doors, vertical ladders, hatches and 60° stairs (Deere et al., 2006). Another feature of the software is the ability to assign agents representing passengers or crew a list of tasks to perform. This feature can be used when simulating emergency or normal operations conditions (Galea et al., 2020). The software has been validated using data from two full-scale evacuation trials on board real passenger ships in operation (Galea et al., 2013).

2.2. ARCEVAC TPIS dataset

The ARCEVAC project provided a dataset to quantify the time required to don the TPIS and the impact of the TPIS on walking speeds at various angles of heel (from 0° to 20°) (Azizpour et al., 2022a, 2022b). The data presented here relates to donning time data for Suit-2 (the Viking immersion suit) (Azizpour et al., 2022a, 2022b) while the walking speed data relates to both suits (Suit-1 and Suit-2, see Fig. 1) (Azizpour et al., 2022a, 2022b). The walking speed data was collected in a purpose built 36 m long facility that could be inclined to the desired angle of heel.

2.2.1. Donning time data

The donning time was introduced into the modified mEX software as a delay time that is randomly generated using Eq. (4), according to the age and the gender of the agent. Based on data from (Azizpour et al., 2022a), the donning time for Suit-2 is defined as follows:

$$\mathrm{TDT} = \mathrm{PT} + \mathrm{XT} + \mathrm{NDT} \tag{4}$$

Where preparation time (PT), extraction time of TPIS from its plastic bag (XT), and net donning time (NDT) are given by,

$$\mathrm{PT} = 1 + \mathrm{U} * \mathrm{X}, \text{and} : \mathrm{U} \sim \mathrm{Bernoulli}\ (0.16), \mathrm{X} \sim \mathrm{Log} - \mathrm{normal}\ (2.35, 0.56) \tag{5}$$

$$\mathrm{XT} \sim \mathrm{Log} - \mathrm{normal}(2.9, 0.39) \tag{6}$$

And,

$$\begin{gathered}\mathrm{NDT}_{\mathrm{modelling}} = 130.3 * 1.0057^{\mathrm{Age}} * 1.32^{\mathrm{Gender}} * \varepsilon; \\ \varepsilon \sim \mathrm{Log} - \mathrm{normal}(0, 0.3), \mathrm{Age} \in (18 - 72), \mathrm{Gender} \in (Male = 0, Female = 1)\end{gathered} \tag{7}$$

It is noted that the measured TDT in the experiments ranged from 75 s to 431 s (for males, 75 s–408 s and for females, 118 s–431 s) (Azizpour et al., 2022a) while there is about 1% chance that the minimum and maximum donning times from Eq. (4) are outside the range of 47 s and a maximum of 678 s.

Clearly, where the donning process occurs is dependent on the stowage location of the TPIS and this in turn is dependent on the procedures employed by the vessel. For example, the TPIS could be stowed in the passenger cabin, as are lifejackets on cruise ships, or they could be stowed in the assembly stations as are lifejackets on passenger ferries. If the TPIS are stowed in the cabins, the passengers might be instructed to don them prior to starting the assembly process or simply to carry them to the assembly station and await instruction for donning. If the TPIS are stowed in the assembly station, a process would need to be developed to distribute them quickly and efficiently to passengers on arrival to the assembly stations. However, the Polar Code requires that the TPIS are stowed in an easily accessible location as close as practical to the assembly station or embarkation station (Polar Code, 2017). Thus, in the simulations considered in this analysis, it is assumed that passengers incur the TPIS donning time once they have arrived in the assembly station, and the assembly phase ends after the donning is completed by all passengers (see Sec. 4.2.3).

2.2.2. Walking speed data

The walking speed (WS) in the IMO evacuation guidelines (MSC/Circ.1533, 2016) is a function of only age and gender and so does not take into consideration TPIS or angle of heel or trim. In reality, the WS is a function of age, gender, deck angle and type of TPIS (Azizpour et al., 2022a). When considering angle of heel, the WS is denoted by HWS and when considering an angle of trim, the WS is denoted by TWS.

The HWS is quantified using a heel reduction factor (HRF) which takes into consideration the impact of suit type, angle of heel, age and gender ($\mathrm{HRF}_{\mathrm{Age,Gender,Angle,Suit}}$) determined from the ARCEVAC experimental data (Azizpour et al., 2022a). The HRF is multiplied by the appropriate WS of the individual (for the specified age and gender) at 0° of heel and while wearing normal clothing – this is the WS that is specified in the IMO evacuation guidelines (MSC/Circ.1533, 2016) – to generate a HWS for that individual (with specified age and gender) appropriate for the suit type and angle of heel ($\mathrm{HWS}_{\mathrm{Age,Gender,Angle,Suit}}$). The HWS is determined using Eq. (8) and Eq. (9).

$$\mathrm{HWS}_{\mathrm{Age,Gender,Angle,Suit}} = \mathrm{WS}_{\mathrm{Age,Gender,Angle=0,Suit=0}} \times \mathrm{HRF}_{\mathrm{Age,Gender,Angle,Suit}} \tag{8}$$

where the reduction factor is given by,

$$\begin{aligned}\mathrm{HRF}_{\mathrm{Age,Gender,Angle,Suit}} = \; & 0.9999^{\mathrm{Angle*Age}} * 0.9970^{\mathrm{Angle*Gender}} \\ & * 0.9934^{\mathrm{Angle*Suit-1}} * 0.9363^{\mathrm{Suit-2}} * 0.9901^{\mathrm{Angle*Suit-2}}\end{aligned} \tag{9}$$

In the following section, we combine these results with the effect of trim from the TNO dataset (Bles et al., 2002) to estimate the walking speed in trim while wearing a TPIS.

3. Modelling assumptions

When a vessel is heeled over at a given angle, passengers will be walking at heel while they are progressing along the length of the vessel from aft to forward (or forward to aft). However, if they need to move from port to starboard (or starboard to port) they will be walking in trim, either up the incline or down the incline, at an angle of trim equal to the angle of heel. However, in the ARCEVAC project, the walking speed experiments only collected data associated with walking along a corridor at different angles of heel while wearing TPIS. As no data is currently available to represent the impact of trim on walking speeds and walking speeds on stairs while wearing TPIS, it is necessary to introduce assumptions to approximate their representation in the modelling.

3.1. Walking speed for angles of heel

Within the modified version of mEX, to determine the $\mathrm{HWS}_{\mathrm{Age,\ Gender,\ Angle,\ Suit}}$ for a given agent (i.e., a given age and gender, while experiencing a particular angle of heel, and while wearing a particular TPIS), the $\mathrm{HRF}_{\mathrm{Age,\ Gender,\ Angle,\ Suit}}$ for the agent is determined using Eq. (9). Once this is determined the HWS can be determined using Eq. (8).

3.2. Walking speed for angles of trim

In this study, we assume that the impact of the TPIS on walking speeds while in trim (TWS) will be the same as the impact of the TPIS on walking speeds in heel. Thus, reduction factors associated with the impact of the TPIS while walking at a given heel angle (HRF) can be applied to walking at the same angle of trim. Furthermore, as the ARCEVAC data does not contain any trim walking speed data, the existing TNO trim dataset (Bles et al., 2002) is used.

From the TNO dataset we have two reduction factors, one for heel ($\mathrm{TNOHRF}_{\mathrm{Age,Gender,Angle,Suit=0}}$) and one for trim ($\mathrm{TNOTRF}_{\mathrm{Age,Gender,Angle,Suit=0}}$). These are currently specified within mEX to provide walking speeds for heel and trim given by,

$$\mathrm{TNOHWS}_{\mathrm{Age,Gender,Angle,Suit=0}} = \mathrm{WS}_{\mathrm{Age,Gender,Angle=0,Suit=0}} \times \mathrm{TNOHRF}_{\mathrm{Age,Gender,Angle,Suit=0}} \tag{10}$$

$$\mathrm{TNOTWS}_{\mathrm{Age,Gender,Angle,Suit=0}} = \mathrm{WS}_{\mathrm{Age,Gender,Angle=0,Suit=0}} \times \mathrm{TNOTRF}_{\mathrm{Age,Gender,Angle,Suit=0}} \tag{11}$$

Table 1
TNO and ARCEVAC walking speeds as a function of gender, age, angle of heel and suit type assuming base case of 1.0 m/s for zero angle of heel and the associated TPISRF.

