Western Norway University of Applied Sciences

Quantifying human performance for simulation of passenger ship evacuation in polar climate

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Thesis for the degree of Philosophiae Doctor (PhD) at
Western Norway University of Applied Sciences,
Norwegian University of Science and Technology,
The Arctic University of Norway, and
University of South-Eastern Norway

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Scientific environment

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Acknowledgement

"Science is a way of thinking much more than it is a body of knowledge" *(Carl Sagan)*

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Summary

The evacuation of passenger ships is always a difficult process, and the availability of time to evacuate is the most critical factor for a safe evacuation of the passengers. Indeed, the cold environment of the polar regions introduces additional hazards and challenges in maritime emergencies where it is necessary to abandon a vessel or an offshore platform. By introducing Polar Code, the International Maritime Organization (IMO) requires that all passenger vessels operating in polar waters shall provide thermal protective immersion suits (TPIS) for all passengers in case of an evacuation and possibility of immersion of passengers in polar waters. While IMO requires that the maximum time allowed for passenger ship assembly and abandonment should be evaluated using advanced computerised simulation of evacuation, the impact of adverse environmental factors such as different vessel angles of orientation, the presence of smoke and heat are not required to be modelled. Hence, IMO recommends using an arbitrary safety factor of 25% in the modelling to account for the impact of all factors that are ignored in the simulation. In the event of a ship evacuation in polar waters, it is critical to determine how much the ship's assembly and abandonment are influenced by the deployment of TPIS and whether the employed arbitrary safety factor (25 %) can accommodate the impact of TPIS deployment on assembly time. Answering this question requires an understanding of how long it takes to put on a TPIS and how a TPIS can influence individuals' walking speeds at different angles of orientation of floor.

This thesis has two main goals. The first goal is to quantify the time required to don a TPIS and measuring the effect of wearing TPIS on individuals' walking speeds. The second goal is to use the acquired data on human performance in a maritime evacuation model to evaluate the impact of donning and walking with the TPIS on passenger vessel assembly and abandonment. The required time for donning a TPIS (Suit-2) was measured in this thesis by collecting donning data from 108 participants who were instructed to don the TPIS as fast and correct as they could. The data analysis revealed that the total donning time ranged between 75 and 431 seconds. Furthermore, the effect of TPIS on individual walking speeds was investigated by collecting data from 210 participants wearing two different types of survival suit (Suit-1 and Suit-2) and walking through a 36-meter-long corridor at different angles of heel (0°, 10°, 15°, and 20°). The findings indicated that the effect of a survival suit on walking speeds is dependent on the type of survival suit and the angle of the heel. In extreme cases (i.e., 20°of heel, Suit-

2, 65-years-old female), wearing a survival suit can reduce individual's walking speed by 38%.

Following the second goal, a maritime evacuation simulation model (maritimeEXODUS) was modified to incorporate the impact of donning and walking with the TPIS during the assembly and abandonment of a passenger vessel. The evacuation of a hypothetical passenger ship was simulated in day and night case scenarios. The simulation results revealed that by deploying the TPIS (Suit-2) during the evacuation, at 0° of heel, the assembly time of the ship was increased by 65% and 38% respectively in day and night case scenarios. The simulation revealed that the arbitrary 25% safety factor is insufficient to accommodate the impact of donning the TPIS within assembly time of a passenger vessel operating in polar waters. Furthermore, results indicated that walking with TPIS increases the travel time during the abandonment leaving less time available for embarkation and launching of the lifeboats.

The findings of this thesis demonstrated that the requirements of the current guideline for evacuation analysis of passenger ships (MSC.1/Circ.1533) may not be adequate to ensure the safety of evacuation for passenger ships operating in polar waters. As a result, this thesis recommends that the IMO guideline for evacuation analysis may require including the time it takes to don the TPIS in the calculation of assembly time for certification analysis of passenger ships operating in polar waters. This thesis suggests several approaches in which this can be achieved. Furthermore, several areas for future research in quantifying human performance during evacuation in polar waters are suggested.

Keywords: IMO, Polar Code, evacuation, passenger ship, agent-based modelling, simulation, survival suit, walking speeds, angle of heel, human performance, donning, certification analysis, safety factor.

List of publications

Paper I: Azizpour, H., Galea, E. R., Erland, S., Batalden, B. M., Deere, S., & Oltedal, H. (2023). Factors influencing the time required to don thermal protective immersion suits correctly. *Safety Science*, 164, 106064. (See Annex I)

Paper II: Azizpour, H., Galea, E. R., Erland, S., Batalden, B. M., Deere, S., & Oltedal, H. (2022). An experimental analysis of the impact of thermal protective immersion suit and angle of heel on individual walking speeds. *Safety Science*, 152, 105621. (See Annex III)

Paper III: Azizpour, H., Galea, E. R., Deere, S., Erland, S., Batalden, B. M., & Oltedal, H. (2023). Analysis of the impact of deploying thermal protective immersion suits on evacuation time for passenger ships operating in polar waters. *Ocean Engineering, 283, 114725.* (See Annex V)

- These articles and their supplementary material are attached to the annexes I to VI of this thesis.

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Chapter 1: Introduction and objectives

This chapter presents the introduction and objective of this research.

1.1. Introduction

Over the past decades cruise holidays have grown in popularity in the maritime tourism market because it provides a nearly all-inclusive vacation. In 1999, cruise ships carried nearly 9 million passengers around the world (Wild & Dearing, 2000). By 2006, this figure had risen to more than 17 million and some passenger ships can carry up to 8000 passengers. While safety has always been a concern in the shipping industry, over 8000 people died or went missing in passenger ferry accidents between 1970 and 2015 (Guha-Sapir, Below, & Hoyois, 2016; Iqbal, Bulian, Hasegawa, Karim, & Awal, 2008).

In the aftermath of the Titanic disaster in 1912 (which resulted in the loss of 1506 lives), systematic safety analysis of passenger ships in terms of evacuation came to the forefront and was introduced as an integrated part of the design process (Vassalos, 2006). This led directly to the International Convention for the Safety of Life at Sea (SOLAS), which was signed on January 20, 1914, in London. SOLAS has been updated and improved over the years. According to SOLAS, all ships, particularly passenger ships, must be equipped with active and passive safety barriers, allowing them to be the safest place at sea as long as they are not in danger of capsizing, sinking, or severe uncontrolled fire. Because ship evacuation is unavoidable in some accidents, the International Maritime Organization's (IMO) Maritime Safety Committee (MSC) has issued a guideline for passenger-ship evacuation analysis (IMO, 2016). The evacuation analysis guideline necessitates an advanced computerised simulation of the vessel to determine the assembly (R+T) and abandonment time (E+L) in which (R) represents the response/pre-movement time, (T) represents the travel time to the assembly station, (E) stands for embarkation time to the lifeboat and (L) represents the launching time of the lifeboats (see Figure 1). The performance standard in the guideline requires simulation to be performed while the ship is at 0° of heel/trim and passengers walk in normal clothing at random walking speeds (specified in the guideline) based on their gender and age group. Due to lack of maritime specific data, the potential impact of different vessel orientations and environmental factors such as smoke spread, heat and water egress is suggested to be compensated by an arbitrary safety factor equal to 25% of the total assembly time (i.e., 1.25(R+T)). Thus, the IMO has urged its member states to collect and submit information and data resulting from research activities and full-scale evacuation tests, as well as findings on human behaviour, for use in the further development of the guideline (MSC.1/Circ. 1533).

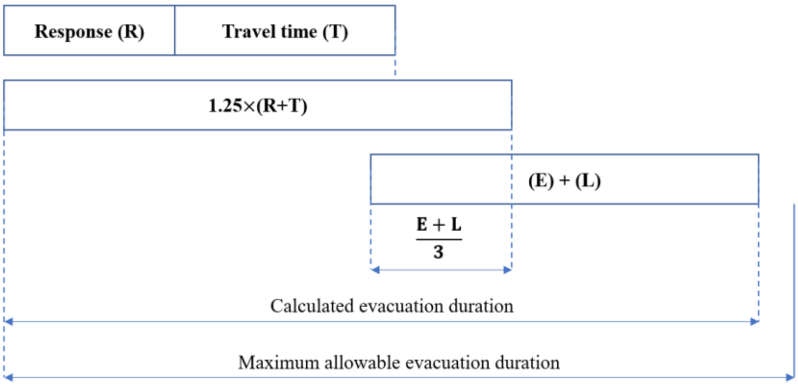

Figure 1: Principal of calculation of the total evacuation duration presented by performance standard (IMO, 2016)

Evacuation of a large passenger ships is a challenging process. Performing this operation in extreme weather conditions, such as in polar regions, presents unique additional challenges. With the increasing popularity of large passenger and cruise ships visiting polar waters in recent years, there has been an increase in the number of accidents with adventure passenger ships in polar regions, several of which required passenger evacuation (Luck, Maher, & Stewart, 2010).

Passenger ship incidents are regarded as having the greatest potential for serious consequences (large number of fatalities) due to the remoteness of the polar region, harsh environmental conditions, cold water temperature, and the long time required for rescue operations. As a result, in the event of an incident, prompt evacuation and rescue are critical. In the wake of several passenger ship accidents in the harsh climate of the polar region (i.e., TS Maxim Gorkiy, MV Explorer etc.), in May 2016, the IMO's maritime safety committee (MSC) acknowledged that the existing safety provisions for passenger ships (IMO, 2014) may not be adequate for ships sailing in polar waters. In light of this, the International Maritime Organization (IMO) issued the Polar Code, which addresses the issues related to the ship design, construction, equipment, operational activities and training, search and rescue as well as the protection of the unique environment and eco-systems of the polar regions (IMO, 2017).

The Polar Code requires passenger ship operators to provide approved thermal protective aids or insulated immersion suits (which is referred to as Thermal Protective Immersion Suit-TPIS) for each person on board as appropriate for the weather conditions such as cold and wind and the potential of immersion in the polar waters

(IMO, 2017). The Polar Code also requires that the survival aids should be stowed in a location as close as practical to the assembly (muster) or embarkation station. Indeed, the requirement for distribution and donning of the TPIS prior to abandonment complicates an already difficult evacuation process. Regarding the Polar Code requirement, maintaining a high level of safety in evacuation may necessitate improvements in vessel design, emergency equipment, and operational procedures, all of which rely on a quantifiable understanding of human performance during evacuation in the extreme environmental conditions of polar waters. According to the international standards, the approved TPIS must be donned within 120 seconds (IMO, 2004; ISO, 2012), and its use should result in no more than a 25% reduction in walking speed (ISO, 2012). However, donning a TPIS and walking while wearing it are challenging, so it's important to specify such limits; those cited are arbitrary and do not reflect their potential impact on evacuation performance.

While research on passenger ship evacuation in less extreme conditions has been conducted (for example (Brown, Galea, Deere, & Filippidis, 2013; Deere, Galea, & Lawrence, 2009; Galea, Deere, Brown, & Filippidis, 2013; Galea et al., 2007; Galea et al., 2004)), no comprehensive, robust, and evidence-based study has been conducted to date, to shed light on the impact of TPIS deployment on passenger ship evacuation, particularly with respect to the requirement of the performance standard for certification analysis of passenger ship evacuation (IMO, 2016).

It is critical to investigate whether the arbitrary 25% (of total assembly time) safety factor (IMO, 2016), which is deemed to be large enough to compensate for the impact of factors such as heel, trim, and the presence of smoke on assembly time, can also compensate for the impact of the time required for passengers to don the survival suit during the assembly phase. Furthermore, it needs to be investigated how wearing the survival suit can impact the abandonment time. The goal of this thesis is to fill a gap in the current state of knowledge by providing an evidence, based on human performance data, through quantifying the required donning time (for the TPIS) and walking performance of the individuals while wearing the TPIS in order to assess the impact of deployment of TPIS on assembly and abandonment of passenger ships that intend to sail in polar region.

1.2. Objectives

According to the performance standard for passenger ship evacuation analysis (IMO, 2016), the arbitrary safety factor equivalent to 25% of total assembly time (1.25 (R+T)) shall account for the adverse effect of various environmental factors such as heel, trim, smoke spread, etc, on passenger assembly time. The Polar Code requires the provision of the TPIS for all passengers onboard on a passenger ship intending to operate in polar waters (IMO, 2017). In the event of an evacuation, the TPIS must be distributed among the passengers during the assembly process. Each passenger must don the TPIS and walk to the lifeboat. Needless to say, the vessel could be heeled/trimmed at any angle or be in a dynamic rolling condition throughout the evacuation. To ensure the safe evacuation of the vessel, it is critical to understand how the deployment of TPIS affects vessel assembly and abandonment, and whether the mentioned safety factor is large enough to account for the impact of required time for distribution and donning of TPIS. This thesis addresses these issues and has the following objectives:

1. To provide an evidence base describing human performance in donning TPIS.
2. To provide an evidence base quantifying the impact of TPIS on walking speeds.
3. To evaluate the impact of TPIS on the time required to evacuate passenger ships.

This thesis also aims to improve current knowledge available to international regulatory authorities (such as the IMO) that specify the requirements for safe operation in polar conditions. The updating of current international regulations must be supported by an evidence-based quantification of human performance for the evacuation of passenger ships in polar waters.

1.3. Research questions

A series of research questions were identified in accordance with the aforementioned objectives. The research conducted within this thesis sought to address the following research questions:

1. How long does it take to properly unpack and don a TPIS?
    a. Which personal factors (such as age, gender, height, weight, experience, and so on) would influence the TPIS donning time?
    b. Which personal factors (such as age, gender, height, weight, experience, and so on) would influence the correctness of donning a TPIS?
    c. Which donning errors impact donning time?

   d. How does donning instruction impact both donning time and correctness? What is the most effective method of instruction for reducing donning errors and donning time?
2. How does the type of TPIS affect walking speeds at various angles of heel?
   a. Does the design/type of survival suit affect people's walking speeds?
   b. Which personal factors (such as age, gender, height, weight, and so on) influence walking speeds?
   c. Does wearing a TPIS significantly increase the difficulty of walking at angles of heel?
   d. How does angle of heel impact walking speeds with and without a TPIS?
3. Does donning and wearing a TPIS significantly impact assembly and abandonment times for a passenger vessel?
   a. How can donning a TPIS be represented in an agent-based evacuation simulation model?
   b. How can the impact of wearing a survival suit on walking speeds be incorporated within an agent-based evacuation simulation model?
   c. Is the arbitrary 25% safety factor assumed in the IMO evacuation guidelines sufficient to accommodate the impact of TPIS in the assembly process?
   d. How significantly is abandonment time impacted by passengers and crew wearing a TPIS?

The answers to the above-mentioned questions can shed light on a highly demanding, complex, and poorly understood problem, allowing for a better understanding of the potential challenges and the extent of impact posed by deployment of survival suits in passenger ship evacuation. This knowledge not only facilitates the investigation of better evacuation options, which improves passenger survivability and resilience in the extreme environment of polar waters, but it also provides input for planning, policymaking, and improving passenger ship design through enhancements to existing computer-based evacuation simulation tools.

1.4. Thesis structure

This thesis is organised in six chapters. The following **chapter 2** provides a brief review of the passenger ship accidents and developments of the IMO guidelines for safe evacuation of passenger vessels. **Chapter 3** presents a brief review of the previous research**. Chapter 4** presents the research methodology, describes procedures for data collection and analysis. **Chapter 5** briefly describes the result of data analysis and modelling corresponding to the content of Paper I, II and III. **Chapter 6** concludes the thesis, highlights the limitations, and provides implication for future research.

Chapter 2: Background

This chapter provides a review of passenger ship accidents and the international guidelines which have been introduced to improve the safety of passenger ships. Furthermore, the importance of time during an evacuation in the event of a ship accident is discussed in this chapter.

2.1. Review of the passenger ships accidents

The abandonment of the ship is a very uncertain process. The severity of reported ship accidents in the last few decades has increased attention on the safety and evacuability of passenger ships. In addition to the Titanic disaster, which claimed 1506 lives in 1912 (Kludas, 1975), a more disastrous passenger ship accident occurred in January 1945 onboard the MV Wilhelm Gustloff, which was carrying approximately 9343 passengers when it was hit by torpedoes, causing the ship to sink and 8439 passengers to perish (Kludas, 1977). The statistical record of passenger ship accidents have revealed that just between 2000 and December 2015, approximately 9945 people died in ship accidents (Statista, 2017). Since April 2009 over 14 severe passenger ship accidents have been reported, resulting in over 4000 fatalities (Brown, 2016). Figure 2 depicts a summary of fatal passenger ship accidents from 1987 to 2016.