Gender	Angle of heel	Age	TNO Walking Speed (m/s)	ARCEVAC Suit-0 Walking Speed (m/s)	$TPISRF_{Suit=0}$	ARCEVAC Suit-1 Walking Speed (m/s)	$TPISRF_{Suit=1}$	ARCEVAC Suit-2 Walking Speed (m/s)	$TPISRF_{Suit=2}$
Male	0°	25	1	1	1.000	1	1.000	0.936	0.936
		45	1	1	1.000	1	1.000	0.936	0.936
		65	1	1	1.000	1	1.000	0.936	0.936
	10°	25	0.947	0.970	1.025	0.908	0.959	0.823	0.869
		45	0.917	0.947	1.033	0.887	0.967	0.803	0.876
		65	0.915	0.924	1.010	0.865	0.946	0.784	0.857
	20°	25	0.909	0.941	1.036	0.825	0.907	0.723	0.795
		45	0.871	0.897	1.030	0.786	0.902	0.689	0.791
		65	0.856	0.854	0.998	0.749	0.875	0.656	0.767
Female	0°	25	1	1	1.000	1	1.000	0.936	0.936
		45	1	1	1.000	1	1.000	0.936	0.936
		65	1	1	1.000	1	1.000	0.936	0.936
	10°	25	0.947	0.942	0.994	0.881	0.931	0.799	0.843
		45	0.917	0.919	1.002	0.860	0.938	0.779	0.850
		65	0.915	0.897	0.980	0.840	0.918	0.761	0.832
	20°	25	0.909	0.887	0.975	0.777	0.855	0.681	0.749
		45	0.871	0.845	0.970	0.740	0.850	0.649	0.745
		65	0.856	0.805	0.940	0.705	0.824	0.618	0.722

Clearly, Eqs. (10) and (11) do not include the impact of the TPIS. It is assumed that the impact of heel for Suit-0, derived from the ARCEVAC data is similar to the impact of heel derived from the TNO study (see Table 1). Thus, we expect that the ratio of the ARCEVAC and TNO HRF for a given angle of heel for Suit-0 to be approximately 1.0, while the ratio ($HRF_{Age,Gender,Angle,Suit}/TNOHRF_{Age,Gender,Angle,Suit=0}$) is an approximation to the reduction factor due to the suit type alone for a given angle of heel. This ratio is known as the TPIS reduction factor (TPISRF) and is a measure of the expected reduction in walking speed due to the suit type for a given age, gender and heel angle compared to the walking speed under the same conditions for Suit-0. As seen in Table 1, $TPISRF_{Suit=0}$ is approximately 1.0 as expected, with a maximum deviation of 6% for both male and female, in age range from 25 to 65 years and for angles of heel up to 20°.

If it is further assumed that the impact of the TPIS is the same on walking speeds in heel and trim for a given angle, then we can approximate the TWS as follows,

$$TWS_{Age,Gender,Angle,Suit} = WS_{Age,Gender,Angle=0,Suit=0} \times TNOTRF_{Age,Gender,Angle,Suit=0} \times TPISRF_{Age,Gender,Angle,Suit} \quad (12)$$

where,

$$TPISRF_{Age,Gender,Angle,Suit} = \frac{HWS_{Age,Gender,Angle,Suit}}{TNOHWS_{Age,Gender,Angle,Suit=0}} = \frac{HRF_{Age,Gender,Angle,Suit}}{TNOHRF_{Age,Gender,Angle,Suit=0}} \quad (13)$$

Thus, within the modified version of mEX, to determine the $TWS_{Age,\ Gender,\ Angle,\ Suit}$ for a given agent (i.e., a given age and gender, while wearing a particular TPIS and while experiencing a particular angle of trim), it is necessary to determine their $TPISRF_{Age,\ Gender,\ Angle,\ Suit}$ using Eq. (13). The TPISRF is a reduction factor that quantifies the impact of the TPIS on walking speeds and as seen by Eq. (13), is determined by dividing the ARCEVAC waling speed by the TNO walking speed.

Implicit in the assumption that the impact of the TPIS is the same on walking speeds in heel and trim for a given angle, is that this impact is independent of the direction of travel on the trim, i.e., whether it is up the slope or down the slope. However, unlike heel, for a given trim angle, positive or negative trim impacts walking speed (which is reflected in the TNOTRF) and so the nature of the TPIS is likely to exert a different influence depending on whether the trim is positive or negative. Thus, in realistic conditions, the TPIS may have a different impact walking up or down the slope. However, as this has not yet been measured, it has not been taken into account in the TPISRF.

3.3. Walking speed on stairs for angles of heel and trim

As part of the ARCEVAC project stair walking speed (SWS) data while wearing TPIS was collected, however, as this data is still in the process of being analysed it is not currently available for inclusion in this study. Furthermore, it is noted that the ARCEVAC trials did not include the impact of heel or trim on stair walking speeds while wearing TPIS. To accommodate this lack of data, as a first approximation, it is assumed that the reduction factor for SWS while wearing a TPIS at a given angle of heel is identical to the reduction factor derived for walking speeds on flat spaces. However, as passage over stairs while wearing TPIS is not required by the simulations presented in this study, details of the suggested stair walking speed TPIS approximation that can be implemented within mEX are not presented in this paper but can be found in the Supplementary Material (see Sec. S2 and S3).

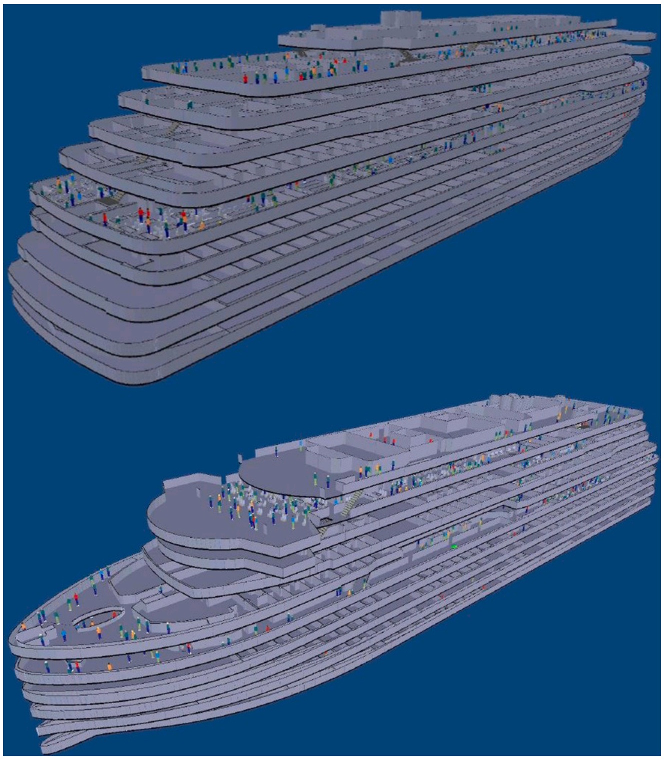

Fig. 2. The hypothetical vessel used within maritimeEXODUS for the evacuation analysis.

4. Ship geometry and benchmark evacuation scenarios

To demonstrate the impact of the TPIS on ship assembly and abandonment times a hypothetical ship geometry based on the layout of an actual vessel is used as described in Sec. 4.1. Furthermore, two core scenarios from the IMO passenger evacuation guidelines (MSC/Circ.1533, 2016) are explored, one associated with the 'Day Case' (see Sec. 4.2) and one associated with the 'Night Case' (see Sec. 4.3).

4.1. Ship geometry and population

To investigate the potential impact of the TPIS on assembly and abandonment times for a passenger ship, a hypothetical ship layout, based on the MS-Roald Amundsen (MSRA) (see Fig. 2) was used. The MSRA was selected as it is passenger ship certified for polar (arctic) exploration. While the actual overall layout of the vessel is used in the analysis, some of the internal layout and specifications have been altered so the model used in the simulations is not an exact replica of the MSRA. The MSRA has an approximate length and beam of 140 m and 23.6 m, respectively, and fulfils the requirements for ice class 1B. The vessel has a cabin capacity for 530 passengers and 151 crew. The ship has four main vertical zones spread throughout 11 decks, of which 8 decks (deck 4 to 11) are accessible to passengers. The cabins are located on decks 4, 5, 7, 8 and 9, while dining rooms and social areas are located on decks 6, 9 and 10. A more complete description of the vessel layout can be found in the Supplementary Material, Sec. S1.

The assembly procedure employed in the analysis assumes that upon hearing the ship alarm, passengers proceed towards their closest ('Day Case') or assigned ('Night Case') assembly station (AS). Located on deck 6 are the vessel's three assembly stations (see Fig. 3 and Supplementary Material, Sec. S1.6 for details). One assembly station is located in the forward section of the vessel (AS-A with a capacity of 448) and two assembly stations are located in the aft of the vessel, one on the port side (AS- B with a capacity of 271) and one on the starboard side (AS-C with a capacity of 671). The lifeboat stations are also located on deck 6, two on the port side and two on the starboard side (see Fig. 3 and Supplementary Material, Sec. S1.6 for details). Thus, from the assembly stations passengers can walk directly to their allocated lifeboat without the need to use stairs.

4.2. IMO day case scenario and its variants

4.2.1. Base Case 1: IMO primary day scenario

Base case 1 follows the requirements of the IMO specified primary 'Day Case' scenario (MSC/Circ.1533, 2016). Within the simulation, each passenger and crew member (simulated agents) are assigned an assembly station. On the sounding of the ship's alarm (i.e., the start of the simulation), after a prescribed delay time associated with the individual's allocated response time (based on the IMO daytime response time distribution), the agent moves to their assigned assembly station. On arrival at the assembly station the assembly process for that agent is completed and their assembly time noted. When the last agent has arrived at their allocated assembly station, the entire assembly process is completed (as TPIS are not required in this case), and the time for the last agent to arrive in the assembly station is identified as the assembly time.

As required by the IMO evacuation guidelines, in the day case scenario it is assumed that passengers are distributed throughout the public spaces of the vessel (i.e., not in the passenger cabins). While the vessel has a cabin capacity for 530 passengers and 151 crew, in the day case the number of passengers and crew are as follows:

- Passengers: public spaces are occupied to 75% of their allocated capacity and so 777 agents are used to represent the passengers.
- Crew: a total of 151 agents are used to represent the crew, of which 126 take part in the assembly process and are distributed as follows (allowing for rounding):
  - o 1/3 of crew (50 agents) are in their cabins and behave as passengers.
  - o 1/3 of crew (50 agents) are in public spaces and behave as passengers.
  - o 1/6 of crew (26 agents) are in service spaces and behave as passengers.
  - o 1/12 of crew (12 agents) are in assembly stations and move towards the most distant cabin allocated to their assembly station.

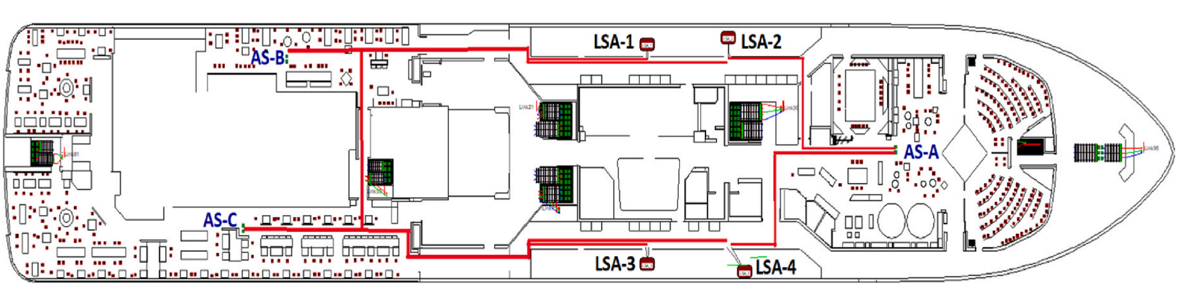

Fig. 3. Deck 6 showing ASs, LSAs and paths from ASs to LSAs.

Table 2
Day and night evacuation cases involving assembly (a) and abandonment (b) with Suit-0 (normal clothing) and Suit-2 (TPIS) investigated using the full ship model.

Scenario			Angle of heel		
Day/Night	**Assembly/Abandonment**	**Suit type**	**0°**	**10°**	**20°**
Day	Assembly	Suit-0	B1a+	S1a*	S2a
	Abandonment		B1b	S1b	S2b
	Assembly	Suit-2	S3a	S4a	S5a
	Abandonment		S3b	S4b	S5b
Night	Assembly	Suit-0	B2a	N/A	
	Abandonment		B2b		
	Assembly	Suit-2	S6a		
	Abandonment		S6b		

+: B=Base case; *: S=Scenario.

On arrival at the allocated cabin, the agent is considered to have completed the assembly process.
- o 1/12 of crew (13 agents) are in their assigned emergency stations and are not represented in the assembly process.

- Total number of agents represented in the assembly process: 903

For simplicity, it is also assumed that passengers are assigned assembly stations, so that each of the three assembly stations are approximately equally populated so that no assembly station is significantly over or under populated. The assembly process is completed once the last agent has arrived at their allocated assembly station or the last crew member has reached the most distant cabin, whichever is greater.

The abandonment process begins once the assembly process is completed. Agents are assigned to a specific LSA, in this case a lifeboat, as part of this process. Passengers walk to their assigned lifeboat and board the lifeboat upon their arrival. The lifeboat is lowered once it has been filled with the required number of passengers and crew. The abandonment process for that cohort of the agents is completed once the lifeboat reaches the surface of the water. The vessel abandonment process is complete when the last lifeboat reaches the surface of the water. The time from the start of the abandonment process (end of assembly process) to the end of the vessel abandonment process is considered the abandonment time (ABT).

In the analysis presented in this paper, the entire ABT is not determined, as reliable data representing the time required by passengers to board the lifeboat and for the crew to launch the lifeboat is not generally available. Thus, only the time required for agents to walk from the assembly station to the LSA (WT) is determined (see Eqs. (1) and (2)). For simplicity, each of the four lifeboats are assigned approximately equal number of passengers and crew so that no lifeboat is significantly over or under populated.

Thus, the base case 1 (B1), i.e., the primary IMO day case, consists of two scenarios, the assembly scenario (B1a) and the abandonment scenario (B1b).

4.2.2. IMO primary day scenario variant involving heel

To assess the impact of heel on evacuation times for the IMO primary day case, base case 1 is repeated at 10° (Scenario 1 or S1) and 20° (Scenario 2 or S2) of heel. As there are two variants of each – one for the assembly process (the ‘a’ case) and one for the abandonment process (the ‘b’ case), there are four additional scenarios in total. Thus, as shown in Table 2, there are three cases to consider for the assembly process, i.e., B1a (IMO day case at 0° heel), S1a (IMO day case at 10° heel) and S2a (IMO day case at 20° heel) and three cases to consider for the abandonment process B1b (IMO day case at 0° heel), S1b (IMO day case at 10° heel) and S2b (IMO day case at 20° heel).

4.2.3. IMO primary day scenario variant involving both TPIS and heel

The six scenarios (i.e., three assembly and three abandonment) described in Sec. 4.2.2. are then modified to represent the impact of the TPIS (both donning and impact on walking speeds) and heel (impact on walking speeds).

For the assembly scenarios, the TPIS are assumed to be located in the assembly stations. When an agent arrives at their allocated assembly station, they are immediately allocated a TPIS and assigned a donning time (from Eq. (4)). The assembly process for the agent is considered to be completed when the agent has donned their TPIS (i.e., the donning time has expired). The assembly process for the assembly station is completed when the last agent assigned to the assembly station has arrived at the assembly station and all the agents assigned to the assembly station have donned their TPIS. The assembly process is considered to have been completed either when the last agent has donned their TPIS, or the last crew member has reached the most distant cabin (see Sec. 4.2.1).

Note that under real conditions, it is likely that there will be a process for distributing the TPIS to passengers and crew in the assembly station, and this will incur additional time delays as passengers and crew queue for their TPIS. However, this has been excluded from the analysis presented in this paper for simplicity. Thus, the predicted assembly times associated with the TPIS are likely to underestimate the actual required assembly time.

For the abandonment scenarios the passengers and crew are assumed to be wearing their TPIS as they make their way to their allocated LSA. Only the impact of wearing Suit-2 (which has a greater impact on walking speeds than Suit-1) is considered in the analysis presented here. Thus there are three additional assembly scenarios involving Suit-2 (S3a, Suit-2, 0° heel; S4a, Suit-2, 10° heel; S5a, Suit-2, 20° heel), and three additional abandonment scenarios (S3b, Suit-2, 0° heel; S4b, Suit-2, 10° heel; S5b, Suit-2, 20° heel) as shown in Table 2.

4.3. IMO night case scenario and its variants

4.3.1. Base Case 2: IMO primary night scenario

Base case 2 follows the requirements of the IMO specified primary ‘Night Case’ scenario (MSC/Circ.1533, 2016). Within the simulation, each passenger and crew member (simulated agents) are assigned an assembly station based on their allocated cabin. On the sounding of the ship’s alarm (i.e., the start of the simulation), after a prescribed delay time associated with the individual’s allocated response time (i.e., the IMO night response time distribution), the agent moves to their assigned assembly station. On arrival at the assembly station the assembly process for that agent is completed and their assembly time noted. When the last agent has arrived at their allocated assembly station the entire assembly process is completed and the time for the last agent to arrive in the assembly station is identified as the assembly time.