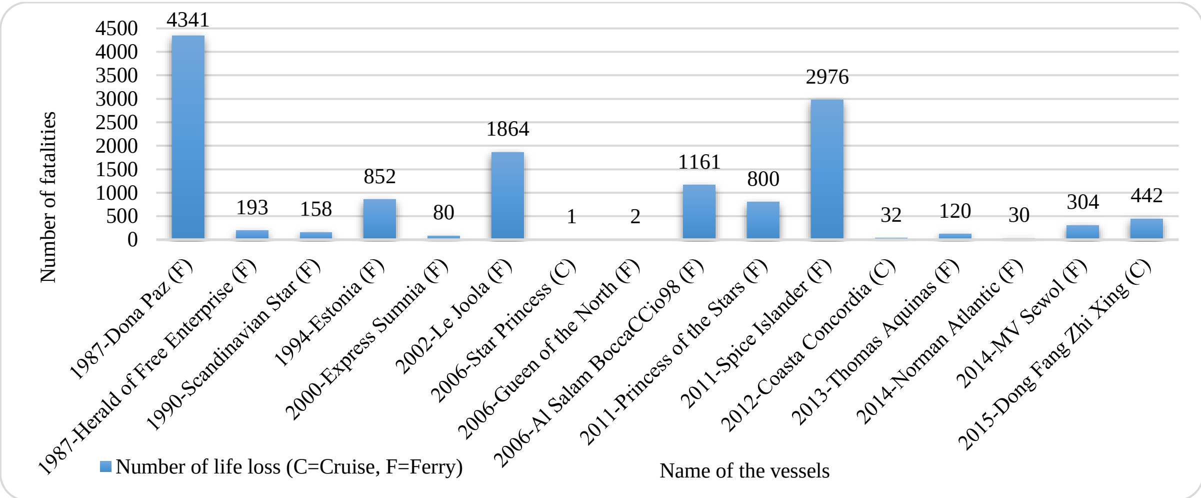

Figure 2: Summery of disastrous passenger ship accident from 1987 to 2016 (Brown, 2016)

As presented in Figure 2, the MV Estonia, which sank on her way from Tallinn to Stockholm in September 1994, claimed the lives of 852 people. According to anecdotal testimony, noises (a metallic bang) and ship motion gave passengers their first impression of an abnormal situation. Ten minutes after the accident, the ship began to list. Evacuation began rather late, after the ship had already tilted, making movement through the corridors difficult and creating a bottleneck in the open spaces (e.g., in front of staircases). Walking became extremely difficult and nearly impossible for passengers when the angle of heel exceeded 20 degrees (Karppinen, 1998).

In another accident, the Costa Concordia collided with the "Scole Rocks" on her way from Civitavecchia to Savona (Italy) in January 2012. After the collision, the ship began to heel. Passengers received the announcement for assembly 50 minutes after the collision and by that time the movement was reported to be difficult due to the angle of heel and that the furniture had shifted around. This made it more difficult to retrieve lifejackets from their storage location. The circumstances caused congestion in the staircase near the lifeboat area. In the Costa Concordia accident, 35 people were killed and 153 were injured. Similar to the Estonia accident, the underlying cause of the improper evacuation appeared to be late announcement of abandon ship, lack of proper instruction, poor communication, and weak leadership (Di Lieto, 2012).

As the Costa Concordia disaster occurred in the calm benign conditions of the Tyrrhenian Sea and very close to shore, the rescue operation was rapid. Had the accident occurred in a remote hostile environment, such as in Polar waters, the outcome of the accident would have been considerably worse. Apart from the remoteness of Polar waters, the evacuation would have required more time as passengers would have needed to retrieve and don thermal protective suits.

According to Allianz Global Corporate & Specialty (AGCS) analysis (Allianz, 2022), the number of reported total losses of passenger ships and RO-RO passenger ships from 2005 to 2021 was 123 and 81 vessels, respectively (see Figure 3). As presented in Figure 3, the number of hull loss does not have a steadily declining trend. Although there was no loss of life in some of the accidents, the potential for loss of life was significant.

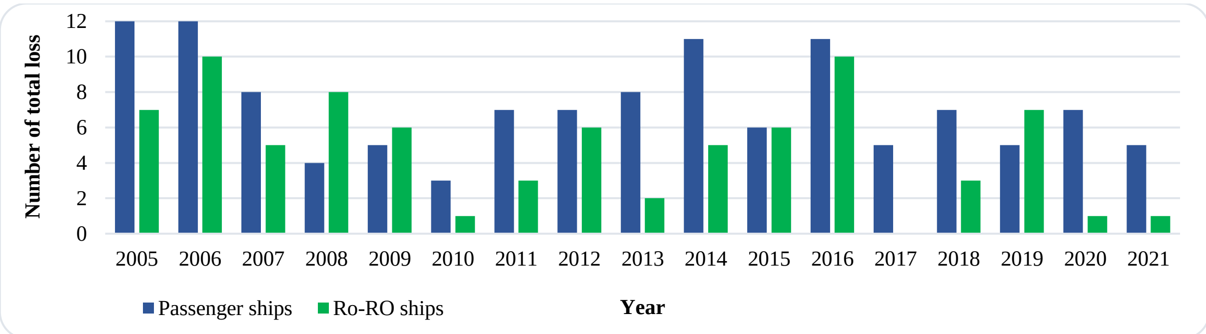

Figure 3 Total loss by type of vessel from 2005 to 2021 (Allianz, 2022)

2.2. Operation and accidents in polar waters

The polar region has received increasing attention in recent decades due to shrinking ice layers and increased interest in polar and arctic expedition voyages. This has resulted in a significant growth in traffic in this area. In 2010, for example, there were four ships navigating the Northern Sea Route. This figure increased to 34 in 2011 and 46 in 2012. The number of ships sailing on the Northern Sea route was reported to be 71 in 2013. Although this number fell in 2014 due to heavy ice cover, the long-term trend shows a significant increase in shipping traffic in polar waters (Allianz, 2017). The arctic shipping status report shows that between 2013 and 2019, the number of ships entering the polar waters grew by 25%. Although the majority of ships sailing in polar waters are reported to be fishing vessels (41%), just in 2019, 73 cruise ships sailed in the polar waters (Arctic-Council, 2020). The increase in arctic water traffic has resulted in an increase in the number of reported accidents in the region. According to a statistical analysis of annual accident reports, the number of reported casualties in the Arctic Circle reached 55 in 2014, up from 3 in 2005 (Allianz, 2017). Clearly, with the increasing trend in the marine traffic and ship accidents in polar waters, an increase in the number of associated fatalities is expected.

As an example of past accidents in polar waters, Maxim Gorkiy collided with an iceberg while sailing from Iceland to Magdalena in the Greenland Sea on June 19, 1989 (Kvamstad, Fjørtoft, Bekkadal, Marchenko, & Ervik, 2009). There were 575 passengers and 378 crew members on board (953 in total). The ship collided with a drifting iceberg at high speed. Rupturing the hull resulted in the vessel taking on water. All of the passengers and one-third of the crew were forced to abandon the ship and await rescue on the nearby ice floes or in lifeboats close to the drifting ice. It took approximately 3 hours for the rescue to arrive. The water ingress was eventually stopped by the ship crew and rescue team and the ship was towed to Svalbard for primary repair. Although there was no loss of life in this accident, it is important to note that when the accident occurred, the weather was extremely good and calm, and there was an iceberg nearby where passengers could evacuate the ship and await rescue. Fortunately, by the time the salvage team arrived, the ship had taken 9000 tons of water, and the technical report revealed that if the ship had taken 9500 tons, the water level would have reached a critical level, causing the vessel to sink. In that situation, the 500 tons of water would take 30 minutes to enter the ship, and the salvage team would be unable to save the ship if they had arrived only 30 minutes later. As a result, Maxim Gorkiy was saved solely by chance. This means that if the weather had been bad, not only would the ship have sunk, but many of the crew and passengers are likely to have perished. At the time of the accident, there were no international regulations requiring thermal protective suits for passengers in vessels sailing in polar waters. As a result, the Maxim Gorkiy passengers only had access to whatever thermal protective clothing they personally had brought onboard for the voyage.

In 1997, the cruise ship Hanseatic became stranded in Murchison fjorden in the Hinlopen Strait at Svalbard (Stewart, Howell, Draper, Yackel, & Tivy, 2010). The ship carried 145 passengers and 115 crew members. When the captain attempted to approach the land to show the area to the tourists, the ship ran aground and tilted to nine degrees of heel. The passengers abandoned the vessel into the lifeboats and were transferred to Longyearbyen with the assistance of Tromsø coast guard. Because of the prompt response of the coastguard and the assistance of good weather, none of the 260 passengers on board were injured in this accident (Klein, 2010).

The expedition cruise ship MV Explorer capsized and sank in Antarctic waters in November 2007 after colliding with a multi-layer ice floe while sailing east of King George Island (Kruke, 2021). The captain promptly ordered the abandonment of the vessel, resulting in all 154 passengers being able to safely evacuate the vessel without injury. During the evacuation, the passengers had difficulty in locating their assigned assembly stations and lifeboats and so did not utilise the lifeboats allocated to them according to the muster list. Fortunately, the weather conditions at the time of the accident were good and the calm conditions assisted in the rapid and safe evacuation of the passengers. However, shortly after the evacuation was completed, the weather conditions changed dramatically, with rough seas and ice around the sinking vessel. Had the accident happened slightly later in the day, the outcome of the evacuation could have been significantly different. According to the accident report, the passengers complained about having difficulty climbing the ladder while boarding the rescue vessel due to the cold temperature. Passengers in this accident were not provided with approved thermal protection clothing for polar environments, which is why they suffered from cold temperatures.

Potential hazards influencing human performance in the polar region include, but are not limited to: cold-weather breathing difficulties, bulky clothing, frost bite, slippery surfaces, and low visibility (Bercha, Brooks, & Leafloor, 2003). An accident or incident involving maritime activities in the polar region places the ship and its crew/passengers in a very vulnerable position, with the possibility of severe consequences due to stressors associated with the harsh polar climate. Hence, the passengers' survival is highly dependent on timely evacuation and rescue. It is also important to note that, in all the aforementioned accidents; the vessels involved complied with SOLAS regulations in force at the time of accident. However, in all the accidents described, TPIS were not issued to the passengers during the evacuation and fortunately, the accidents occurred during good weather conditions with the timely arrival of external rescue. Had the conditions been worse, as frequently occurs in polar conditions, or if rescue had been delayed, the number of fatalities is likely to have been higher.

2.3. Regulatory framework for passenger ship evacuation

The experience of passenger ship disasters over the past decades, and the growing number of large passenger ships in operation has brought attention to the importance of effective and safe passenger evacuation as the last line of defence (layer of protection) for people in a passenger ship emergency. This resulted in the adoption of SOLAS II-2/28-1.3 in the international conference on Safety of Life at Sea, which stated that the escape routes onboard RO-RO ferries must be evaluated using appropriate evacuation analysis. As a result, an interim guideline for the execution of the evacuation analysis in RO-RO ferries was developed (MSC/Circ.909). This guideline introduced a framework for simplified evacuation analysis of RO-RO passenger ships.

In the interim guideline, the awareness time (response time) was assumed to be 10 minutes at night and 5 minutes during the day. The evacuation time was calculated according to the methodology presented in Figure 1. The data for calculating the travel time on the stair, corridors, and doorways was adapted from the handbook of fire protection engineering (SFPE) (Hurley et al., 2015).

Later in June 2001, the IMO Fire Protection Sub-Committee approved an interim guideline for simplified evacuation analysis of high-speed passenger crafts. It was proposed in May 2002 that evacuation analyses shall be performed not only on RO-RO passenger ships, but also on all new and existing passenger ships. MSC/Circ.1033 (which replaced MSC/Circ.909) introduced two methodologies for evacuation analysis of passenger and RO-RO passenger ships. The accepted evacuation time was determined by a fire risk analysis. Due to a lack of data on human evacuation performance in ships, all member governments were encouraged to collect and submit information and data resulting from research activities and full-scale evacuation tests, as well as findings on human behaviour, for future development of the interim guideline. In January 2005 Guideline for simplified evacuation of high-speed passenger crafts amended to SOLAS (MSC/Circ.1166).

MSC/Circ.1033 was revised and replaced in May 2007 by MSC.1/Circ.1238, which used an arbitrary safety factor of 1.25 to calculate assembly time (response time plus travel time – (R+T)). Response time duration is advised to be considered log-normal distributed (in both day and night cases) in the advanced evacuation analysis, with the given probability density function derived from the response data from the full-scale ship evacuation trials (Galea et al., 2007). The IMO's maritime safety committee revised the guideline for evacuation analysis of new and existing passenger ships in May 2016, making the analysis mandatory not only for RO-RO passenger ships but also for other passenger ships built on or after 01.01.2020.

According to the IMO guideline, the maximum total evacuation time (n) of a vessel should not exceed 60 minutes if the ship is a RO-RO passenger ship or has less than three main vertical zones (MVZ) (IMO, 2016). In the performance standards, the maximum allowed total evacuation time (n) for passenger ships with more than three MVZ is 80 minutes. The total evacuation duration is calculated using the Eq. (1):

$$1.25\,(\mathrm{R}+\mathrm{T}) + \frac{2}{3}(\mathrm{E}+\mathrm{L}) \leq \mathrm{n} \tag{1}$$

Where, (E) stands for Embarkation, (L) represents the launching time and $(\mathrm{E}+\mathrm{L}) \leq$ 30 min.

The total evacuation is divided into two stages: assembly (R+T) and abandonment (E+L). According to evacuation analysis guidelines (IMO, 2016), ship abandonment should not take longer than 30 minutes under any circumstances.

Despite the aforementioned improvements, the guideline (MSC.1/Circ.1533) remains incomprehensible in addressing all the uncertainties caused by the various scenarios that influence evacuation. This is due to a lack of maritime-related data and practical experience in developing simulation models (IMO, 2016). For example, the impact of smoke, heat, toxic fire products, family/group behaviour, and ship motion/heel or trim is not considered in the evacuation performance of crew/passengers, and the guideline only introduces an arbitrary safety factor equivalent to 25% of the assembly time (R+T).

Indeed, these parameters can have a significant impact on the performance of passengers during the evacuation (David A. Purser & McAllister, 2016). Furthermore, the population demography is assumed to be identical across all types of passenger ships, underestimating the impact of ship type and route on passenger demography. Passengers on passenger ferries and RO-RO ships are more likely to be commuters and middle-aged (25- to 50-year-old) passengers (Wang et al., 2020), whereas travelling on a cruise ships (especially in winter time) is expected to be more popular among elderly people (Field, Clark, & Koth, 1985).

Furthermore, the guideline suggests using a formulation based on linear regression to calculate an individual's unhindered walking speed on flat terrain. It is assumed that the data (walking speed) is distributed uniformly within each age group. The given formula for walking speed is based on age and gender, but the data is gathered based on walking performance of people in train (corridor) and buildings (up and down the stairs). Clearly, the environment in the train or building cannot be compared to that of the passenger ships in emergency. The layout and size of the enclosure are not the only differences between a train/building and a ship. A passenger vessel could be at an angle of heel or in dynamic motion while being evacuated. These issues are not addressed in the guideline (MSC.1/Circ.1533) due to lack of maritime-related data, and the IMO recommends further investigation for the collection of maritime-specific data.

2.4. Polar Code

SOLAS specifies the minimum requirements for the provision of life-saving appliances in merchant and passenger ships; however, this requirement does not specify the functionality and survival time of life-saving equipment in harsh environments (i.e., polar condition). In the wake of reported accidents in the polar region, IMO acknowledged the necessity of specific requirements concerning the safety of passenger ships operating in polar waters. Thus Polar Code was introduced by IMO in November 2014, as an amendment to SOLAS (IMO, 2017). The adoption of Polar Code occurred ahead of the recent growth of shipping in the Northern Sea route, emphasising the need for shipping companies to be proactive in terms of regulatory change concerning safety. The Polar Code addresses design, construction, equipment, operational activities, training, and search and rescue.

According to the requirements of the Polar Code (IMO, 2017), all ships operating in the defined waters of the Arctic and Antarctic must have the Polar Ship Certificate, which classifies the ships into A, B, and C categories based on the thickness of the ice that ship will be allowed to operate in. General safety instructions in the Polar Code require ships to have the Polar Water Operational Manual (PWOM), which provides information about the ship's operational capability and limitations to the owners, operators, master, and crew. Nonetheless, many issues concerning polar water safety (such as crew training, evacuation procedures, and so on) remain unspecified. Since the PWOM will be approved by flag states and classification societies, the ultimate question is the flag state's and classification societies' quality (Allianz, 2017).