As required by the IMO evacuation guidelines, in the night case scenario it is assumed that passengers are all in their allocated cabins, and the number of passengers represents the maximum berthing allocation for the vessel. Thus, in the night case scenario the passengers and crew are distributed as follows:

- Passengers: maximum berthing allocation for vessel, and so 530 agents are used to represent the passengers.
- Crew: a total of 151 agents are used to represent the crew, of which 126 take part in the assembly process and are distributed as follows (allowing for rounding):
  - o 2/3 of crew (100 agents) are in their cabins and behave as passengers.
  - o 1/6 of crew (26 agents) are in service spaces and behave as passengers.
  - o 1/12 of crew (12 agents) are in assembly stations and move towards the most distant cabin allocated to their assembly station. On arrival at the allocated cabin, the agent is considered to have completed the assembly process.

Table 3
The time required for an agent with unimpeded walking speed of 1.5 m/s to walk a distance of 30m along a corridor at different angles of heel wearing Suit-0 and Suit-2 as calculated by maritimeEXODUS and by hand (using Eqs. (8) and (9)).

Gender	Angle of heel	Age	Time (s) Hand Calculation Suit-0	Time (s) maritimeEXODUS Suit-0	Time (s) Hand Calculation Suit-2	Time (s) maritimeEXODUS Suit-2
Male	0°	25	20.0	20.0	21.4	21.4
		65	20.0	20.0	21.4	21.4
	20°	25	21.0	21.3	27.3	27.8
		65	23.8	23.5	31.0	30.6
Female	0°	25	20.0	20.0	21.4	21.4
		65	20.0	20.0	21.4	21.4
	20°	25	22.3	22.7	29.0	29.7
		65	25.3	25.0	32.9	32.5

o 1/12 of crew (13 agents) are in their assigned emergency stations and are not represented in the assembly process.
• Total number of agents represented in the assembly process: 656

For simplicity, it is also assumed that passengers are assigned assembly stations so that each of the three assembly stations are approximately equally populated so that no assembly station is significantly over or under populated. The assembly process is completed once the last agent has arrived at their allocated assembly station or the last crew member has reached the most distant cabin, whichever is greater.

Once the assembly process is completed the abandonment process begins. This follows the process outlined in Sec. 4.2.1.

Thus, base case 2 (B2), i.e., the primary IMO night case, consists of two scenarios, the assembly scenario (B2a) and the abandonment scenario (B2b).

4.3.2. IMO primary night scenario variant involving TPIS

To reduce the number of scenarios that are explored, the night case scenario is repeated only for the case where the TPIS (Suit-2) is used at 0° heel as this is all that is required to demonstrate that the IMO recommended 25% safety factor is inadequate to compensate for all the other factors not included in the simulation. Thus, there is one additional assembly scenario exploring the impact of Suit-2 (6a, Suit-2, 0° heel) and one additional abandonment scenario exploring the impact of Suit-2 (6b, Suit-2, 0° heel) as shown in Table 2. The assembly and abandonment variants follow the processes described in Sec. 4.2.3.

Table 4
Walking distances from each AS to each LSA as a function of heel and trim distance assuming vessel is heeled to port side.

Start - End	Total Distance	Walking distance orientation		
		Heel	Trim (up)	Trim (down)
AS-A - LSA-2	27.5 m	19m	0	8.5m
AS-A - LSA-4	27 m	19 m	8 m	0
AS-B - LSA-1	43 m	41.5 m	1.5 m	0
AS-B - LSA-2	52.5 m	51 m	1.5 m	0
AS-C - LSA-1	64.5 m	47 m	1.5 m	16 m
AS-C - LSA-3	51 m	47 m	2.5 m	1.5 m
AS-C - LSA-4	60.5	56.5 m	2.5 m	1.5 m

5. Results of the modelling

In this section the main results for the ship evacuation simulations are presented. However, prior to presenting these results, a series of elementary tests is performed to verify that the modified software has the correct implementation of the walking speed formulation for Suit-2 under conditions of heel (see Sec. 6.1). In addition, the impact of heel is explored on walking typical routes from various assembly stations to lifeboat stations while wearing Suit-2 (see Sec. 5.2). Finally, the results for the assembly and abandonment simulations are presented (see Sec. 5.3).

5.1. Verification of walking speed implementation at angles of heel with Suit-2

To verify that the walking speed under conditions of heel while wearing Suit-2 is correctly implemented, a single agent is required to walk along a 30 m corridor while wearing Suit-0 and Suit-2 at angles of heel 0° and 20° and the results generated by the modified maritimeEXODUS software compared with the results generated using Eqs. (8) and (9). A distance of 30 m was selected as this represents the approximate minimum distance from an assembly station to an LSA (i.e., AS-A to LSA 4). The unconstrained initial walking speed of each agent is set to 1.5 m/s. Results are generated for both male and females for ages 25 years and 65 years (see Table 3). As seen in Table 3, the results predicted by the modified software agree with the hand calculations using Eqs. (8) and (9) to within 2.4%, verifying that the heel walking speed equations have been correctly implemented. Additional verification concerning the trim walking speeds can be found in the Supplementary Material, Sec. S4.

5.2. Impact of heel and suit type on walking times from assembly stations to LSAs

To demonstrate the impact of suit type and heel angle on walking times for distances typically encountered during the abandonment phase, a series of simulations was undertaken using a single male agent – aged 25 years or 65 years. The agent was placed at the centre of each assembly station and assigned one of the LSAs. The walking speed of the 25-year-old agent at 0° of heel while wearing Suit-0 is 1.5 m/s while the speed of the 65-year-old agent is 1.0 m/s as provided in the IMO

Table 5
Walking times from AS to LSA.

Start – End (average distance)	Age	Time (s) (% difference compared with **0**°, Suit-0)			
		0°, Suit-0	**20**°, Suit-0	**0**°, Suit-2	**20**°, Suit-2
AS-B – LSA2 (52.4 m)	25	34.2	37.6 (7%)	37.4 (6%)	49.1 (40%)
	65	52.9	62.5 (18%)	56.2 (6%)	82.0 (55%)
AS-C – LSA1 (59.0 m)	25	39.4	42.3 (7%)	42.2 (7%)	55.0 (40%)
	65	59.3	70.6 (19%)	63.1 (6%)	91.4 (54%)

evacuation guideline (MSC/Circ.1533, 2016) (HRF = 1 in Eq. (8)). For other angles of heel, and with Suit-2, the walking speed is adjusted based on Eqs. (8) and (9), with reduction factor HRF < 1 and hence slower walking speeds than those provided by IMO. It is noted that if the vessel is at an angle of heel, the agent will have to walk through trim angles if they travel from port to starboard and this will have an impact on their walking speeds different to that of heel. In the simulations presented in this paper, the vessel is assumed to be heeled to the port side (left side of vessel when looking forward).

The direct walking routes from each AS to an LSA is depicted in Fig. 3, while Table 4 presents the associated total walking distances and the walking distances experienced in heel and trim (both up and down). As can be seen, the total walking distances vary from 27 m to 64.5 m, while the walking distances under conditions of heel vary from 19 m to 56.5 m, and the trim distances vary from 0 m up to 16 m. It is noted that for this vessel, the ASs and LSAs are all on the same deck, and so passengers will not need to traverse stairs during the abandonment phase. This is ideal as avoiding the use of stairs will reduce the impact of the TPIS and heel angle on abandonment times.

While simulations were conducted for many combinations of AS and LSA, here we present the results for:

- AS-B to LSA2, representing a total travel distance of 52.5 m, 51 m in heel and 1.5 m in trim (up).
- AS-C to LSA1, representing a total travel distance of 64.5 m, 47 m in heel, 1.5 m in trim (up) and 16 m in trim (down).

Presented in Table 5 are the predicted increase in walking times from an AS to the LSA for an individual agent. As can be seen, the maximum increase in walking time due to heel alone for a 65-year-old passenger is 19% or 11.3 s, the maximum increase in walking time due to TPIS alone is 6% or 3.8 s, while the maximum increase as a result of both TPIS and heel is 54% or 32.1 s. Taken individually, the impact of heel has a greater effect on walking time than TPIS and hence abandonment time, but both are small. However, the combined impact of the TPIS and heel on walking time to the LSA is almost three times the impact of heel alone and almost 10 times the impact of TPIS alone. While this represents a large percentage increase in the time required to walk to the LSA, in absolute terms it is a small increase of just over half a minute when compared to the time for 0° of heel and no TPIS. This may appear insignificant given that a maximum of 30 min is available for the abandonment phase, however, given the accumulative impact this may have over all the passengers, this modest individual increase in walking time may become significant overall.

5.3. Impact of heel and TPIS on ship assembly and abandonment times

The results for the day (see Sec. 4.2) and night (see Sec. 4.3) evacuation scenarios for the full ship geometry (see Sec. 4.1) are described in this section. First, the time required for the day scenarios are presented (see Sec. 6.3.1), followed by the time required for the night scenarios (see Sec. 6.3.2).

To satisfy IMO evacuation certification requirements (MSC/Circ.1533, 2016), each scenario must be run 500 times and the times for the 95th percentile case are considered representative for the scenario. The large number of repeated simulations is required to take into consideration the randomness that occurs within each simulation due to allocation of response times, passenger walking speeds, age and gender distributions and precise starting locations.

However, as the simulations presented here are only intended to demonstrate the potential impact of heel and TPIS on evacuation times, each scenario is repeated only 50 times in order to reduce the time required to run and analyse all the simulations. However, the 95th percentile case (48th longest simulation) is used as the representative simulation for each scenario specified in Table 2. Thus, a total of 16 scenarios are simulated 50 times each, resulting in a total of 800

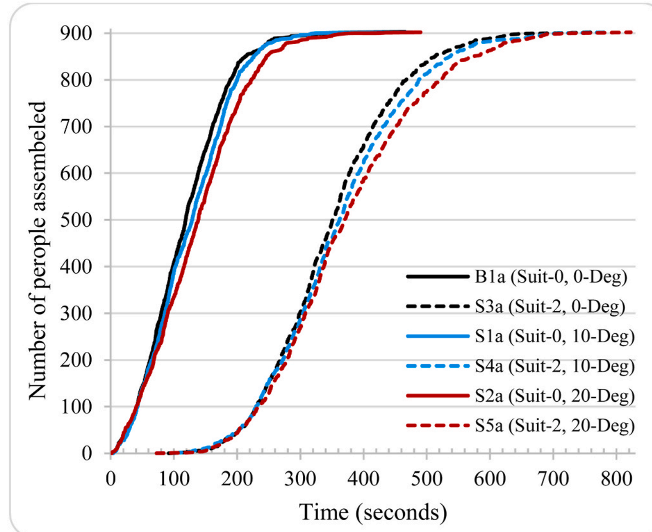

Fig. 4. Assembly times (95th percentile case) for the Day Case Scenarios.

simulations.

In addition, when comparing the results of one scenario with another to determine the impact of parameters such as heel angle or TPIS on assembly and abandonment times, it is often also informative to compare times produced not by the last person but by, for example, 95% of the population. This is because the time for the last person or the last few people could be impacted by chance events, such as for example, the oldest person with the longest response time being initially placed at the furthest location. This could bias the results, producing unrepresentative long tails within a distribution that have little to do with the parameters being explored within the scenario. Thus, when comparing assembly or abandonment times for different scenarios we also consider the times produced for 95% of the passengers, i.e., the 858th person in the day case or the 623rd person in the night case. However, for IMO certification purposes, the time for the last person in the 95th percentile case is taken as representative for the scenario.

It is noted that as the vessel design comprises four vertical fire zones (see Sec. 4.1), IMO requires that the predicted abandonment process takes no longer than 80 min (MSC/Circ.1533, 2016). Furthermore, as the abandonment process is assumed to require the maximum 30 min, from Eq. (1), the predicted assembly time (ASST) for each scenario cannot exceed 48 min taking into consideration the 25% safety factor in order to comply with IMO requirements. If the safety factor is not included, the ASST must not exceed 60 min.

Finally, for the abandonment process, only the time required for the passengers to walk to the LSA (i.e., WT) is considered in the abandonment scenarios.

5.3.1. Results for the day Case scenarios

The day case scenario results are presented in two parts, first for the assembly process (5.3.1.1) and then the abandonment process (5.3.1.2). It is noted that for each repeat simulation, while the number of passengers within each compartment remains the same, the nature of the attributes describing the passengers is completely randomised within the constraints stipulated. This enables the assessment of the impact of the key parameters of angle of heel and TPIS on scenario outcomes.

5.3.1.1. The day case assembly process. The assembly curves for the 95th percentile case for each of the six day-scenarios (B1a, S1a, S2a, …, S5a) are presented in Fig. 4. As can be seen from Fig. 4, the impact of heel alone on the assembly time curve is relatively minor, producing a 12% (27 s) increase in time for 95% of the population (i.e., the 858th person) to assemble when the heel angle is increased from 0° to 20° (without

Table 6
95th percentile times for the Day and Night assembly and abandonment scenarios at various angles of heel and with and without TPIS. Numbers in brackets represent the minimum and maximum assembly times from the 50 repeated simulations.

Primary Scenario	Phase	Heel Angle	95th perc. time (s) Suit-0 (min-max)	Suit-0% Increase compared to Suit-0 at **0**°	95th perc. time (s) Suit-2 (min-max)	Suit-2% Increase compared to Suit-0 at **0**°
Day case	Assembly	0°	465.6 (344–470)	N/A	769.4 (631–781)	65%
		10°	477.2 (350–486)	3%	791.3 (642–793)	70%
		20°	490.2 (345–510)	5%	822.5 (697–835)	77%
	Abandonment	0°	210.8	N/A	224.1	6%
		10°	243.3	15%	280.1	33%
		20°	274.2	30%	361.0	71%
Night case	Assembly	0°	779.3 (715–789)	N/A	1075.4 (933–1100)	38%
	Abandonment	0°	118.7	N/A	127.6	7%

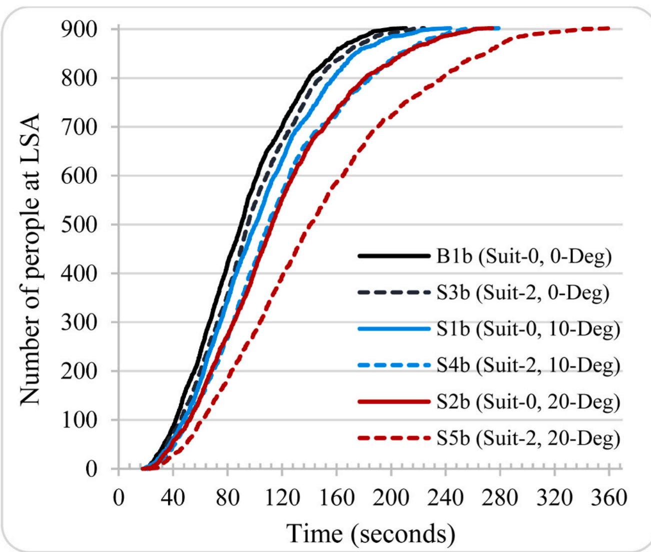

Fig. 5. Abandonment times (WT, 95th percentile case) for the Day Case Scenarios.

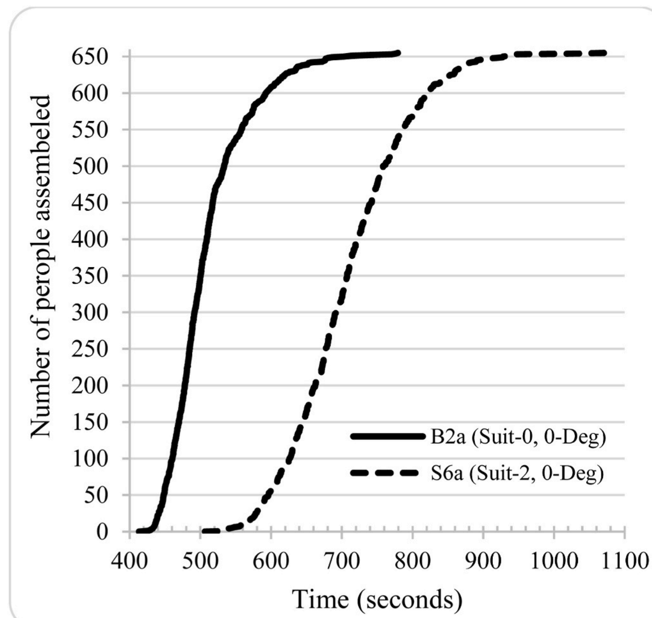

Fig. 6. Assembly times (95th percentile case) for the Night Case Scenarios.

donning). If donning the TPIS is included, the absolute increase in assembly time for 95% of the population is twice as large being 60 s (compared to 27 s) when heel angle is increased from 0° to 20°. However, in relative terms, this increase is only 11% and so comparable to the case without donning.