In terms of passenger survival, the Polar Code states that all life-saving appliances and associated equipment must provide safe and timely evacuation under possible adverse environmental conditions.

According to Polar Code (IMO, 2017):

1. *"Adequate thermal protection shall be provided for all persons onboard taking into account the intended voyage, the anticipated weather condition (cold and wind) and potential for immersion in the polar water where applicable".* (Section 8.2.3.1).
2. *"For passenger ships, a proper sized immersion suit or a thermal protective aid shall be provided for each person on board and where immersion suits are required, they shall be of the insulated type".* (Section 8.3.3.1).
3. The survival equipment *"shall be stowed in easily accessible location as close as practical to the muster or embarkation station".* (Section 8.3.3.3.3.2).

The life-saving appliance (LSA) code (SOLAS) requires that adult lifejackets shall be designed in such a way that at least 75% of people who are completely unfamiliar with the lifejacket can correctly don it within one minute without assistance (IMO, 1998). Nonetheless, past experiences have shown that many passengers may fail to put on their lifejackets within the required time (Glen, Igloliorte, Galea, & Gautier, 2003). When ships are sailing in cold weather, the difficulty of donning the life-saving equipment is magnified. SOLAS specifies a maximum donning time of two minutes for immersion suits in the ambient temperature of 18° to 22° Celsius. This means that individuals must be able to fully unpack and don the suit without the assistance of others within the time limit (120 s). Furthermore, according to ISO standards (ISO, 2012), wearing TPIS should not reduce the average walking speed by more than 25% (ISO, 2012). Compliance with this requirement is demonstrated by calculating the average walking speed produced by six people wearing the TPIS and walking over 30 metres with a heel angle of 0°.

Thermal protective suits may include an extra insulation layer (which makes them bulky), therefore passengers who wear them may take up more space. The bulkiness and nature of the suits may cause some restriction or inconvenience in the movement of passengers. The thickness of gloves, for example, has been found to interfere with full hand and finger functionality (Solberg, Gudmestad, & Kvamme, 2016). Furthermore, the nature of the thermal protective suits, which may cause extra weight, may influence the walking speed of the passengers. Walking with the survival suit could be even more difficult if the person is walking at an angle of heel/trim. The effect of Thermal Protective Immersion Suits (TPIS) on passenger performance during evacuation in polar waters is poorly investigated. Passengers' performance to don a TPIS in the stressful environment of a ship's emergency is likely to be longer than the two minutes stipulated by regulations. Thus, it is important to understand how long it actually takes to put on a TPIS and how walking speeds at different angles of orientation of the floor are impacted by wearing a TPIS. This is critical with respect to the application of 25% arbitrary safety factor in the certification analysis of passenger ships that are intended to operate in polar waters (IMO, 2016).

2.5. Availability of evacuation time

In any ship accident involving significant damage, prompt evacuation is critical. To gain a better understanding of the expected available time in the event that the ship must be evacuated, we may need to first examine the major hazard/accident types that result in the ship's inevitable evacuation. The study of passenger ship accidents revealed that fire, grounding, and collision were the most common causes of passenger ship accidents resulting in vessel evacuation (Skjong & Vanem, 2004). According to studies, among the three major threats to passenger vessels, grounding and collision are even more critical in terms of passenger ship evacuation (Vanem & Skjong, 2006), because in a typical fire accident, fire escalation is normally delayed by firewalls that separate the fire zones. As a result, evacuating a specific affected fire zone rather than the entire ship becomes more critical. Furthermore, ships that sink as a result of the fire will usually begin sinking after a certain time period, which is typically in the order of days. As a result, the time required to evacuate the entire ship may be sufficient for all passengers who are not directly exposed to fire before the fire spreads throughout the vessel. However, for those in the fire zone, time to escape may be very limited before the heat and toxic gases become a major threat to their life and health.

Presented in Figure 4 is the expected available evacuation time for various accident types. It clearly demonstrates that collision and grounding are more critical than fire.

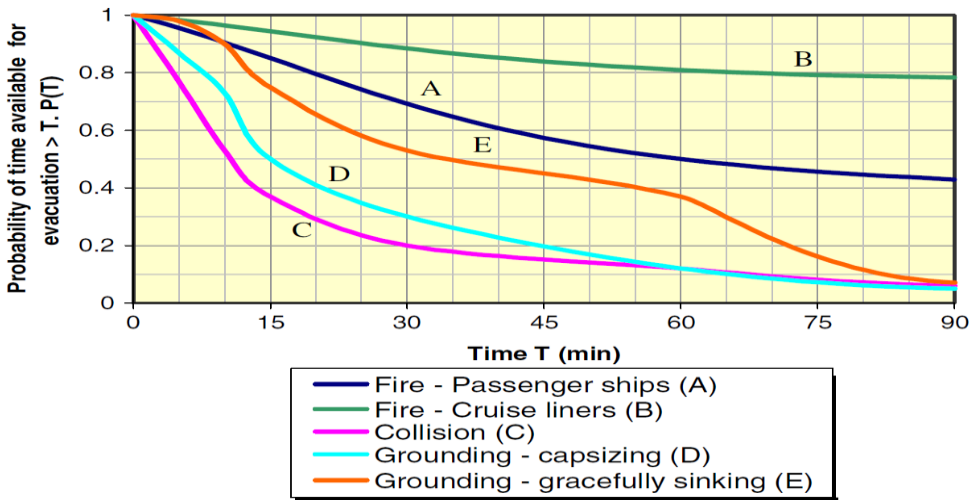

Figure 4: Expected available evacuation time (Vanem & Skjong, 2006)

As can be seen from Figure 4, in case of collision and grounding (capsizing), within the first 15 minutes after the accident the probability of time available for evacuation decreases to 40% and 50% respectively while this probability remains over 80% in case of a fire accident. This shows the criticality of early evacuation.

The concept of evacuation from the ship can also be divided into two categories of precautionary and emergency (Vanem & Skjong, 2006). When there is no immediate threat to the passengers, a precautionary evacuation may be initiated in which the duration of the evacuation is inconsequential. In the other hand, time is critical in emergency evacuation, and the overall goal of emergency evacuation is to muster as quickly as possible before it is too late, because failure to evacuate on time will be fatal. In severe accidents such as collisions, grounding with subsequent large-scale water ingress, and uncontrolled fire escalation, emergency evacuation is performed.

In all types of ship accidents, an emergency evacuation is unavoidable if the ship is believed to be sinking. The manner in which the ship sinks can also have an impact on the amount of time available for evacuation. Vanem and Skjong (2004) distinguished two types of ship sinking: gracefully sinking and capsizing sinking. In the former case, the ship begins sinking in an upright position, and there is usually enough time for evacuation because the deck of the ship remains horizontal to some extent. However, if the grounding causes the ship to capsize, the ship sinks much faster, because the list typically increases as the ship tilts to one side. If the ship's list exceeds a critical angle of 20°, lifeboat abandonment is no longer possible, and a high percentage of fatalities among passengers remaining onboard is expected (Vanem & Skjong, 2006).

Chapter 3: Theory and previous research

This chapter reviews previous research on human performance in maritime evacuation and presents a brief theory of evacuation modelling.

3.1. Evacuation phases

The early cues of an emergency can be ambiguous for many of the occupants, resulting in some time elapse before occupants become fully aware and convinced of the need for proper action. To estimate and quantify the evacuation time, occupant performance is measured in two stages. According to Fire Safety Engineering standards these two phases are defined as pre-movement (response) and movement (travel) phases (ISO, 2009).

The pre-movement (response) phase begins when an occupant receives an emergency warning and ends when an occupant makes the first purposeful movement toward an exit (Lovreglio, Kuligowski, Gwynne, & Boyce, 2019). Recognition and response time are included in the pre-movement time (ISO, 2009). The travel time for an occupant of a specific part of a building is the time it takes from the start of the movement toward the exit to the time the occupant arrives at a safe/assembly location (D. A. Purser & Bensilum, 2001). Analysis of incidents has revealed a link between a delayed evacuation and a high death or injury rate, especially in large buildings with complex layouts. As a result, response time and behaviour have a significant impact on calculating required escape time (Fahy & Proulx, 2001; Guylene Proulx, 2003).

In the maritime safety concept, the total evacuation (abandonment) time for each passenger on a passenger vessel is divided into three distinct phases. Similar to the definition of the evacuation process in a building, there is a pre-movement (response (R)) and travel time (T) (which are referred to as the assembly phase, i.e., R+T), in addition there is a ship abandonment phase after assembly (E+L)(Vanem & Skjong, 2004). A wide range of influencing factors such as the structure's layout (width of the doors, arrangement of exits, etc.), organisational factors (safety drills), communication between passengers, group behaviour, and environmental factors (effect of heat, toxins and smoke, debris, etc.) influence the behaviour of passengers during an emergency (Kim, Park, Lee, & Yang, 2004; Steven C Mallam, Lundh, & MacKinnon, 2015, 2017).

Regardless of the methodology, modelling the evacuation requires data on the passengers' behaviour and performance. For example, their likely actions during the evacuation and the walking speed for individuals in different environments based on their age, gender, and mobility level (Boyce, 2017; Geoerg et al., 2019). The terms "pre-movement time," "initial response time," and "time to start" are used interchangeably in the literature to describe the amount of time that occupants delay before starting to move towards the exits. This has been investigated and documented through a series of semi-unannounced evacuation trials in buildings and offices (Lee, Kim, Park, & Park, 2003; Guylène Proulx, 1995; G. Proulx et al., 1995). The trials used video cameras to collect data on the response time of occupants of various ages with different mobility abilities in different environments, and the results revealed that the response time was nearly doubled in the winter compared to the summer. That could be because the occupants need to gather their warm clothing before proceeding to the exits.

When it comes to the application of evacuation analysis in the maritime sector, the lack of data on human performance is clearly highlighted in the IMO guideline for evacuation analysis of passenger vessels (IMO, 2016). The experimental studies in maritime evacuation can be divided into two types: full-scale trials and small-scale trials. Full-scale trials are typically carried out at sea (on board a vessel), whereas small scale data collection can be carried out in land-based facilities or onboard a vessel. The section that follows presents a brief review of the experimental work that are conducted to quantify human performance, particularly in the maritime environment.

3.2. Quantification of walking speeds (small-scale trials)

Physical characteristics such as height, weight, gender, and age influence people's uninterrupted movement speed. Furthermore, study of ship accidents revealed that the ship's heel/list, motion, crowd density, and psychological factors in emergencies had the greatest influence on evacuation time (Lee et al., 2003). The motion and orientation of the vessel (hell/trim) can influence psychological factors and crowd density. The ship list reduces the effective width of escape routes because the walls lean towards the passengers, reducing effective floor space and thus passengers need to hold the handrail (Boer & Skjong, 2001) and this can cause congestion. The amount of space occupied by the passengers, dependents on whether they are carrying a child or some objects such as a life jacket or warm clothing which may also have a significant impact on their mobility condition on a flat trail and stairs (Boyce, Purser, & Shields, 2012; G Proulx, 2002).

The collection of data on waking speed began in the early 1900s (Fahy & Proulx, 2001). Early studies included collecting data on the movement speed of individuals through exit paths, doorways, and stairs (Board, 1958; Fruin, 1971; Predtechenskii & Milinskiĭ, 1978). Later, data on walking speed of adults with various disabilities was collected in Northern Ireland (Boyce, Shields, & Silcock, 1999a, 1999b, 1999c, 1999d)

The study of movement speed showed that walking speed on a flat floor for Asians ranged between 0.98 and 1.39 m/s and this speed may differ for individuals of a different race who have a higher average height/weight (Fukuchi, Shinoda, & Imamura, 1998; Hwang, Chung, & Lee, 1991). The walking speed of 985 people on a ship was measured by Brumley and Koss (2000). Age, gender, and level of impairment were found to have a significant influence on the passengers' walking speeds. The study found a significant difference in walking speeds for passengers with the age of over 65 years old. Males were 18% faster than females on average, and people with mobility impairment performed significantly slower than able-bodied people.

The Dutch Research Institute (TNO) designed an experimental setup for land-based simulation of the ship's evacuation with the capability of simulating the motion (heel and trim). The set up was a $4 \times 2.4 \times 2.3\ m$ cabin which was placed on a hydraulic foundation and could be heeled and trimmed to different angles. The experiment included people between 18 to 83 years old. The experiment showed that the average walking speed along the corridor was 1.32 m/s and the speed was reduced by up to 35% on the upward slope (trim). According to the findings, increasing the heel angle to 15° can reduce walking speeds by up to 15%. Walking speeds were 15% slower in people over the age of 60 (Bles, Nooij, Boer, & Sharma, 2002). These findings supported Brumley and Koss (2000) argument that age had an effect on walking speeds in different age groups. In the absence of heel/trim, the average walking speed on the stairs was 0.48 m/s, while for upward and downward trim, the walking speeds decreased by up to 40% and 30%, respectively.

A series of land-based experiments in a simulator facility that could be tilted up to 21° was conducted through Ship Evacuation Behaviour Assessment (SHEBA) project (Glen et al., 2003). The simulator comprised a muster room at one end of a 10m long corridor and a flight of stairs ascending to a platform connected to the exit on the other side. The design was based on the standard dimensions of corridors and stairs found on passenger ships. A series of video cameras and optical sensors were installed throughout the setup to monitor the participants' performance. The participants (males and females) between

8 to 80 years old walked through the facility at various degrees of heel. According to this study, walking speeds generally reduce with increasing angle of heel above about 10°, females experience a greater reduction in average walking speed than males with increasing angle of heel. Furthermore, older participants experience a greater reduction in average walking speed with increases in angle of heel compared to younger participants and maximum reduction in average walking speed was about 12% at 20° of heel. The results of the experiments also revealed that wearing lifejackets reduced the walking speed of the participants at zero degrees of heel (Glen et al., 2003).

The walking speeds of individuals were also studied by (Sun, Lu, Lo, Ma, & Xie, 2018; Wang, Liu, Loughney, et al., 2021; Wang, Liu, Wang, et al., 2021) in a dead-end corridor with the size of $10\,m(L) \times 1.8\,m(W) \times 2.2\,pam(H)$ and the capability of being tilted between $0°\ to \pm 15°$ of heel and $0°\ to \pm 20°$ of trim. Four cameras were installed in the corridor and recorded the participants' movement patterns and performance. Males had a faster walking speed than females, and both genders' walking speeds were reduced by increasing the angle of heel and trim. This study found that trim angle had a greater influence on individual walking speeds compared to the angle of heel (Sun, Guo, Li, Lo, & Lu, 2017). Although the study addressed the effect of heel and trim in both individual and group movement of people, the population did not represent the expected population of a typical passenger ship because the participants were chosen from a group of students (6 males and 6 females, all between the ages of 23 and 26) with a very slight difference in physical characteristics such as weight and height.

While the aforementioned studies projects provided useful insight into the impact of heel and trim of the floor on individual walking speeds, the test subjects in all studies walked a relatively short distance compared to what passengers on a typical vessel might encounter during an evacuation. Furthermore, none of the studies considered the effect of TPIS on individuals' walking speeds.

3.3. Response and assembly time (full-scale trials)

Since the early 2000, researchers have made several attempts to collect appropriate data on human performance in maritime evacuation. Yoshida, Murayama, and Itakaki (2001) conducted a full-scale ferry evacuation trial in the port of Onahama, Japan, in which 356 students and teachers, as well as 27 ship officers, participated in the evacuation of a passenger ferry moored in the port. The evacuation was based on a fire scenario. The data was collected using 26 video cameras which were installed along the escape routes to record the behaviour of evacuees. In addition, barcodes were assigned to the students, and a barcode reader on the assembly station scanned each individual upon arrival. However, a large number of people were involved in this trial, the population was mostly students, and the demography did not represent the population of a typical passenger ship. Furthermore, unlike in a real emergency, the trial evacuation was announced in advance, and passengers were instructed to go to their cabins, put on their life vests, and wait for further evacuation instructions.

In another approach in the Mustering and Evacuation of Passengers (MEP) design project, conducted an experiment to collect data on the assembly performance of 592 passengers using Radio Frequency Identification (RFID) technology (Jørgensen & May, 2002). During the experiment, the crew members were assembled before beginning the evacuation (to receive necessary instructions), and passengers were instructed to remain in their place in the meantime, causing the evacuation to be delayed. Many of the passengers were still eating when the evacuation time was announced, and the crew had to ask them to leave their seats and walk to the assembly station.