However, it is also clear from Fig. 4 that donning the TPIS has a significant impact on assembly times at all angles of heel compared to the equivalent cases without donning. For example, the assembly time for 95% of the people to assemble at 0° of heel is increased by 135% (302 s) when donning the TPIS is required. It is also noted that the increase in assembly times due to the donning process observed in this case (i.e., 302 s) is well within the donning time range observed in the trials (76 s–431 s) and produced by Eq. (4) (47 s–678 s).

The assembly time for the 95th percentile case, along with the minimum and maximum assembly time for each of the six day-scenarios (B1a, S1a, S2a, …, S5a) are presented in Table 6. It is noted that the maximum achieved 95th percentile assembly time for the day case is 822 s (Suit-2, 20° heel) is well under the maximum 2880 s (48 min) permitted assembly time assuming a 25% safety factor and so even considering heel and TPIS, the vessel satisfies the IMO certification requirement for the day case assuming Suit-2 is used by the population.

It is also noted that the 95th percentile assembly times increase by 5% (24.6 s) due to the impact of heel alone but increase by 65% (304 s) when donning is required (without heel) and 77% (357 s) when heel and donning is included.

5.3.1.2. The day case abandonment process. The abandonment curves for the 95th percentile case for each of the six day-scenarios (B1b, S1b, S2b, …, S5b) are presented in Fig. 5. It should be noted that the abandonment times presented in Fig. 5 and Table 6 do not include the time to board (BT) and launch (LT) the LSA and so only represent the time required for people to walk to the LSA (WT).

In contrast to the assembly times, the impact of the TPIS alone on the abandonment time curve is small, with the increase in time for 95% of the people (i.e., the 858th person) to reach the LSA being 5% (9.2 s) when wearing the TPIS compared to not wearing the TPIS at 0° of heel. The angle of heel has a greater impact on abandonment times than wearing the TPIS, the increase in abandonment times for 95% of the people being 32% (52.5 s) when heel is increased from 0° to 20° without wearing TPIS. However, it is also clear from Fig. 5 that wearing TPIS together with a 20° heel has a significant impact on abandonment times, resulting in an increase in the abandonment time for 95% of the people of 70% (113 s).

The 95th percentile abandonment time for each of the six day-scenarios (B1b, S1b, S2b, …, S5b) are presented in Table 6. It is noted that the maximum achieved 95th percentile abandonment time for the day case is 361 s (Suit-2, 20° heel) is well under the maximum 1800 s (30 min) permitted abandonment time. However, it is noted that this time represents only the WT component of the abandonment time. Thus, even under the most adverse conditions (20° heel while wearing TPIS)

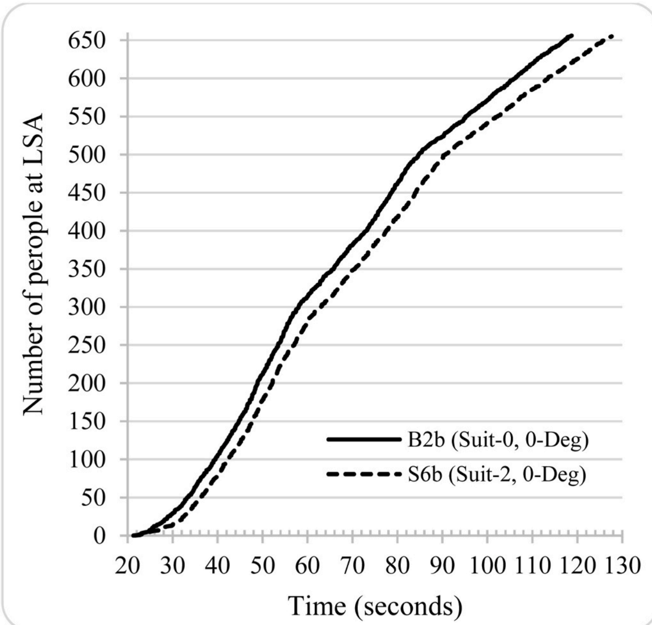

Fig. 7. Abandonment times (WT, 95th percentile case) for the Night Case Scenarios.

there is still 1439 s (24 min) to complete the boarding and launching components (BT + LT) of the abandonment process.

It is also noted that the 95th percentile abandonment times increase by 6% (13.3 s) when passengers wear the TPIS (without heel), 30% (63.4 s) due to the impact of 20° heel alone and increases by 71% (150 s) with the combined effect of 20° heel and passengers wearing the TPIS.

5.3.2. Results for the Night Case Scenarios

The night case scenario results are also presented in two parts, first the assembly process (5.3.2.1) and then the abandonment process (5.3.2.2).

5.3.2.1. The night case assembly process. The assembly curves for the 95th percentile assembly time for the two night-scenarios (B2a and S6a) are presented in Fig. 6. As can be seen from Fig. 6, donning the TPIS has a significant impact on assembly times at 0° of heel. In this case the time for 95% of the population (i.e., the 620th person) to assemble is increased by 38% (231 s) when donning the TPIS is required. As in the day case scenarios, it is also noted that the increase in assembly times due to the donning process observed in this case (i.e., 231 s) is well within the donning time range observed in the trials (76 s–431 s) and produced by Eq. (4) (47 s–678 s).

The 95th percentile assembly time, along with the minimum and maximum assembly time for the two night scenarios (B2a, and S6a) are presented in Table 6. It is noted that the maximum achieved 95th percentile assembly time for the night case is 1075 s (Suit-2, 0° heel) is well under the maximum 2880 s (48 min) permitted assembly time assuming a 25% safety factor and so even considering TPIS, the vessel satisfies the IMO certification requirement for the night case. It is also noted that the 95th percentile assembly times increase by 38% (296 s) when donning is required.

5.3.2.2. The night case abandonment process. The abandonment curves for the 95th percentile abandonment time for the two night-scenarios (B2b and S6b) are presented in Fig. 7. As with the day case scenarios, it should be noted that the abandonment times presented in Fig. 7 and Table 6 do not include the time to board (BT) and launch (LT) the LSA and so only represent the time required for people to walk to the LSA (WT).

As in the day case scenarios, in contrast to the assembly times, the impact of the TPIS alone on the abandonment time curve is small, with the increase in time for 95% of the people (i.e., the 620th person) to reach the LSA being 7.5% (8.3 s) when wearing the TPIS compared to not wearing the TPIS.

The 95th percentile abandonment time for the two night-scenarios (B2b and S6b) are presented in Table 6. It is noted that the maximum achieved 95th percentile abandonment time for the night case is 128 s (Suit-2, 0° heel) is well under the maximum 1800 s (30 min) permitted abandonment time. However, as with the day case, it is noted that this time represents only the WT component of the abandonment time. Thus, while wearing TPIS at 0° heel there is still 1672 s (27.9 min) to complete the boarding and launching components (BT + LT) of the abandonment process. It is also noted that the 95th percentile abandonment time increase by 7.5% (8.9 s) when passengers wear the TPIS (without heel).

6. Discussion

The main results for this work are presented in Sec. 5.3 and demonstrate that both assembly and abandonment times are increased by the requirement to don TPIS during the evacuation of passenger ships operating in polar waters. The observation that both the assembly and abandonment times are increased by the requirement to don TPIS is perhaps not surprising, but the questions that remain to be addressed are: Is this increase in the required evacuation time significant or potentially significant, and should it be represented within the evacuation certification analysis?

6.1. The significance of TPIS during the assembly process

It is important to emphasise that for the assembly process considered in the analysis presented in Sec. 5.3, it is assumed that passengers only attempt to don their TPIS once they have arrived in the assembly station, and only once the donning is completed has the passenger been acknowledged to have completed the assembly process. These are optimistic assumptions that tend to underestimate the impact of TPIS on assembly times. If the TPIS were stored in passenger cabins and passengers were to don their TPIS in their cabins, they would still incur a donning time, as in the simulations presented in Sec. 5.3, but they would also have to walk to the assembly station while wearing the TPIS. The maximum distance from a cabin to the nearest assembly station is approximately 70 m and this involves descending three decks from deck 9 to deck 6. As seen in Sec. 5.2, walking 59 m on a level deck while wearing the TPIS increases the walking time by 6% alone. Thus, travelling a greater distance and having to ascend or descend several flights of stairs while wearing the TPIS would considerably increase the assembly time if passengers were to don the TPIS while in their cabins. In addition, in the simulations presented in Sec. 5.3 it was assumed that the passengers were provided a TPIS as soon as they entered the assembly station, in reality, there would be a distribution process involving passenger queueing, further delaying the assembly time. Finally, it is noted that in polar conditions, it is not possible to commence the abandonment process until the passengers have donned their TPIS and so it is reasonable to assume that the assembly process is not completed until the passengers have donned their TPIS.

It was noted in Sec. 5.3 that the model vessel easily satisfies the standard IMO evacuation certification requirement for both the primary day and night scenarios. The ASST for the day scenario is 466 s or 16% of the IMO permitted maximum of 2880 s (48 min) assuming the 25% safety factor, while the night scenario is 779 s or 27% of the IMO permitted maximum. Thus, for this vessel, any conceivable increase in ASST due to TPIS donning is unlikely to have a significant impact on the acceptability of the vessel. Indeed, when donning is included, even though the ASSTs for the day and night scenarios increase by 65% and 38% respectively, resulting in 769 s and 1075 s respectively, these times are still considerably shorter than the IMO permitted maximum.

However, it is conceivable that another vessel may have ASSTs much closer to the acceptable maximum ASST and so inclusion of the donning process could mean that the vessel does not satisfy the IMO ASST requirement. Thus, while in this case inclusion of the donning process did not make a substantial difference to the outcome of the IMO assessment, it is clearly important to consider the possibility.

Another important consideration is whether the IMO imposed evacuation safety factor of 25% is sufficient to accommodate the donning process, along with the other factors for which it is intended to compensate. If the 25% safety factor can accommodate the impact of the donning process, along with all the other factors it is intended to compensate for, then it would not be necessary to include the donning process in the benchmark IMO evacuation certification analysis. For example, consider the impact of heel on the assembly process. In the day case, the ASST is noted to increase by only 5% or 24.6 s (see Table 6) due to the impact of heel alone (with heel increased from 0° to 20°). Thus, this increase is comfortably accommodated within the 25% IMO evacuation safety factor. This supports the IMO view that it is not necessary to incorporate the impact of heel within the evacuation analysis as the imposed safety factor, that increases the predicted ASSTs when heel is ignored, is sufficiently large to take this and other factors into consideration.

However, when donning time is included, the predicted ASST for the day case is increased by 65% or 304 s and 38% or 296 s in the night case while at 0° heel, i.e., when there is no heel. Thus, the impact of donning alone greatly exceeds the IMO imposed safety factor for both the day and night case. And with the combined effects of heel and donning, the ASST in the day case is increased by 77% or 357 s (see Table 6). Thus, clearly the IMO imposed 25% safety factor is insufficient to compensate for the impact of donning.

It is noted that while both the day and night ASSTs are increased by about 300 s, the percent increase in ASST for the day case is significantly greater than that for the night case. This is because the base assembly time for these scenarios is quite different, while the increase due to donning is approximately the same in both cases. The increase in ASST is due to the nature of the TPIS, for Suit-2, this represents approximately 300 s, but for some other type of TPIS, it could be some other factor.

Clearly, the 25% safety factor is insufficient to accommodate the effects of donning, let alone the combined effect of heel and donning. There are several ways to address this issue, the simplest is to increase the safety factor when considering passenger ships intended for missions in polar waters. The precise magnitude of the modified safety factor is difficult to assess as it will be dependent on specific design characteristics of the TPIS. However, for TPIS which are considered appropriate for polar use, as is Suit-2, it is suggested that the safety factor should be doubled to 50%. While somewhat arbitrary, it is no more arbitrary than the existing 25% safety factor. If a 50% safety factor were used for the vessel in this analysis (with four vertical fire zones, see Sec. 4.1) and assuming the maximum 30 min for the abandonment time, then the acceptable predicted ASST cannot exceed 40 min or 2400 s. Using this criterion, the vessel in the analysis would still be considered acceptable, which is consistent with the conclusions of the full analysis.

Alternatively, in addition to the 25% multiplicative safety factor which compensates for issues excluding the TPIS, a new additive safety factor could be included to increase the predicted day and night assembly times to compensate for the donning time. This again will be dependent on the specific nature of the TPIS, however, if appropriate data is not available, 300 s as determined for Suit-2 could be used. Using an additive factor to reflect the impact of the donning process on the ASST is preferred, as the donning process is independent of the time required by the passengers to reach the assembly stations, and the time required for donning is generally smaller than the time required to assemble. Once again, using this criterion, the vessel in the analysis would still be considered acceptable, which is consistent with the conclusions of the full analysis.

Finally, rather than including a safety factor to address the donning process, the assembly simulation could be expanded to include the donning process as was done using the modified version of maritimeEXODUS. This would require a total donning time distribution for the specific TPIS, as given by Eq. (4) for Suit-2. However, if this is not available for the specific TPIS used on board, the total donning time distribution for Suit-2 could be adopted as a benchmark distribution, just as is done for the response time distribution used in the IMO evacuation certification.

Clearly, using either the first or second approach may be preferred by the IMO as it has the advantage that the evacuation analysis for existing vessels not originally intended for polar operations would not need to be remodelled.

6.2. *The significance of TPIS during the abandonment process*

It is important to emphasise that for the abandonment process considered in the analysis presented in Sec. 5.3, only the time required by passengers to walk to the LSA, i.e., WT is included in the analysis as there are no estimates for the boarding time (BT) or the launch time (LT). It is also assumed that the abandonment time (AT) is the maximum allowed, i.e., 30 min.

Thus, from Eq. (3) we have,

$$BT + LT \leq 30 - WT \tag{14}$$

So, by determining the WT through the simulation of the abandonment process, it is possible to estimate how much time is available for BT and LT. It is important to note that of the three components of the abandonment process, the time required to walk to the LSA (WT) and launching the LSA (LT) probably requires least time, while boarding the passengers into the LSA (BT) requires most time. Boarding passengers into the LSA requires considerable physical exertion and may be difficult for elderly passengers, children and passengers that may be disabled or injured. Thus, it is essential that as much time as possible is provided for the BT (and LT) process(es) and so as little time as possible is consumed by WT.

According to the IMO LSA code (LSA Code, 2017), the maximum capacity of lifeboats is 150 and it must be possible for the lifeboats full complement of persons to board in no more than 10 min (see Sec. 4.4.3.1 of (LSA Code, 2017)). This suggests that on average each person boards, locates a seat (as far away from the entry point as possible), moves to it and occupies it in 4 s. Any delays in this process will decrease the boarding rate and hence increase the required boarding time. Furthermore, as the lifeboat fills, the boarding rate is likely to decrease due to difficulties in moving around the partially filled lifeboat and occupying available empty seat. Compliance with this requirement is usually demonstrated using a full-scale evacuation exercise. However, these exercises are undertaken in ideal conditions, i.e., dead calm, without adverse vessel orientation, in day light, using informed volunteers in good health, with no mobility constraints and who are not obese. Thus, the maximum acceptable 10 min in these ideal situations grossly underestimate the time that is likely to be required in more realistic situations involving a more representative population and adverse conditions. And while the volunteers are wearing lifejackets, they are unlikely to be wearing TPIS.

For B1b, i.e., the base day case (0° heel and no TPIS), the WT was 211 s or 3.5 min (see Table 6). Thus, from Eq. (14), for the day case, the time available for boarding and launching (BT + LT) is no more than 26.5 min. This means that a maximum of 26.5 min is available for the LSA boarding and launching process in normal (ideal) conditions. If we assume it takes approximately 2.5 min to launch the lifeboat, then approximately 24 min is available for the boarding process. This is considerably greater than the 10 min maximum acceptable time identified in the LSA code and represents another form of safety factor incorporated within the IMO evacuation guidelines, this time associated with the abandonment component. This is intended to take into consideration the omissions previously identified in the LSA testing process.

If passengers and crew are wearing TPIS, WT increases to 224 s or 3.7 min (see Table 6) and so the time available for the LSA boarding is approximately 23.8 min, a moderate reduction in the time available to complete the abandonment process. However, given that the passengers are wearing TPIS, it is reasonable to assume that the passengers will require considerably more time to board the LSA then under ideal conditions and under the test conditions used to certify the LSA. This increase in the required boarding time is likely to be due to a number of reasons such as, difficulty in walking due to the cumbersome TPIS shoe covering, difficulty in manoeuvrability due to the bulky ill-fitting nature of the TPIS, restricted vision due to the nature of the head covering and reduced hand dexterity due to the bulky gloves (Azizpour et al., 2022a; Mallam et al., 2014). Furthermore, if there is a 20° heel and the passengers are wearing TPIS, the WT increases to 361 s or 6 min (see Table 6) and so only 21.5 min is available for boarding the LSA. Given that passengers are wearing TPIS and the vessel is at a 20° heel, it is reasonable to assume that the BT will take significantly longer than in the base case. Indeed, it is questionable if the boarding process could be completed within 21,5 min, 2.5 min less than what is expected to be possible in ideal conditions. At the very least, data from appropriate trials is required to demonstrate that the boarding and launching could be accomplished under such conditions within the available time.