Despite the fact that RFID technology successfully collected data from passengers, the results were not used in the validation of evacuation models because the author concluded that the reality of the exercise did not correspond with the reality of the accident due to data artificiality (May, 2001). The MEP design project also investigated passengers' attitudes toward safety by interviewing over 1200 passengers via questionnaires while sailing in the Baltic Sea. The findings shed light on various aspects of human performance in an emergency, such as alarm response, way finding, walking speed under ship motion, group binding, panic, and noncompliance with crew instructions.

In response to the demand for a comprehensive maritime-specific data, a series of full-scale sea trials was conducted through SAFEGUARD project. The trials were designed to address the data shortage for calibration and validation of ship-based evacuation models by providing datasets from a series of full-scale evacuation trials. Five semi-unannounced full-scale assemblies were conducted on three different passenger ships as part of this project. Five datasets of passenger response times and two full-scale validation datasets were collected. The assembly trial on a Color Line RO-PAX ferry and a Royal Caribbean Cruise Ship (CS) resulted in the collection of two validation datasets. The passengers were informed that the assembly trial would take place onboard at some time during the voyage, but the exact time was not specified. Digital video cameras were used to collect response time data. The assembly data for each passenger was collected by Infrared (IR) tags (worn by passengers) and a set of mounted beacons (each emitting unique infrared signals) to cover the evacuation paths throughout the vessel (Galea, Deere, Brown, & Filippidis, 2014). The data collection methodology which was used in these experiments was accurate enough to measure the passengers' response and assembly time, but the data from IR tags did not provide an accurate result for calculating the walking speed of each individual in different sections of the ship. Because all trials were conducted in relatively good (calm) sea conditions, the data does not include the impact of cold weather and harsh sea conditions; nevertheless, the results indicated that the response time of individuals can vary depending on the type of vessel and time of day.

Previous small- and full-scale trials revealed only the tip of the iceberg in the research required to understand human performance during evacuation. The impact of harsh environmental conditions, such as cold temperatures in the polar region, on evacuation performance of individuals has been scantily researched. Most human evacuation software rely on quantifying human performance based on physical factors (i.e. gender, age, walking speeds) (Nevalainen, Ahola, & Kujala, 2015). The current state of knowledge does not provide a solid foundation for simulation and analysis of (ship) evacuation performance in polar waters because there is a little knowledge available to shed light on the time required to don a TPIS and the impact of wearing TPIS on walking speeds of individuals. As a result, more reliable data on passenger behaviour is needed to improve evacuation models so that the human performance during evacuation of passenger ships in polar waters can be predicted and simulated more realistically.

3.4. Modelling the evacuation

The outcome of an evacuation scenario is influenced by many factors, including the complexity and size of the enclosure, demography and characteristics of the population, visibility/availability of escape routes, and the impact of heel/trim (maritime application), etc. The combined effect of the influencing factor and randomness in human behaviour produces a variety of outcomes, ranging from the best to the worst-case scenario. It is nearly impossible to study the movement of people in all evacuation scenarios by conducting full-scale evacuation trials for each scenario (Gwynne et al., 2020). Therefore, researchers and engineers attempt to assess and understand the evacuation performance of an enclosure by the use of computerised simulation tools which can simulate the effect of various factors such as smoke, fire and different angles of heel or trim in (maritime) evacuation.

The evacuation models are classified into two types based on whether the evacuees' decision-making is taken into account (Gwynne, Galea, Owen, Lawrence, & Filippidis, 1999; Kuligowski, Peacock, & Hoskins, 2010; Thompson, Nilsson, Boyce, & McGrath, 2015). Decision making is incorporated into the behaviour of the evacuee in behavioural models, whereas movement models move the evacuee from A to B without considering human behaviour (Gwynne et al., 1999). There is a third type of modelling which reflects the human behaviour in the analysis by implementing a set of predefined rules for human response while moving from A to B. This model is called Partial Behavioural Model (Kuligowski et al., 2010).

The evacuation models are also classified into three types based on their purpose: optimisation, simulation, and risk assessment. Unlike simulation models, optimisation models do not consider individual behaviour or non-evacuation activities, and the paths chosen are assumed to be optimal. The risk assessment modes address the risks associated with evacuation as a result of an accident, such as a fire (Gwynne et al., 1999).

3.4.1. Presentation of the population

The evacuation models represent the population in two ways: individually or globally. The individual representation can track the movement of individuals throughout the simulation, whereas the global approach considers all occupants as a homogeneous group of people. If the user is only interested in the location of the congestion points and the total evacuation time, rather than knowing the position of each occupant throughout the evacuation simulation or assigning individual characteristics to the population, the global view is sufficient for the simulation. In scenarios where all occupants are familiar with the layout, the global representation of the population is more applicable (Kuligowski et al., 2010).

3.4.2. Presentation of the structure

The structure is represented in models based on a fine, coarse, or continuous network. The area is divided into a number of small grid cells in the fine network, and the occupants move from and to them. In a coarse network, the structure is divided into separate compartments such as rooms, corridors, and so on, and the evacuees move from one compartment to another, while the exact location of evacuees within the compartment is not clearly defined. When analysing local movement and navigation activities, such as overtaking or interacting of evacuees with obstacles in compartments, the use of coarse networks can have some limitations (Gwynne et al., 1999). In the continuous network, the evacuees may travel from one point in the space to another rather than being tied to a specific cell in the geometry and a set of rules defines the minimum distance between the evacuees and the obstacles (Kuligowski et al., 2010)

3.4.3. Presentation of behaviour

In the behavioural aspect of evacuation models, the agents in the model can interact with three types of elements: people with other people, people with the structure (enclosed structure), and people with environmental (e.g., atmosphere, heel/trim). These interactions can be addressed in various ways in a simulation models. The interaction is simulated in the implicit representation of behaviour, for example, by assigning a specific delay in response or action (by the agents) that affects their movement in the structure. The agents' actions/reactions in the model can be deterministic based on a set of pre-defined rules (conditional or rule-based approach) or stochastic within a set of potential actions. In both cases, the outcome analysis necessitates the repetition of a certain number of simulations to cover all possible behavioural scenarios. Another method that has been used in some of the evacuation models is the use of artificial intelligence, which attempts to simulate human intelligence throughout the evacuation (Gwynne et al., 1999).

3.4.4. Movement of the evacuees

The movement of the evacuees throughout the structure in the simulation models is based on pre-defined or user-defined algorithms in the software (Gwynne et al., 1999). One method for representing occupant movement is the Density Correlation (DC) model, which bases the speed and flow of individuals or crowds on the density of the space. The databases used in this method were compiled over 30 years ago and are all based on land-based data (Kuligowski et al., 2010). Movement models are not restricted to the DC model. The following section provides a brief overview of the various models for movement evacuees.

Cellular automata models

Cellular automata models are microscopic simulation models in which the area is defined by discrete cells, with each cell containing a single evacuee or an obstacle/object. The evacuee can move to an empty neighbouring cell at each time step. The evacuee's decision is based on the status of the adjacent cell (whether it is occupied or not) and the pre-defined sets of rules. The status of cells is updated either sequentially or in parallel over time, with the case movement only being executed once all conflicts between the evacuees (agents) have been resolved (Vermuyten, Beliën, De Boeck, Reniers, & Wauters, 2016).

Social-force model

Another type of microscopic approach developed by Dirk Helbing (1991) and Dirk Helbing and Molnár (1995) is the social-forced model, in which evacuees have a desired velocity toward their destination and different forces influence their acceleration/deceleration. Both time and space are continuously modelled. The model is well-known for its ability to simulate self-organising crowd phenomena, such as lane formation in bidirectional flows and oscillatory effects at bottlenecks. Although the model produces realistic results for dense crowd flow scenarios, it does not yet fully represent complex scenarios.

Fluid dynamic models

Crowd movement can also be described using a model that is analogous to the fluid property. According to Henderson (1971), the crowd in motion "behaves like gases or fluids." A later study found striking similarities between the crowd's motion and the motion of a fluid at medium and high densities (D Helbing, Farkas, Molnar, & Vicsek, 2002). In the fluid dynamical model, time-dependent density and velocity profiles are modelled using partial differential equations.

Continuum models

A continuum model is a microscopic simulation model that treats the crowd as a fluid, rather than a collection of individuals, by measuring characteristics, such as density at a given location. The average velocity, flow rate, density at a specific time and the location are just some of the variables that are expressed by the system of partial differential equations that make up the continuum model. Time and space are both understood to be perpetually evolving concepts. The behaviour of very large crowds can be modelled with the continuum model, and average quantities can be estimated with the continuum model because of its computational efficiency (Bellomo, Piccoli, & Tosin, 2012).

Agent-based model

Compared to cellular automata, social force, and fluid dynamic models, agent-based simulations are more time and energy consuming to run on a computer. However, agent-based models make the modelling of population heterogeneity easier by permitting each agent (evacuee) to have a unique performance and behaviour (e.g., different walking speed in old or young people). The model's macroscopic behaviour is determined by the actions and interactions of the agents, which is why agent-based models are considered as a bottom-up approaches. The agent-based model is flexible enough to accommodate both discrete and continuous representations of time and space. Discrete choice frameworks allow agents to make decisions about movement based on the relative importance of various factors, such as the presence or absence of other evacuees (Antonini, Bierlaire, & Weber, 2006). Agent-based modelling has many benefits, including its ability to capture emergent phenomena, its natural description of the system, and its adaptability (Bonabeau, 2002).

3.4.5. Maritime evacuation simulation software

Based on the different methodologies for representation of geometry, population, behaviour and movement of the passengers in an evacuation model, number of maritime evacuation software are developed such as EVAC, Evi, ODIGO, SIMPEV, AENEAS, IMEX, maritimeEXODUS (mEX), etc. While all of these evacuation models are capable of simulating the evacuation in passenger vessels, the results of simulation might vary depending on the data that is used in the simulation model and the methodology of representing the geometry, population, behaviour and movement of the evacuees. In this thesis a modified version of mEX was used for modelling the evacuation of passenger ship in polar waters. mEX is an agent-based simulation model developed by the University of Greenwich's Fire Safety Engineering Group (FSEG). The software was initially designed to simulate evacuation in aircraft and complex enclosures, but it was later expanded for use in maritime evacuation (mEX). The software can simulate the effects of dynamic ship movement, static trim and heel, fire and smoke etc. Experiment data from full-scale passenger ship evacuation trials (Galea, 2002) are used to validate the software. A more detailed description of mEX evacuation model is presented in section 5.3.

Chapter 4: Data collection methodology

The time needed to safely evacuate a population from a hazardous enclosure is referred to as the "evacuation time estimate" (ETE). The need to don and walk with a TPIS may affect the assembly and abandonment time of each passenger, which in turn lengthens the ETE of a passenger ship intending to operate in polar waters. Following the research questions 1 and 2 (section 1.3), data collection on human performance was necessary to quantify the time required to unpack and fully don a TPIS, and to measure the effect of wearing TPIS on individual walking speeds (at different angles of heel). This chapter describes the data collection methodology.

4.1. Planning and preparation

In order to collect maritime specific data for use in ship evacuation modelling, it would be ideal to conduct a series of small-scale trials on board the ship; however, donning trials on board would present logistical challenges, and heeling the floor (tilting the ship up to 20°) was impractical due to safety concerns. Therefore, it was decided to run a series of land-based trials in which participants would don the TPIS and walk through a corridor twice, once when the corridor is heeled at an angle ranging from 10° to 20° and second time when the corridor is at a neutral angle of heel (0°). It was also critical that the test subjects could represent both genders across all age ranges, and that the experimental environment was similar to the conditions that passengers might encounter on a passenger ship.

Choosing a data acquisition methodology necessitated taking into account a number of factors, including:

- The trial location's availability (to the staff ad participants during the day from 08:00 to 21.00 including weekdays and weekends).
- The location's accessibility, such that transportation for participants could be easily arranged.
- The logistical cost of moving and rigging the test facility (corridor).
- The availability of an indoor space for conducting donning trials and storing the equipment.
- The availability of a flat and open outdoor area where the test facility (corridor) could be rigged and maintained for the duration of the data collection.
- The cost, reliability, and precision of data collection equipment.

- Simple installation of the data collection equipment, including mounting, adjusting, and disassembling processes.

A few months before the trials, extensive planning was undertaken, including an application for ethic approval, evaluation of potential trial locations, decision on the number and types of survival suits, purchase of data collection equipment, preparation of questionnaires, and trial procedures. The planning also included detailed documentation of the required number of staff and their tasks in donning and corridor location. The task included directing participants to the location, setting up and collecting the cameras, responsibility for registration and giving the preamble, tilting the corridor to different angles of orientation, handing out and collecting questionnaires at donning and the corridor locations, packing up, and so on.

Following extensive planning and assessment of all available options, it was decided to conduct the data acquisition trials in Tromsø at the Arctic University of Norway and Arcos safety centre. However, when the data collection in Tromsø was finished, the number of participants in Tromsø (125 of which 84 of them participated in donning while everyone walked through the corridor) was deemed insufficient to provide enough data points in all different cohorts corresponding to different age groups, gender, type of survival suit and angle of heel of the corridor. Therefore, the trials were replicated in Haugesund at the ResQ safety centre, where another 85 (of which 24 participants participated in the donning trial) volunteers took part in the experiments. The following sections describe the data collection process in detail.

4.2. Ethics approval

Ethical concerns are always paramount in any research or experiment that directly or indirectly is involved with humans. In general, the experiment should produce beneficial results for society. This means that the potential benefits of the research should outweigh any risks, and the physical or mental well-being of the participants should not be compromised under any circumstances. Participants should be informed about the consent process, their voluntary participation, and the fact that they can withdraw from the study at any time without any consequence.

Video cameras are frequently used to record human behaviour in experiments. Human welfare protection may entail assurances that identifiable information about research participants, as well as identifiable research data, will be protected, and that individuals' information will be kept confidential. In this regard, the general procedure and intention of the experiment were explained to the participants at the start of the experiment, and participants were informed that their identities would be anonymised during the analysis and all videos would be deleted once the results were published. If any of the footage is kept for training or demonstration purposes, the faces of the applicants will be blurred such that they cannot be recognised.

Prior to the experiments, a comprehensive risk assessment concerning the donning trial and heeling of the container was performed, and all precautionary measures were documented to ensure the safe conduct of the experiment. The risk assessment also included the identification of safe operating procedures for the container setup, initial testing for heeling the containers, heeling of the containers during the experiment, and disassembling of the container. Furthermore, a clear emergency procedure was documented, and all staff were briefed on their role in the event of an emergency.

On 01.03.2018, an application for research ethics approval was submitted to the Norwegian centre for research data (NSD) along with all necessary documents, and it was approved on 28.03.2018 with the reference number 59548/3/LAR.

4.3. Recruitment of the participants

The main goal of the recruitment process was to have a diverse population composition among the participants. A sizable sample of naïve test subjects was necessary due to the fact that most of the ship's passengers may not be familiar with wearing the TPIS. A cross-section of the local population, representative of all walks of life, should be enlisted to take part in the trials. 450 men and women between the ages of 18 and 72 were expected to volunteer. This would provide 50 participants in each cohort (of the total 9 cohorts) associated with different survival suits (Suit-1, Suit-2, and Suit-0)) at three angles of heel (10°, 15° and 20°), assuming that everyone consequently walks on 0°. A minimum of 15 participants per group was also established, so a total of 135 people would be needed at the very least. Participants should be in good health and free of any disabilities that might hinder their mobility or eyesight. Participants were recruited via word of mouth, as well as through announcements in local and social media. The recruitment began about 8 weeks before the experiments and went on for the duration of the data collection.

4.4. Location and environment of the experiments

The data collection commenced in Tromsø and Arcos safety centre (in Tromsø) provided both indoor and outdoor space for the experiment. The classrooms were used for donning experiments, and there was an open area for a helicopter landing where the corridor facility was rigged right outside the building.

At the ResQ safety centre in Haugesund, where the second series of trials were conducted, similar to the facilities in Arcos safety centre, a building (with a couple of classrooms in it) was located right outside of a flat parking lot. Donning trials were held in the classrooms, and the corridor facility was set up in the parking lot.