7. Limitations

It is accepted that any modelling exercise is an approximation to reality, and so modelling incorporates a range of assumptions and hence limitations that need to be considered when reviewing and interpreting modelling results. This work is no exception. The modelling work presented here incorporates a range of limitations in terms of the data used in the modelling, the nature of the scenarios implemented and the capabilities of the modelling tool. The primary limitations of the current study are identified as follows:

- The modelling scenarios investigated follow the IMO evacuation certification base day and night cases. As such, the scenarios are intended to be benchmark scenarios and so are idealisations of reality. They are not intended to accurately reproduce actual performance of the vessel, crew and passengers in real situations. Furthermore, only the IMO primary day and night scenarios were implemented and so the analysis presented does not reflect the entirety of the IMO certification evacuation analysis.
- There is currently no data to describe the impact of trim on walking performance on flat decks while wearing TPIS. Thus, in this study the impact of trim on walking performance while wearing TPIS is assumed to be identical to the impact of TPIS in walking in angles of heel. Furthermore, it is expected that the TPIS will impact walking speeds differently under conditions of positive and negative trim. In the analysis presented here, the impact of the TPIS was identical regardless of whether the trim was positive or negative. However, in the simulations presented here, walking at angles of trim while wearing the TPIS is only experienced in the abandonment scenarios and in these cases, the passengers experience very little trim. Thus, the impact on study findings is expected to be small.
- There is currently no data to describe the impact of TPIS on walking performance on level stairs and stairs while in heel or trim. While a method to include the impact of the TPIS on stair performance is suggested in the paper (see Supplementary Material Sec. S3 and S4 for details), this is acknowledged to be a crude first approximation. However, in the simulations presented here, walking on stairs while wearing the TPIS was not considered and so this limitation has no effect on the study results or conclusions.
- The donning time data used in the analysis was collected under conditions of static 0° heel and applied to all the heel scenarios. Under conditions of heel, it is reasonable to assume that donning times may be increased. Thus, the impact of donning the TPIS under conditions of heel presented in this paper may underestimate the required donning times.
- Within the simulations, the TPIS distribution process has been idealised. When passengers have reached the assembly station it is assumed that they are instantly in possession of a TPIS and can start the donning process. Under realistic conditions, it is expected that there will be an organised TPIS distribution process which will require the passengers to queue for their TPIS. Thus, there is expected to be a TPIS collection time, that will be determined by the precise nature of the process employed by the vessel. The TPIS collection time will further prolong the assembly process, and so the assembly times presented in this paper are expected to underestimate the time required to complete the assembly process.
- There is no data currently openly available describing LSA boarding and launching time for the vessel used in the analysis. Furthermore, no data is available describing the LSA boarding time for passengers wearing TPIS at 0° and 20° of heel. As a result, only the walking time from the assembly station to the LSA was directly measured in the abandonment analysis. As a result, the impact of wearing TPIS on the abandonment phase can only partially be addressed.
- Only a single vessel layout and a single type of TPIS are considered in this analysis. It is acknowledged that different vessel layouts and different TPIS may result in different outcomes under the idealised IMO benchmark scenarios. However, the analysis presented here has demonstrated that TPIS can impact both the assembly and abandonment process sufficiently to warrant modification to the IMO evacuation certification requirements for vessels operating in polar waters.

8. Conclusion

Thermal protective immersion suits (TPIS) are required by the International Maritime Organization (IMO) to be deployed on all the vessels operating and sailing in polar waters and available for all passengers and crew (if the immersion to the polar waters is applicable). While international standards exist that limit the time required to don the TPIS and the impact they may have on walking speeds on a level deck, there is no evidence to support that these standards-imposed limitations are appropriate for passenger ship evacuation conditions. Thus, a key motivation of this work was to demonstrate the potential impact of TPIS on passenger ship evacuation and determine whether this needs to be explicitly included in IMO certification evacuation analysis (as described in IMO/MSC, Circ 1533) for passenger ships operating in polar waters.

To investigate the cumulative influence of TPIS donning time on the assembly process and the TPIS impact on the abandonment process, an evacuation analysis incorporating the IMO standard day and night case evacuation scenarios were investigated using a generic ship configuration certified for sailing in polar waters based on the MS-Roald Amundsen. The analysis was undertaken using the maritimeEXODUS agent-based ship evacuation simulation software that was modified to include donning data and walking speed data at angles of heel up to 20° while wearing a TPIS approved for polar use.

The key findings and recommendation of this work include:

1) Donning the TPIS can increase assembly times by as much as 303 s (65%). While this did not make a difference in the pass/fail assessment for the particular vessel, clearly an increase in assembly time of this magnitude could be significant. Furthermore, the increase in assembly time is dependent on the specific characteristics of the TPIS and whether this is significant or not is dependent on the nature of the vessel. Nevertheless, an increase in assembly time of this magnitude cannot be ignored and so it is important to consider the TPIS donning process as part of the evacuation analysis.

2) The IMO imposed assembly time safety factor of 25% is insufficient to compensate for the donning process, let alone the other factors it is intended to compensate. It is thus essential that the IMO include consideration of TPIS in evacuation certification analysis for passenger vessels intended for polar operations. This can be accomplished by any of the suggested three approaches:
   a. Increase the safety factor to at least 50%.
   b. In addition to the existing 25% safety factor, include another safety factor that is added to the predicted assembly time to represent the increase expected due to donning the TPIS. An additive safety factor of 300 s is suggested based on the performance of the TPIS used in this study, which is approved for polar operations. This is the preferred option as the donning process is independent of the time required by the passengers to reach the assembly stations.
   c. Include TPIS donning in the modelling of the assembly process as demonstrated in this study. If a donning distribution is not available for the TPIS in question, a benchmark donning time distribution could be used in the same way as the passenger response time distribution is currently used in the evacuation certification analysis. The donning time distribution for the TPIS used in this study could be used.
3) The reported impact of the TPIS on assembly times reported in this study is optimistic and in reality, the increase in assembly times is likely to be greater, thus it is important that emergency procedures on board vessels are carefully considered, in particular:
   a. The TPIS should be stored in the assembly areas as was assumed for this study. This is an important consideration, since if the TPIS are stored elsewhere, for example in passenger cabins, the assembly time will be further increased due to the negative impact of the TPIS on walking speeds.
   b. An efficient process should be developed to distribute the TPIS to the assembled passengers. In the current study it was assumed that the passengers were instantly provided the TPIS on arrival to the assembly area. In reality unless there is an efficient process for distributing the TPIS to potentially hundreds of passengers, this will further delay the donning process and hence the assembly process.
   c. Donning the TPIS can be a difficult task, and so it is essential that sufficient floor space is allocated to each passenger in the assembly station. If there is insufficient space, this can constrain the passengers during the donning process, further delaying the donning process and hence the assembly time.
4) Given the time required to walk from the assembly station to the LSA while wearing the TPIS, the maximum time available to board and launch the LSA is reduced from 26.5 min in ideal conditions to 24 min in conditions of 20° of heel and while wearing the TPIS. It is questionable whether this process could be completed in the available time and so data is required to demonstrate the impact of wearing TPIS on the abandonment process.

As the popularity of polar cruises increases and larger passenger ships operate in polar waters, it is essential that maritime safety and the safety of passengers and crew is maintained. It is not sufficient to simply impose arbitrary requirements on donning times and walking performance associated with TPIS. For these requirements to be meaningful, they must be demonstrated not to adversely impact existing evacuation provision. It is thus essential that the additional requirements associated with the assembly of passengers and the abandonment of vessels in extreme cold conditions are reflected within the IMO passenger ship evacuation certification guidelines.

CRediT authorship contribution statement

Hooshyar Azizpour: Investigation, Methodology, Resources, Formal analysis, Writing - original draft, Writing - review & editing. **Edwin R. Galea:** Investigation, Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Steven Deere:** Investigation, Methodology, Formal analysis, Writing – review & editing. **Sveinung Erland:** Formal analysis, Writing – review & editing, Supervision. **Bjørn-Morten Batalden:** Investigation, Methodology, Resources, Funding acquisition, Supervision, Writing - review & editing. **Helle Oltedal:** Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing 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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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