4.5. The environment for donning experiments

The donning trial should also take place in a room with an ambient temperature of 18° to 22°C, as recommended by SOLAS and ISO standards (IMO, 1998; ISO, 2012). It was planned to mark a $3m \times 3m$ square area on the floor so that the participants would stay within the marked area while donning the suit (see Figure 5). It was decided that no more than 15 participants could use the squared area for donning at the same time. Given the available area in the marked square, this would provide a minimum area of 0.6 m^2 to the participants, which is larger than the minimum required deck space for assembly station (0.35 m^2/person) (IMO, 1998). This method not only provided a situation similar to donning on the muster station where the space could be somewhat encumbered, but it also guaranteed that the participants would not move to an area out of the camera's field of view. In both trial locations (Arcos and ResQ safety centres), a large screen was available in the classrooms to show the donning instruction (two-minute video) to some of the participants (see Figure 5).

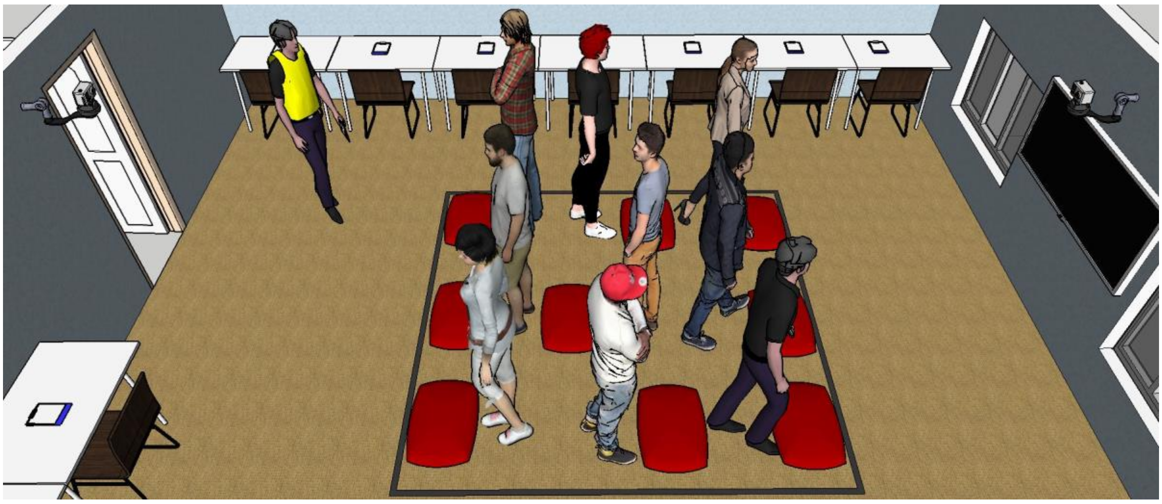

Figure 5: Position of participants and the cameras during the donning trials

4.6. Registration and preambles

The trials were designed such that participants would receive information and a consent letter outlining the purpose of the experiment, how their information and data would be handled, and that they could opt out at any time. Participants must complete both the consent letter and the registration form at the same time. In the registration, demographic data was collected from the participants, and each volunteer was assigned a random ID number (between 1 and 25) that was used to identify and anonymise them at a later stage of the data analysis. After everyone in the group had registered, the group received the preamble to the experiment. The participants were instructed in the preamble to take out their extra warm clothing and belongings (i.e. coat, jacket, purse, etc.) and stand within the squared area behind the TPIS (see Figure 5) and, upon hearing GO, try to don the suit as quickly and correctly as they could without assisting or talking to each other. Participants were instructed to raise both hands when they deemed the donning task was complete (Please see Annex I and II)

When the donning trial was completed, participants were directed to the corridor location where they received the preamble for walking through the corridor. They were instructed to walk as fast as they could (when they heard Go) without running, and that they could use their hand to touch the wall, stop to regain balance, and withdraw at any time. Participants were led down the corridor one by one, one person at a time (Please see Annex III and IV).

4.7. Type of the survival suit

It was decided that the experiments would require at least two different types of survival suits, preferably covering the two extreme ranges of available survival suits in terms of bulkiness and weight. Since the budget of the project was constrained, it was decided to borrow some of the survival suits. Therefore, the Hansen protection suits which were provided in vacuum package (SeaPass passenger suit) were purchased from the manufacturer, while the Viking suits (Viking YouSafeTM Blizzard) were borrowed from the manufacturer at no cost.

The thermal protective immersion suit produced by Viking (Viking YouSafeTM Blizzard), as shown in Figure 6. was a universal size immersion suit with integrated buoyancy elements and a layer of thermal insulation. The suit came with a hood made of a water-resistant fabric (the same as the suit's body) and a thermal protection layer.

The hood was designed to cover the entire head, neck, ears, forehead, cheeks, and jaw. The survival suit's zipper featured a brass tooth design. When the zipper was zipped up, it could create a waterproof seal by pressing the rubber surfaces (located beneath the zipper) together. Because the gloves were not attached to the sleeves, the wrist of the suit was equipped with a rubber seal that could shrink to individuals' wrists and prevent water ingress. If necessary, the provided straps could be used to tighten the rubber seal around the wrist. The gloves were made of neoprene fabric in a universal-size and were attached to the suit by a narrow strap.

The survival suit was made to be worn barefoot. A flat rubber sole was sewed beneath the foot cover to provide a shoe-like foot covering that allowed people to walk on various surfaces. One strap around each ankle was provided to keep feet (inside the foot covering) in place, when fastened. The suit was also equipped with two length adjusting straps on both sides of the waist for adjusting the universal size of the suit to the height of individuals. The length-adjusting straps could lift the gusset and bunch up the excess fabric of the legs and upper body area, shortening the suit and improving its fit. The suit also included a lifting harness to aid in the retrieval of a person from the water.

Donning instructions were provided in three languages (Danish, English, and Icelandic) and were laminated both on the carrying bag and inside the suit. The instruction included information for donning, maintenance, packaging, service/repair, and inspection.

Figure 6: Immersion Suit (TPIS) produced by Viking (YouSafe Blizzard) (referred as Suit-2)

Presented in Figure 7 is the second type of survival suit that was chosen for the experiment (walking through the corridor). The survival suit which came in a vacuumed packaging, was a PU-coated nylon immersion suit and very light in weight considering it had no insulation and no built-in buoyancy. The suit included integrated socks, gloves, a neoprene hood, and ankle straps. This suit was designed to be worn with shoes inside or over the suit and to be used in survival kits or as an additional thermal protective aid onboard passenger and recreational vessels. In case of abandoning the vessel, a lifejacket should be worn over the suit.

Figure 7: Immersion suit produced by Hansen protection (SeaPass Passenger Suit) (Referred as Suit-1)

4.8. Set up of the corridor

One of the difficult tasks was to set up a corridor facility that could be easily heeled to different angles. The ideal plan was to construct a 50-meter-long corridor that could be tilted to various angles of heel ranging from 0° to 20°. A variety of solutions were considered. The initial thought was to build the corridor on a hydraulic platform similar to the SHEBA facility (Glen et al., 2003), but building a similar facility with a length of 50 metres would necessitate having a solid foundation and would require long time to be built and tested. Because the setup was only intended to be used for a short period of data collection, building a 50-meter-long corridor on a hydraulic platform would be prohibitively expensive given the limited budget available, so a less expensive solution should be considered.

4.8.1. Corridor in Tromsø

After a thorough assessment of different available options, it was decided to use the corridor containers for construction sites, which were each, 6m long (1.76 m (Width)×2.2 m (Height)) and weighed 1200 kg. The maximum corridor length was limited to 36 m due to the size of the helicopter landing area at Arcos safety centre (Tromsø), which only allowed for six containers to be lined up. Hence, six corridor containers were arranged in a row to create a 36-meter-long corridor (see Figure 8). The walking performance of the test subjects in survival suits must be evaluated over a distance of minimum 30 m in accordance with the testing requirements for immersion suits (ISO, 2012). The remaining 6 m of the corridor were divided in half, with 3 m at the entrance for acceleration and 3 m at the exit for deceleration. The first 3 meters and last 3 meters of the corridor were marked, showing the start and end point. In order to prevent participants from slowing down before passing the finish line and to ensure that they maintain a constant speed for the entire 30 m, an additional line, 1.5 m apart from each end of the corridor was marked (see Figure 8 and Figure 9).

Figure 8: set up of the corridor in Arcos safety centre

The corridor containers were made of metal and were painted in blue. The corridor's walls were crooked, and the floor had patterns. Obviously, none of the interior features of the corridor container resembled a typical ship's corridor. Thus, plywood panels were used to cover the corridor's walls and floor, creating an even surface in a light colour (see Figure 9 and Figure 10). The top of the plywood panels on the floor were covered with a layer of grey carpet, which provided an even floor similar to that found in passenger ship accommodations.

Mid-Point (15m) | Mid-Point (15m) | Full Length (30m) | Full Length (30m)

Figure 9: Measurement through the length of the corridor

In the corridor container, a set of fluorescent ceiling lights was installed. When the corridor was lined up and the ceiling lights were turned on, the luminosity in the corridor was measured and found to range between 430 and 591 lux, which was considerably higher than the minimum required luminosity in the corridor of passenger ships (40 lux) specified in the standard (IEC, 2019; IMO, 1993).

Figure 10: Covering the walls and floor of the container corridor by plywood panels

4.8.2. Heeling the corridor and calculation of the stability

Heeling the corridor was a non-trivial task, because of the weight of each section of the corridor container (1200 kg). Concerning the procedure's safety, the first and most important task was to calculate the stability of the corridor at the most extreme angle of heel (20°). Some assumptions were made for this calculation, which are as follows:

- The mass of each section (M_C) in the corridor is concentrated in the centre of gravity of the section, which is located 110 cm from the floor and 88 cm from each of the walls. The weight force of the corridor is calculated as: $F_C = M_C \times 9.8$

- One person at a time will be walking through the corridor.
- The person in the corridor has the mass of (M_P= 100 kg), and the total weight force ($W_P = M_P \times 9.8$) of the person is applied to the nearest wall to the person's position at the height of 150 cm from the floor (see Figure 11).

Based on the assumptions stated above, the corridor would become unstable if $t_2 \geq t_1$, where t_1 and t_2 are torques. As a result, the corridor's stability at the most extreme angle was subject to having t_1 in all conditions much greater than t_2.

t_1 and t_2 were calculated as follow:

(2)

$$t_1 = F_1 \times 0.88\text{m}$$

(3)

$$t_2 = (W_2 \times 1.5\text{m}) + (F_2 \times 1.1\text{m})$$

Where:

$$F_1 = F_C \times \cos(20°),\ F_2 = F_C \times \sin(20°) \quad \text{and } W_2 = W_P \times \sin(20°)$$

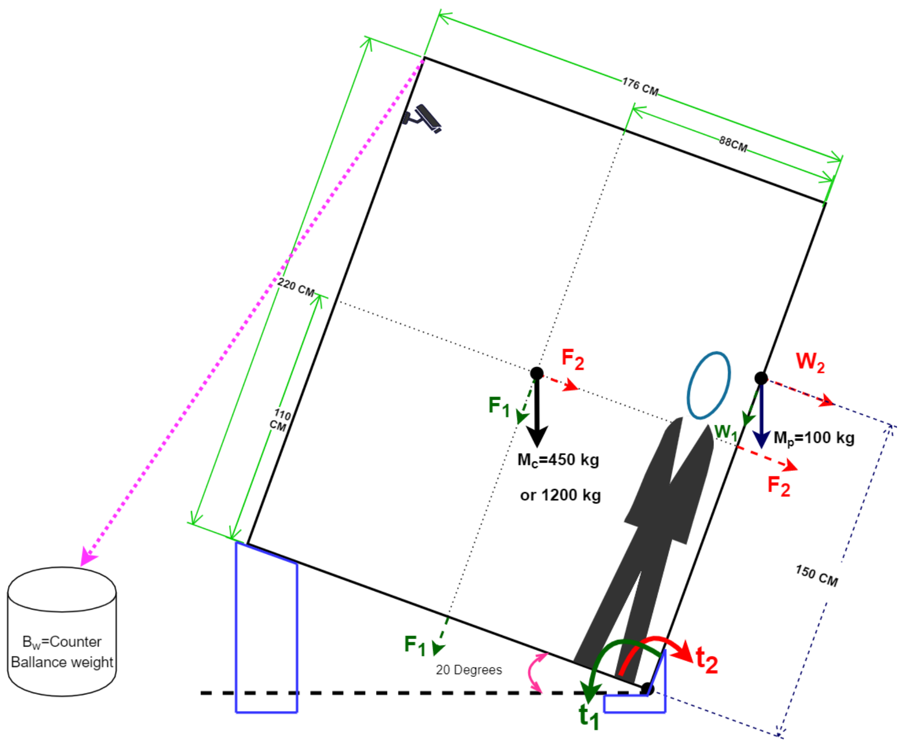

Figure 11: Calculation of stability in the corridor

By considering the aforementioned assumptions and using the Eq.(2) and Eq.(3), the t_1 and t_2 were calculated and are presented in Table 1.

Table 1: Calculation of the corridor balance

Type and weight of one section of the corridor (6 meters)	t_1	t_2
Construction site container ($M_C = 1200kg$)	8840.62 N.m	4927.06 N.m
Corridor constructed by wood ($M_C = 450kg$)	3664.75 N.m	2161.78 N.m

The corridor was found to be quite stable in both construction types (metal and wood), as shown in Table 1. A series of counterbalance weights were connected to each section of the corridor (in both locations, Arcos and ResQ safety centre) as an additional safety measure to ensure that the corridor does not tip over under any circumstances (see Figure 11). In the Arcos safety centre, six pieces of 220-liter oil barrels filled with water were connected to each section of the corridor using lashing belts, whereas in the ResQ safety centre, the corridor was secured to a series of 1000-liter water drums that were available on the site.

4.8.3. Design of legs and procedure of tilting the corridor

Tilting the corridor had to be performed safely, quickly, with the fewest people possible, and without the use of specialised equipment, such as a forklift. To heel the corridor safely and efficiently, a relatively simple solution was conceived, developed, and successfully implemented. A series of legs were designed for the different heel angles (0 °,10°, 15° and 20°) based on the corridor's exterior dimensions. The container legs were supposed to be made of steel in the original design. However, due to its heavy weight, high fabrication cost, and lengthy production time, steel was not the best material for building such a setup. It was decided to build the container legs out of wood after consulting with a few workshops and construction companies. The wood material was much less expensive, lighter, and less labour intensive to fabricate, while still being strong enough to withstand the load of the containers. Figure 12 depicts the design of the series of legs which were used for heeling the corridor containers at Arcos safety centre.

Figure 12: The container legs for $0°, 10°$ *and* $20°$ *in Arcos safety centre (Azizpour et al., 2022b)*

When the container legs arrived on site, the area was marked and prepared for rigging the corridor containers. The containers were transported by crane trucks and placed on the legs, as shown in Figure 13.

Figure 13: Rigging the container corridor on 0° legs at Arcos safety centre

When all of the containers were lined up and the interior of the corridor was prepared, the tilting procedure was tested. A hydraulic jack was used to lift the corridor from one side (see Figure 14.a). The corridor was heeled section by section, and the process required four people: one person jacked up the corridor, two others replaced the legs, and one person observed the back of the corridor during the tilting process (see Figure 14.b). When the tilting process finished, the lashing belts connecting to the counterbalance weights were tightened (see Figure 14.c). In practise, it took about 30 minutes to heel the six containers from 0° to 20°. Dropping the containers from an angle of heel to 0° was quicker. Changing the heel from 20° to 0° took about 15 minutes.

a. Hydraulic jack   b. Heeling the corridor from 0° to 10°   c. The entire corridor at 10° of heel

Figure 14: Procedure and equipment of heeling the corridor

4.8.4. Corridor in Haugesund

The data collection was replicated at the ResQ safety centre in Haugesund. The data was collected in the same conditions as at the Arcos safety centre. With the knowledge gained from the trials in Tromsø, it was decided to build the entire corridor out of wood. The corridor was designed with the identical interior dimensions (six sections, each 6 metres long) (see Figure 15).

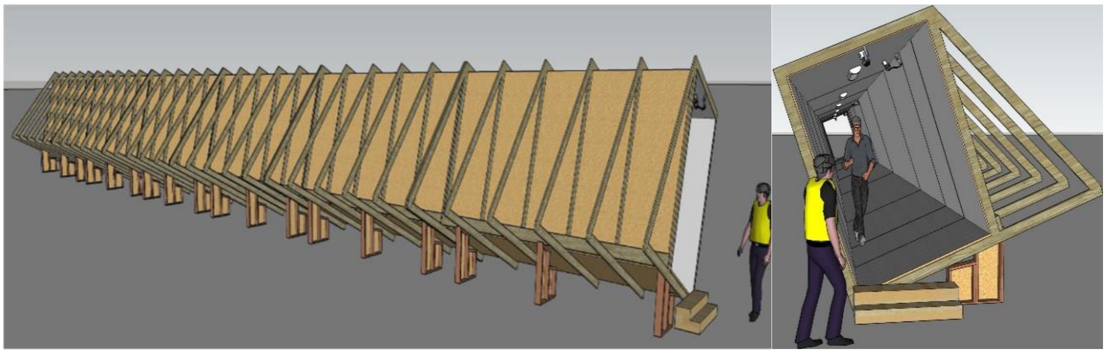

Figure 15: Set up of wooden corridor in ResQ safety centre

Construction of the corridor with the new design (wood structure) was presented to a couple of local construction companies, and after negotiating the price and the commissioning deadline, the deal was finalised with Saga Bygg AS. The corridor's construction took about two weeks, and the entire corridor was built on the site (see Figure 16).

Figure 16: Construction of the corridor in ResQ safety centre

To heel the corridor, similar to the heeling procedure that was adapted for the corridor in Arco scenter, a set of legs were designed based on the exterior dimensions of the corridor. The legs were designed in such a way that the corridor could have a 0° heel when landing on asphalt and could be heeled from one side to 10°, 15° and 20° using the legs shown in Figure 17.

Figure 17: Corridor legs for heeling the corridor to 10° and 20° (Azizpour et al., 2022b)

When the corridor at ResQ safety centre was built, the heeling procedure was tested to ensure the stability at different angles of heel (10°, 15° and 20°). Figure 18 depicts the corridor at three angles of 0°, 10° and 20°. The procedure for heeling the corridor was identical to that used in Arcos safety centre (Tromsø) (see section 4.8.3), with the exception that because the corridor was made of wood and was lighter, it took less time (approximately 15 minutes) to heel it to 20° and approximately 8 minutes to lower it back to 0°.

a. Corridor at 0°of heel b. Corridor at 10° of heel c. Corridor at 20° of heel

Figure 18: Test of heeling the corridor

Inside the corridor, a series of fluorescent lights were installed on the ceiling, and the floor was covered with carpet identical to that used at Arcos safety centre (Tromsø) (see section 4.8.1). Figure 19.a depicts the entire corridor heeled at 20°, and Figure 19.b presents the interior view of the corridor at the same angle of heel.

a. The entire corridor at 20° of heel b. Interior of the corridor

Figure 19: Corridor at 20° of heel (Azizpour et al., 2022a)

4.9. Position and resolution of the cameras

The research objectives influence the choice of data collection tools. The most appropriate method for collecting data on TPIS donning was recoding the performance of the participants using video cameras. The video footages could be used not only to analyse the donning time but also to observe the correctness of donning and the behaviour of participants during the experiment.

To ensure that the view of the camera could cover the entire place, the camera should be mounted on a wall or on a tripod in a location that allowed capturing all the activities of every single participant who was standing within the marked square area (see Figure 5). To get reliable and precise measurement of duration of activities, the appropriate resolution of the camera was also essential. The range of the observable area (by the camera) determined the proportion of the space covered by each camera and, the number of cameras required to cover the whole area. The amount of detail visible in the images depended on the camera's resolution. Obviously, the highest resolution is preferred, but the higher the resolution, the greater the need for storage capacity in the camera. Therefore, the resolution needed to be high enough different activities could be clearly observed in the footages for analysis at a later stage (i.e., the start and end of donning for each participant and their sequence of actions and their behaviour during the experiment).

The frame rate of the camera determines the accuracy of measurement in video analysis. Thus, the higher the frame rate, the lower the error. Obviously, the higher the frame rate of the camera, the greater the storage capacity required. Therefore, the frame rate should be high enough to provide an acceptable level of accuracy in measuring the duration of different activities. Furthermore, the storage and battery capacity of the camera had to be sufficient to power recording the entire experiment. The frame rate (Frame Per Second = FPS) of a video camera is the frequency or rate at which consecutive images (frames) are captured. It was decided that GoPro Hero action cameras would be suitable for data collection (see Figure 20.a and Figure 20.b). The cameras were connected to an external battery supply (power bank) that could power the cameras for up to 14 hours of continuous recording. The cameras were configured to record the footages at a resolution of 1080p and a frame rate of 25 FPS, and the camera's 128 GB memory allowed it to record 12 hours of video. In terms of time measurements, the 25 FPS frame rate would yield a maximum error of 0.04 second, which was deemed accurate given the nature of the data (measurement of the donning time).

There are several methods for collecting data from individuals' walking performance. The best data collection method is determined by a variety of factors, including data collection setup, system cost, accuracy, logistic challenges, and ease of installation and deployment. Tracking technologies such as Radio Frequency Identification (RFID), Infrared (IR) tracking systems, or Global Positioning System (GPS) were not an option for measuring walking speeds in the corridor because, when compared to conventional video recording, none of the aforementioned technologies can record the exact time of passing a line with an accuracy of 0.04 second. The use of timing/laser gates, which are quite popular for recording the speed in sporting events, could be an option, but since the behaviour of the participants had to be filmed in the corridor, using two different technologies in addition to the extra cost, would just add complexity to the data collection method. Therefore, it was decided to use action cameras (i.e., GoPro Hero) to record the walking performance of the participants. The corridor was equipped with a total of five action cameras. Three action cameras were looking at the corridor's start, mid, and end lines (see Figure 20.c), while the other two action cameras were mounted at both ends of the corridor and were looking throughout the corridor to record the behaviour of participants. The GoPro cameras in the corridor were set to record the footage at 25 FPS with a resolution of 1080p.

a. GoPro Hero action cameras

b. GoPro flexible arm

c. Position of the camera at the start line

Figure 20: Action cameras and mounting accessories

4.10. The questionnaires

In the study of human behaviour, quantification of human performance solely based on observation of video footage may involve some degree of personal judgement by the observer. This means that relying entirely on video footage in data collection is not an error-free method. Because each method of data collection has advantages and disadvantages, combining different methods in a triangulating fashion compensates for the shortcomings of each technique (Yin, 2013).

Questionnaires were used as a supplement to video recordings of individuals' performance. Questionnaires are a set of written questions that participants in an experiment reply to in writing. One advantage of using questionnaires is the strict format and consistency of the questions, which is achieved by providing the same type of information to all respondents. However, the format has some limitations, such as the limitation of asking probing questions or obtain clarification.

The questions can be presented as open or closed questions. An open question requires respondents to write their own responses, whereas a closed question gives them response options. Open questions allow people to express themselves without being influenced by the researcher's suggestions. The answers should (ideally) reflect what is important to the respondents; however, there may be factors that prevent people from mentioning the most important matter. Respondents, for example, may fail to mention things that they believe are obvious (Foddy, 1993). With open questions in questionnaire analysis, all responses must be classified (e.g., coded), and this coding is often a time-consuming process, with the risk of misinterpretation or loss of data (Chisnall, 1993).

Closed questions, on the other hand, inform respondents of the expected answers through the provided options, making the closed questions a selection between a set of provided responses, which may result in missing the important answers. Therefore, using closed questions requires providing a list of options that includes all the relevant alternatives. The inclusion of response options in questionnaires has the advantage of acting as memory cues, causing respondents to recall answers that they might otherwise have forgotten (Chisnall, 1993; Foddy, 1993). In terms of the benefits and drawbacks of using open and closed questions, they can complement each other in many ways. As a result, it is frequently advised to use a combination of open and closed questions (Schuman & Presser, 1979).

The reliability of the collected answers is also an important consideration that must be addressed when developing the questionnaires. One of the most important factors for improving the reliability of the answers is to ensure that the questions are interpreted similarly by all respondents. Respondents' responses vary and are unreliable due to misinterpretation of the questions. Studies have also shown that aspects such as wording, ordering, and context influence how questions are perceived (Foddy, 1993). Because evaluating the effect of all potential factors (influencing the perception) is difficult, it is recommended that a pilot work of the method be performed before finalising it (to reveal if the questions are correctly interpreted) (Chisnall, 1993).

Two sets of questionnaires were prepared for this study, one for donning the survival suit and the other to investigate the experience of walking with the survival suit through the corridor at various angles of heel. Both sets of questionnaires included include a mix of open and closed questions, with the closed questions appearing as multiple choice or Likert scale responses. The open question at the end of the questionnaire allowed participants to share their thoughts, experiences, or suggestions.

The questionnaires were prepared in English, translated into Norwegian and pilot tested for readability and intelligibility in both languages. Each questionnaire was read, clearly understood, and the questionnaire was answered in less than two minutes by the pilot test subjects. The questions that were used in the questionnaire are presented in Table 2 and Table 3:

Table 2: Summary of the questionnaire for donning trials

#	**Question**	**Answer/Options**
1	Have you worn this type of survival suit before?	Yes/ No
2	How easy was it for you to put on the survival suit?	Very Difficult/ Difficult/ Neither difficult nor easy/ Easy/ Very easy
3	Would you have found it easier to put on the survival suit if You were given verbal instructions?	Yes /No/ I don't know/ Some other aspects, please explain
4	Would you have found it easier to put on the survival suit if You were shown a visual demonstration?	Yes /No/ I don't know / Some other aspects, please explain
5	Would you have found it easier to put on the survival suit if Someone physically assisted you?	Yes /No/ I don't know/ Some other aspects, please explain
6	Imagine you were at sea and experiencing rough conditions. Do you think this would have an impact on how quickly you could put the survival suit on?	No influence/ Would increase the time slightly/ Would increase the time significantly / I don't know/ Any other comments:
7	Do you think wearing the survival suit will have an impact on your ability to walk along a corridor?	Yes/ No/ I don't know
8	Do you have any suggestions as to how to improve the survival suit? For example, changes to the design that could make it easier to put it on?	Please specify:

Table 3: Summary of the questionnaire for walking through the corridor

#	Question	Answer/Options
1	Do you think your walking speed through the corridor was different to your normal walking speed?	Much slower/ Slower/ No different/ Faster/ Much faster
2	Did you stop while walking through the corridor? If Yes, was this related to (please check all that apply)?	No/ if yes: Felling tiered/ Felling discomfort due to the clothing/ Needing to adjust the clothing/ Other reasons please specify:
3	Was the corridor tilted? If Yes, how would you describe your experience of walking through the tilted corridor?	No/ if yes; Very difficult/ Difficult/ Neither difficult, nor easy/ Easy/ Very easy
4	What angle of inclination do you think the corridor was that you just walked through?	0° / less than 5° / 5° to 15° / 15° to 20° / Greater than 20°
5	Please indicate the influence each of the following factors had on your walking performance:	
5A	What you were wearing	Very negative/ Negative/ No influence/ Positive/ Very positive
5B	Angle of inclination	Very negative/ Negative/ No influence/ Positive/ Very positive
5C	Level of lighting in the corridor	Very negative/ Negative/ No influence/ Positive/ Very positive
5D	Type of the floor surface	Very negative/ Negative/ No influence/ Positive/ Very positive
5E	Lack of a handrail	Very negative/ Negative/ No influence/ Positive/ Very positive
5F	Temperature inside the corridor	Very negative/ Negative/ No influence/ Positive/ Very positive
5G	Type of wall surface	Very negative/ Negative/ No influence/ Positive/ Very positive
6	Please indicate the influence each of the following factors had on you while walking through the corridor	
6A	The fit of the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6B	The bulkiness of the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6C	The weight of the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6D	Your ability to move while wearing the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6E	Your body temperature while wearing the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6F	Your ability to see while wearing the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
6G	The comfort of the footwear	Very negative/ Negative/ No influence/ Positive/ Very positive
6H	Your ability to hear while wearing the suit	Very negative/ Negative/ No influence/ Positive/ Very positive
7	Given your experience, do you have any suggestions as to how to improve the survival suit? For example, changes to the design that could:	
7A	Improve your ability to walk through the corridor	
7B	Improve your comfort while walking through the corridor	
8	Please feel free to write any additional comments	

4.11. Challenges with the data collection

The data collection was initially scheduled for one week at the Arctic University of Norway-UiT (Tromsø) at the end of July 2018. The experiment was delayed because the recruitment of the participant was not as successful as anticipated (approximately 38 participants were recruited just prior to the start of the originally planned date of the experiment). Since the trial date was changed, the location for rigging the corridor had to be changed because the initial location (the parking lot at the UiT) was not available in the rescheduled time window. This meant that a new location had to be found quickly and with little notice. The change in trial location created some logistical challenges and necessitated re-planning transportation for the staff, participants, and equipment (corridor containers). Arcos safety centre was chosen as an alternative location because it could provide access to indoor facilities for donning trials and a flat outdoor area for rigging the corridor. The Arcos safety centre was approximately 3 kilometres away from the UiT.

Due to a change in the date and location of the experiments, the delivery time of the corridor containers was rescheduled, resulting in a delay in the arrival of the containers to the site. Therefore, preparation for the corridor (attaching the plywood panels to the walls and the floor) began late and the first day of the corridor trials (Saturday) was cancelled, allowing sufficient time to safely prepare the corridor containers. This meant that there was less available time to conduct the data collection.

The survival suits (Suit-1 and Suit-2) were identified several months in advance, but they arrived in the hands of the team couple of days before the trials started. This created a number of problems, including:

- The donning questionnaire was created solely based on pictures of the suit, and it was not guaranteed that the suit that arrived would be identical to the pictures. As a result, the suit-related questions in the questionnaires could not be designed to be very specific to the suit's features.
- The research team did not have access to the suits and so could not familiarise themselves with the correct donning of the suits prior to the start of the trials to identify the potential problems associated with wearing the suits. They could also not seek prior advice from professionals (who had experience in donning of the suits) regarding the correct method of donning of the suits.
- The late arrival of the suit made it very hard to source instructional videos demonstrating the correct donning of the suits. Therefore, the donning

instruction videos was recorded during the actual trials. Nevertheless, since a professional safety instructor from the Arcos safety centre performed the donning instruction, the two minutes instruction was prepared on time and was presented to 19 random participants throughout the trials.

Because it was not permitted to drill or nail into the asphalt, the container legs were not fixed to the asphalt and could shift when the containers' angles were changed. Despite the fact that the container legs were designed to provide adequate friction (with the asphalt), the team noticed a slight shift in the containers after heeling and lowering the corridor several times. Although the slight shift in the container did not pose a hazard, the containers needed to be realigned several times throughout the experiment. Three hydraulic jacks were used to lift the containers and push them into the right position.

With the experience gained from the Tromsø experiment, the data collection trials at the ResQ safety centre (Haugesund) were conducted more efficiently, with none of the aforementioned issues arising. Both experiments were carried out safely. The only minor injury which occurred at the corridor site in Arcos safety centre was a 64-year-old male who suffered a minor bleeding cut between the knuckles of his left hand, even though he was wearing safety gloves. The cut was treated by applying a bandage to it.

Chapter 5: Data analysis and modelling

This chapter summarises the results of data collection and modelling. The results of the measurements of donning time and correctness of donning for TPIS are published in Paper I (section 5.1) and can be found in Annex I and Annex II. The details of the data analysis for the impact of TPIS on walking speeds in the corridor (Paper II) are presented in Section 5.2, and the findings are presented in more detail in the corresponding paper in Annex III and IV. Section 5.3 of this chapter provides a brief summary of the modelling work, while the modelling paper (paper III) and the supplementary material for modelling paper are presented in Annex V and VI.

5.1. Donning of the TPIS (Paper I)

Following objective 1 (see section 1.2), the study in Paper I addressed the research question 1 (including 1.a, 1.b, 1.c and 1.d.). The following section provides a brief discussion of the study that was published in Paper I, with more information available in Annex I and II.

According to SOLAS requirements for safety of passenger ships, whenever passengers are to be onboard for 24 hours or longer, there must be a mustering drill for passengers prior or immediately upon departure in which they will be instructed how to use the lifejackets/vests, survival equipment, and action to be taken in any emergency. Individual or group safety briefings must be provided to new/late arriving passengers before the ship sails. The briefing is delivered over the public address system and, if necessary, supplemented by video display facilities or similar (Elnabawybahriz & Hassan, 2016). If the ship is sailing in polar waters, thermal protective aids or Thermal Protective Immersion Suits (TPIS) must be provided for all passengers and crew and if the immersion of passengers to the polar water is applicable, the suit should be insulated type (IMO, 2017). In case of using TPIS, according to SOLAS (IMO, 2004) individuals must be able to fully unpack don the TIPS within 120 seconds without assistance.

In this study, one type of polar approved TPIS (manufactured by Viking Production) was used in data collection (see Figure 6). Presented in Figure 6, YouSafe Blizzard survival suit, is a thermal protective immersion suit with integrated buoyancy elements and is one of the bulkiest of its kind on the market. Given the weight, bulkiness, and design of the suit, it was predicted that donning this suit would be a difficult task, and that the donning time of this suit could result in a conservative result for representation of donning time of a thermal protective suit which is needed for simulating the evacuation of passenger ships intended to operate in polar waters.

The donning data was collected in both the Arcos safety centre (Tromsø) and the ResQ safety centre (Haugesund). The donning trials were conducted indoors at temperatures ranging between 18° to 22°C (see sections 4.1 to 4.7). In total, 108 male and female volunteers participated in the donning data collection, and their performance was captured using action cameras (GoPro Hero). While all participants had access to the reading instruction, 19 people were chosen at random to receive a two-minute video instruction prior to donning the survival suit. The age distribution of the volunteers in the donning data collection is presented in Figure 21.

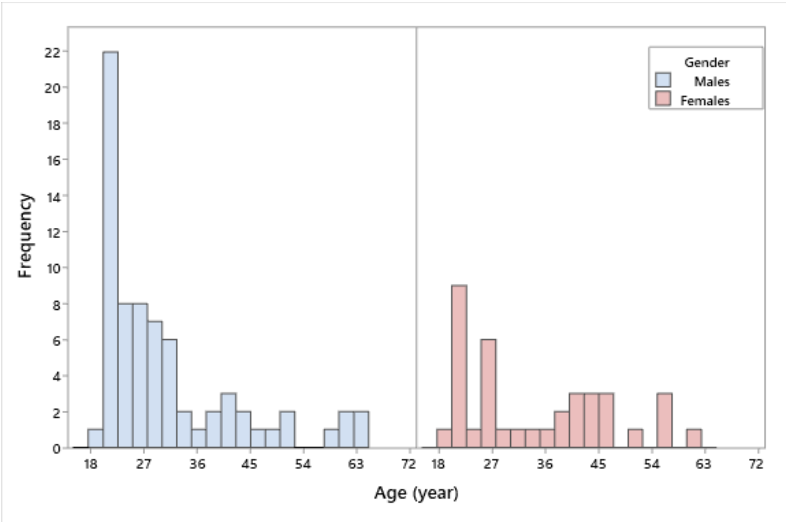

Figure 21: Age distribution of the volunteers in donning trials

5.1.1. Data extraction

As described in section 4.9, action cameras were used to record the performance of the individuals during donning trials. The first step in data analysis was defining the parameters that needed to be quantified, such as the duration of different activities (i.e. preparation time, package opening time, Net donning time etc.) and donning correctness. A data dictionary was developed, and all of the activities were clearly defined (with an example picture). Figure 22 presents the time sequence for the various phases of donning. The data dictionary was developed based on the different donning phases presented in Figure 22.

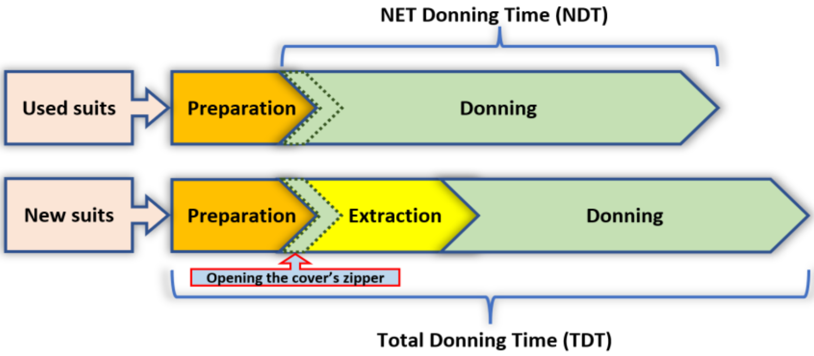

Figure 22: Time sequence for donning of the TPIS

Table 4 defines various variables that were quantified during the video analysis.

Table 4: Definition of variables in the data dictionary for the video analysis

Variable	Definition	Options
PT = Preparation time	From hearing Go to the moment of touching the zipper of the cover	Time (MM:SS:xx)
XT = Extraction time (opening the package)	From the moment of grabbing the plastic bag (inside the cover) to the moment of taking out the suit from the plastic bag.	Time (MM:SS:xx)
NDT = Net donning time	From the moment of touching the tracker of the covers' zipper to the time of rising both hands up, indicating donning is completed.	Time (MM:SS:xx)
Taking the shoes off	If the participants took their shoes off prior to the first donning attempt	Yes/No
Shoes were taken off	If the participants had finished the donning without having the shoes on.	Yes/No
Zipper	If the zipper was pulled all the way up	Yes/No
Gloves	If both gloves were put on	Yes/No
Wrist straps	If both wrist straps were fastened	Yes/No
Ankle straps	If both ankle straps were fastened	Yes/No
Hood	If the hood was on	Yes/No
Length straps	If both length straps were adjusted	Yes/No
Front buckle	If the front buckle was done	Yes/No
Having difficulty with donning	If participants struggled with any feature of the suit (to be explained)	Hood, gloves, zipper, ankle and wrist straps, opening the packaging, length straps.
Stance of the participant during donning	If the participant was standing, seating or combination of both during donning task	Standing, seating, combination of both
Looking at others	If participant looked at other during the donning trial	Yes/No

5.1.2. Inter-rater and Intra-rater reliability

To verify the clarity of the defined variables and assess the analyst's bias, a set of video footages of donning the TPIS (performance of 20 participants) were randomly selected, and two independent raters were assigned to extract data from the video footages and quantify the variables presented in Table 4. The Interclass Correlation Coefficient (ICC) was used to compare (time) duration measurements, and Kappa statistics was used to compare the quantified behavioural variables. The acceptance criteria required very good agreement (ICC and Kappa ≥ 0.81). If the acceptance criteria were not met, it would be necessary to determine the reason, revise the data dictionary, and retrain and retest the raters with a new subset of data until the desired agreement could be achieved. The results of the inter-rater reliability test revealed a very good level of agreement between the two raters, with an average ICC value of 0.99 and a Kappa value of 0.85 for duration measurement and behavioural data, respectively. Once the clarity of variables in the data dictionary was verified, the data extraction was started and completed by one rater. Since during data analysis, there is always the possibility of variability within a single analyst, when the video analysis task was completed, the analyst's Intra-rater reliability was assessed by selecting some random footages and analysing them by both the same analyst (who did the analysis) and an external rater. The results confirmed excellent consistency and accuracy in the measurements, so the formal Intra-rater reliability test was not performed.

5.1.3. Data analysis and results

The data analysis commenced when the data extraction was finished. The analysis revealed that the preparation time (PT) (which was measured from the moment participants hear GO to the moment they touch the zipper of carrying cover in order to open it) was on average 2.5 seconds ranging from 1 second to 35 seconds. The preparation time was presented by Eq. (4):

$$\mathrm{PT} = 1 + U * X \tag{4}$$

Where: $U \sim \text{"}Bernoulli\text{"}\ (0.16)$ and $X \sim \text{"}Log-normal\text{"}\ (2.35, 0.56)$

14 of the TPIS in the experiment were brand new, which meant the new suits were in a plastic bag and were placed in the carrying cover, whereas the old suits were folded and placed inside the carrying cover. The extraction time (XT) of the brand-new TPIS (see Table 4) was defied as the time required to extract the new suits from the plastic bag and was approximated by log-normal distribution as presented in Eq. (5):

$$\mathrm{XT} \sim \text{Log-normal}(2.9, 0.39) \tag{5}$$

The preliminary results revealed that the Net Donning Time (NDT), which was measured from the moment individuals touched the zipper of the cover to the time they raised both hands (see Figure 23), followed a log-normal distribution for both males and females. The NDT of the male and female groups can be represented by log-normal (5.25, 0.2974) and log-normal (4.938, 0.3339), respectively. The suit's total donning time (TDT) was defined as the sum of the preparation time (PT), extraction time (XT), and NDT.

The analysis of NDT also revealed that on average, males performed significantly faster than females, and that NDT increased as the age of both genders increased. The correlation of various influencing factors was investigated using a log-linear regression model and results revealed that at the 5% significance level, age, gender, video instruction, previous donning experience, and taking the shoes off prior to don the suit (the correct donning procedure), all had a significant influence on the NDT.

a. Start of the NDT b. End of the DNT

Figure 23: Start and end of the measurement of Net Donning time (NDT) (Azizpour et al., 2023a)

The video instruction, preparation time, and prior experience all had a significant impact on the correctness of donning the suit. Analysis also revealed that having proper and clear instruction would significantly influence the likelihood of adopting the correct donning procedure, which (in this case) was taking the shoes off prior to don the TPIS. This means that failing to take off the shoes at the beginning could increase donning time approximately by 26%. Figure 24 presents the relationship between various influencing factors on donning time and correctness of donning.

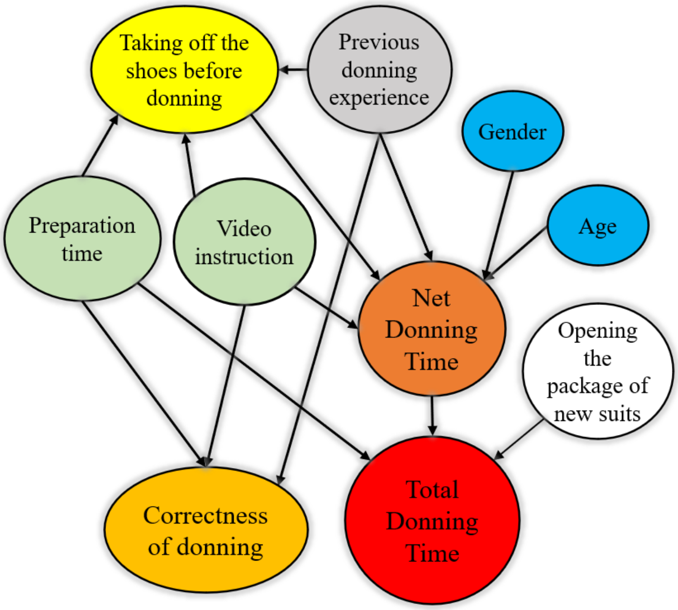

Figure 24: Correlation between predicting factors that influenced donning time and correctness of donning according to the collected data

In order to approximate the donning time (by a regression model) for application in ship evacuation simulation, since the guideline for evacuation analysis of passenger ships (IMO, 2016) quantifies individuals' walking speeds based on the two factors of age and gender, these two factors and the previous experience (shown in Figure 24) were used in a log-linear regression model. The log-linear regression model was used to predict the NDT based on the donning data from 89 participants who did not receive the video instruction. The TDT of the TPIS for modelling application was defined by Eq. (6):

$$\mathrm{TDT} = \mathrm{PT} + \mathrm{XT} + \mathrm{NDT} \tag{6}$$

Where PT and XT are determined by Eq. (4) and Eq. (5), respectively, and NDT is defined by Eq.(7), as follows:

$$\mathrm{NDT} = 130.3 * 1.006^{\mathrm{Age}} * 1.32^{\mathrm{Gender}} * 0.79^{\mathrm{Experience}} * \tilde{\varepsilon}\ ; \tag{7}$$

$$\tilde{\varepsilon} \sim \text{Log-normal}\ (0, 0.3)$$

$$\mathrm{Age} \in (18 - 72), \qquad \mathrm{Gender} \in (\mathrm{Male} = 0, \mathrm{Female} = 1)$$

$$\mathrm{Experience} \ \in (\text{People without donning experience} = \ 0, \text{People with donning experience} = 1)$$

If the above-mentioned equation is used to represent the donning time of inexperienced passengers during an emergency, the experience factor in the calculation of TDT can be set to zero.

The results of the donning trial highlighted the importance of paying attention to the instructions and adopting the correct procedure for donning the suit. In our study, more than 90% of the participants filed to don the suit within the 120 seconds time limit specified by the IMO and ISO guidelines (IMO, 1998; ISO, 2012). The mean donning time of a TPIS may vary depending on the design, type, and material of the suit; however, until more specific data is available, the donning time of Suit-2 can provide a reasonably conservative input for modelling applications.

5.2. Impact of TPIS and angle of heel on walking speed (Paper II)

Following objective 2 (see section 1.2), the study in Paper II addressed the research question 2 (including 2.a, 2.b, 2.c and 2.d.). The following section provides a brief discussion of the study that was published in Paper II, with more information available in Annex III and IV.

In the event that passengers need to evacuate a passenger ship in polar waters, each passenger may need to walk a distance while wearing the TPIS. In an emergency, the vessel could be in dynamic motion or have a static angle of heel. Understanding the impact of survival suit and angle of orientation of the floor on individual walking speeds is critical not only for modelling application and certification analysis but also for understanding the risk and challenges of managing emergencies in polar waters.

According to the studies, the behaviour of individuals in ship and building emergencies is similar (Casareale, Bernardini, Bartolucci, Marincioni, & D’Orazio, 2017). As a result, the findings of experiments on individuals’ performance (walking speeds) in land-based facilities can be applied to maritime applications. A 36-meter-long corridor that could be tilted to different angles of heel (0°, 10°, 15° and 20°) was built on land and walking speeds of 210 was measured. Participants wore different types of survival suit while walking at different angles of heel. 125 participants participated in the experiment at Arcos safety centre (Tromsø), and another 85 participants participated in data collection at ResQ safety centre (Haugesund). Participants were recruited from the local population (males and females) between the ages of 18 and 72. Figure 25 presents the age distribution in the male and female groups.

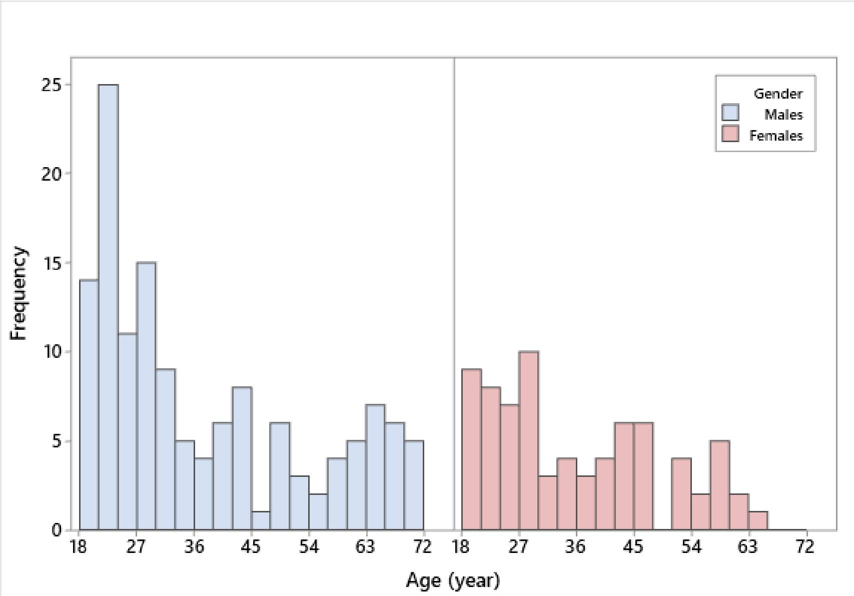

Figure 25: Age distribution of participants in the corridor trial

Throughout the data collection trials, each participant was instructed to either wear one of the two different types of survival suits, namely Suit-1 and Suit-2 (see section 4.7) or walk with normal clothing (Suit-0) through a 36-meter-long corridor two times (see section 4.8). First time through the corridor at an angle of heel (10°, 15°, and 20°) and subsequently when the corridor is at 0° of heel. The data was collected using GoPro cameras, and the participants' walking performance was measured within a length of 30-meter in the corridor.

5.2.1. Data extraction

Following the completion of data collection, all variables that needed to be quantified during the video analysis were listed and defined in a data dictionary. The moment of crossing the lines (beginning, middle, and end) was defined as the time when the person's leading foot (or any part of the leading foot) crossed the line (either on the floor or on the wall whichever is visible). If the leading foot crossing the line could not be seen in the footage, the closest frame just before crossing the line was used as the starting point. Because the video footage was recorded with 25 FPS, each frame was 0.04 second, resulting in a +/- 0.04 second error in the measurements. Table 5 shows a list of all variables that were quantified through the video analysis.

Table 5: Definition of parameters in the data dictionary for analysis of walking speeds in the corridor

Variable	Definition	Options
Starting time	(Time of passing start line) – (time of hearing the whistle)	Time (MM:SS:xx)
Mid corridor (15m) time	(((time of passing the middle line) – Time of hearing the whistle))- (Starting time)	Time (MM:SS:xx)
Entire corridor (30m) time	(((time of passing the end line) – Time of hearing the whistle))- (Starting time)	Time (MM:SS:xx)
Trip, stumble, miss-step	The stumble/miss step/trip is an involuntary body movement while walking. A miss-step is footing that is not formal for walking. No other part of the body should touch the floor (except for the feet).	Counting the numbers
Number of stops	Number of times a participant stops in the entire corridor.	No stop = 0 / one stop = 1 / 2 stops = 2 / 3 stops = 3 / 4 stops = 4 / 5 stops = 5 / over 5 stops = 6
Touching the wall	Number of times the person touches the wall to keep balance.	Never = 0 Occasionally = 1 to 5 times Majority of the time = over 5 times
Falling	Counting the number of times, a part of the body, other than the feet, touches the floor. If more than one body part touches the floor at the same time, it will still only be counted as one fall.	Counting the numbers
Foot sliding down	If the participants foot appears to slide down towards the wall.	No, Yes
Difficulty with footwear/ foot cover	If the foot covering of the suit sided/slipped underneath their foot while walking causing inconvenience.	No, Yes
Running	Running is defined as a stage during travel in which both feet are off the floor. This may be difficult to identify in the analysis. Therefore, it might become a subjective measure and the analyser's best guess.	No, Yes

5.2.2. Inter-rater and Intra-rater reliability

A set of video footages from 20 participants' walking performances were selected, and two independent raters were assigned to quantify the variables using the definitions provided in the data dictionary (see Table 5). For comparing walking speed measurements, Interclass Correlation coefficients (ICCs) were used, and Kappa statistics were used for comparing quantified behavioural variables (i.e., touching the wall, mis step, running, etc). Comparison of results showed an excellent agreement between the measurements by the two raters, with an average Kappa value of 0.84 and an ICCs value of 0.98 for the behavioural and speed data, respectively. When the clarity of the definitions was verified, all the video footages were analysed by one rater. The consistency of the rater's measurements (intra-rater reliability) was evaluated several times throughout the video analysis process and the results confirmed that the measurements were consistent and accurate.

5.2.3. Data analysis and results

In total, 18408 data points were collected from video analysis, registration, and questionnaires. Because the participants were instructed to walk as fast as they could without running, some of the participants (26 participants out of 210) were disqualified after the video analysis, because they were deemed to be either running or not being properly engaged with the experiment (see supplementary material for paper II in Annex IV), thus the data from the remaining 184 participants were used for the analysis.

A log-linear regression model was used to investigate the effect of various personal and environmental variables on individual walking speeds based on a total of 368 walking speed measurements which came from the performance of 184 participants who walked through an angle of heel and the flat angle (0°). At a 5% significance level, the results showed that increasing age, weight, and angle of heel reduced walking speeds, whereas increase in height increased the walking speeds. Men were on average significantly faster than women and wearing the survival suit significantly reduced the walking speed of all participants at various angles of heel. Figure 26 presents the relationship between different factors influencing the walking speeds.

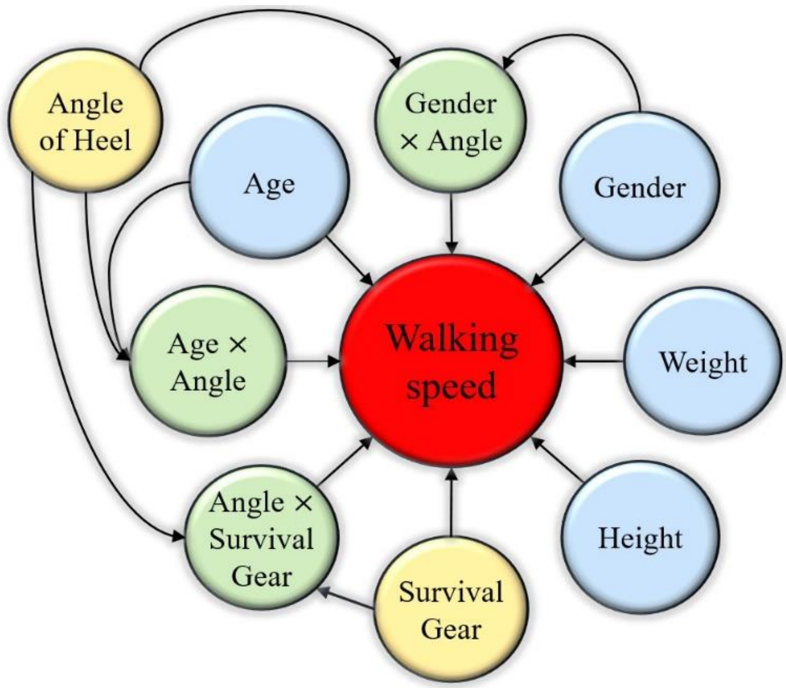

Figure 26: correlation between different factors in the log-linear regression model that significantly influence walking speeds according to the collected data (Azizpour et al., 2022a)

As shown in Figure 26, increasing the angle of the heel influenced the negative effect of the survival suit (Gear) and age factor on walking speeds. The angle of the heel appeared to have a greater negative impact on female walking speeds than their male counterparts. The green nodes in Figure 26 present the interactions of angle of heel with gender, age, and survival suits (Gear).

According to the log-linear regression model, the walking speeds can be estimated by Eq. (8):

$$\mathrm{Y} = 1.5872 * 0.9982^{\mathrm{Age}} * 0.9323^{\mathrm{Gender}} * 0.9999^{\mathrm{Age*Angle}} * 0.9969^{\mathrm{Gender*Angle}} * 0.9928^{\mathrm{Angle*Suit-1}} * 0.9392^{\mathrm{Suit-2}} * 0.9898^{\mathrm{Angle*Suit-2}} * 1.0037^{\mathrm{Height}} * 0.9975^{\mathrm{Weight}} * \tilde{\varepsilon}, \quad where\ \tilde{\varepsilon} \sim \mathrm{logNormal}(0, 0.1463). \tag{8}$$

Table 6 presents the range of the quantified variable that contributed to the Eq. (8).

Table 6: Definition and range of factors contributing to walking speed (according to the collected data)

Age $\in$ 18 − 72 year old	Angle $\in$ 0° to 20°	Using Suit-2 $\in$ Yes = 1, No = 0
Gender $\in$ Male = 0, Female = 1	Using Suit-1 $\in$ Yes = 1, No = 0	Height $\in$ 154 − 195 cm
Weight $\in$ 48 − 123 kg)		

According to the Eq. (8), by keeping all other variables constant, an increase in age (to 72 years old) and angle of heel (to 20°) can result in a 24% decrease in walking speed. The negative impact of the survival suit was exacerbated by an increase in the angle of heel, and the negative impact of Suit-2 was greater than Suit-1 at all angles of heel. Suit-1 had an impact ranging from 0% at 0° to -13% at 20°, whereas Suit-2 had an impact ranging from -6% at 0° to -23.5% at 20°.

The analysis revealed that the impact of the survival suit and angle of heel on walking speeds is significant and should not be underestimated in evacuation modelling. The unhindered mean walking speeds of individuals at 0° of heel are defined as a function of age and gender in the IMO guidelines for evacuation analysis (IMO, 2016). To quantify the impact of survival suits on walking speeds for use in evacuation modelling, the log-linear regression model was repeated, this time including age, gender, angle of heel, and survival suit, as shown in Eq. (9):

(9)

$$Y = 2.55 * 0.9979^{Age} * 0.9213^{Gender} * 0.9999^{Angle*Age} * 0.9970^{Angle*Gender} * 0.9934^{Angle*Suit-1} * 0.9363^{Suit-2} * 0.9901^{Angle*Suit-2} * \tilde{\varepsilon}\ ;\ \text{where}\ \tilde{\varepsilon} \sim \text{logNormal}(0, 0.1495)$$

The reduction factor (RF) corresponding to age, gender, angle of heel, and type of survival suit was defined as the ratio of walking speed based on the individual's age and gender, type of survival suit at a specific angle of heel over the walking speed of the same person (age and gender) at 0° heel and Suit-0. Eq. (10) gives the RF using this definition:

(10)

$$RF_{age,\ gender,\ angle,\ Suit} = \frac{Y_{Age,\ Gender,\ Angle,\ Suit}}{Y_{Age,\ Gender,\ Angle=0,\ Suit=0}} = 0.9999^{Angle*Age} * 0.9970^{Angle*Gender} * 0.9934^{Angle*Suit-1} * 0.9363^{Suit-2} * 0.9901^{Angle*Suit-2}$$

According to Eq.(10) Individuals' walking speeds can be reduced up to 39% depending on their age (20 to 72 years old), gender (male/female), angle of heel (0° to 20°), and type of survival suit (Suit-1 or Suit-2). Using the reduction factor in Eq. (10) the walking speed (WS) proportional to the angle of heel and the type of survival suit was defined by the Eq. (11). In Eq. (11), the walking speeds (based on age and gender) recommended by the guideline of evacuation analysis (IMO, 2016) ($WS_{Age,Gender,Angle=0,Suit=0}$) are multiplied by the corresponding RF calculated from Eq.(10).

(11)

$$WS_{Age,Gender,Angle,Suit} = WS_{Age,Gender,Angle=0,Suit=0} \times RF_{Age,Gender,Angle,Suit}$$

When simulating the evacuation of a passenger ship in polar waters, passengers must walk with the survival suit to the lifeboats after donning the suit at the assembly station. If passengers wear the survival suit, the flow of passengers in the evacuation model may change due to changes in the passengers' walking speeds. By incorporating Eq. (11) into a ship evacuation model, passengers can adjust their walking speeds according to the angle of heel of the floor and the type of survival suit. This allows engineers and operators to simulate the evacuation of passenger ships intended to operate in polar waters and obtain a more realistic estimate of the impact of survival suits on passenger ship abandonment.

5.3. Modelling of ship evacuation in polar waters (Paper III)

Following objective 3 (see section 1.2), the study in Paper III addressed the research question 3 (including 3.a, 3.b, 3.c and 3.d.). The following section provides a brief discussion of the study that was published in Paper III, with more information available in Annex V and VI.

The evacuation of a passenger ship is divided into two stages: assembling and vessel abandonment. According to the evacuation analysis for passenger ships (IMO, 2016), the total evacuation time (TET) is calculated by summing the assembly and abandonment times as shown in Figure 1 and is defined by Eq. (1) as follows: TET=1.25(R+T)+2/3(E+L). In the Eq. (1) the assembly time (R+T) for each passenger should be determined using advanced evacuation simulation and the total assembly time should be calculated for all passengers (agents) in the model. The embarkation and launching time (E+L) - which can also be simulated - should not exceed 30 minutes under any circumstances (IMO, 2016).

During the mustering phase of a passenger ship, passengers should assemble at a predetermined mustering point, which is usually close to the lifeboat location. If the ship is operating in polar waters, all passengers should be issued with TPIS (if immersion of the passengers to the polar waters is applicable) (IMO, 2017). The thermal protective clothing should also be stored near the assembly/embarkation station. Distribution and donning the survival suit at any point during the assembly phase can affect the total assembly time. Furthermore, wearing the survival suit may affect the individuals' walking speed and consequently prolonging the abandonment.

There is always a chance that the severity of the accident and rough sea conditions cause rolling or static list/trim in a passenger vessel in emergency. Furthermore, the smoke and fire spread might make some of the evacuation routes unavailable. While the aforementioned factors might significantly impact the assembly and abandonment of the vessel, the guideline of evacuation analysis passenger ships (IMO, 2016) requires certification analysis to be carried out for the vessel at 0° of heel without considering the impact of above-mentioned stressors. To account for the impact of the mentioned underestimated factors, the guideline has introduced an arbitrary 25% safety factor which is multiplied by the assembly time (see Eq. (1)). The passenger ship that operates in the polar water may deploy the TPIS during the evacuation. Therefore, it is critical to assess the impact of deploying TPIS (during evacuation) on assembly time and determine whether the arbitrary 25% safety factor (suggested by Eq. (1)) is sufficient to account for the time required to distribute and donning of the TPIS during the assembly phase, in addition to the impact of heel/trim, smoke etc.

To address this issue, the results of studies on donning time of TPIS (Paper I) and the impact of TPIS on walking speeds (Paper II) were deployed in maritimeEXODUS evacuation model to simulate the evacuation of a hypothetical passenger vessel in polar waters. The software was modified to incorporate the donning time of TPIS (by Eq. (6) for Suit-2) during the assembly phase for each passenger in the model. The modification was introduced such that after donning the suit, the passengers walking speeds would be adjusted based on the walking speed reduction factor (Eq. (10)) (Azizpour et al., 2022a) corresponding to their age, gender, angle of heel/trim, and survival suit type (Suit-2).

5.3.1. maritimeEXODUS evacuation model

maritimeEXODUS (mEX) is an agent-based evacuation model developed by the University of Greenwich's fire safety engineering group (FSEG). mEX is a comprehensive software that simulates the egress of a large number of passengers from a passenger ship, taking into account the impact of heel and trim, as well as the eventual cessation or delay of movement due to extreme heat or the effect of toxic gases.

The general characteristics of the mEX are listed but not limited to the following (Łozowicka & Czyż, 2008):

- Each evacuee is represented in the model individually.
- The abilities of each individual are determined by a set of parameters which might be probabilistic.
- The movement of each person is recorded.
- The value of the defined parameters (i.e., response time, waking speeds, etc,) varies between individuals depending on their age, gender, time of day (day or night), and environmental conditions such as the angle of orientation of the floor.
- mEX features an itinerary list in which each passenger must complete a certain number of tasks before exiting the enclosure. The potential actions on the itinerary list are manifold, such as returning to a location to pick up a cloth,

performing a task in accordance with safety-related instructions, or even searching for a member of the family/group (e.g., a lost child).

- Last but not least, allowing evacuees to avoid congestion during general movement is one of the mEX's distinguishing features.

mEX simulates the evacuation in the specific vessel layout by simulating the individual evacuees. Each passenger onboard is labelled individually based on their initial position onboard. Parameters such as response time, age, gender, etc, which determine an individual's performance and capabilities, are generated at random from a pre-defined distribution function. Throughout the simulation, passengers move towards their predetermined goal, such as a specific muster station or lifeboat, based on a probabilistic decision algorithm with the high probability of taking the shortest path (Vanem & Skjong, 2006). It is also possible to track each passenger and the path they took during the evacuation. The simulation's output includes information such as the number of people who could successfully evacuate as a function of time and the number of fatalities as a function of time. It is also possible to determine the location of the fatalities as well as their starting position. Furthermore, bottlenecks and congestion points are easily visible in the simulation.

In the mEX, the spatial and temporal dimensions are represented by a two-dimensional spatial grid and a simulation clock. The geometry of the structure, as well as the locations of the exits, internal compartments, and obstacles, are represented by a spatial grid in which the nodes represent the corresponding regions of space, and the arcs represent the distance between the regions. The software can represent multiple floors connected by staircase. The structure layout can be imported into the software using DXF format, and the ship's abandonment system (e.g., lifeboats, rafts, etc.) can be modelled explicitly within the layout.

5.3.2. Modifications in the maritimeEXODUS

mEX can use a variety of custom-defined evacuation procedures. Because the Polar Code recommends that TPIS shall be stored close to the assembly/embarkation station, it was decided that in the modelling, passengers should walk to the assembly station where the TPIS(s) are issued. As a result, the survival suit donning time had to be introduced as a randomly generated delay time at the assembly station. Using Eq. (6) and Eq. (7), the random delay time was assigned to each passenger based on their age and gender (see section. 5.1.3). When the passenger arrives at the assembly station and the donning delay time runs out, the passenger is considered assembled.

During the abandonment phase, the agents must walk with the TPIS from the assembly station to the lifeboat (LSA equipment). Depending on the location of the lifeboats (from the assembly station), the agents must walk a distance on a flat surface (which can be at an angle of heel/trim) and also up/down the stairs (if applicable).

The walking speeds of the passengers in the model was determined by Eq. (10) and Eq. (11) in which the $\mathrm{WS}_{\mathrm{Age,Gender,Angle=0,Suit=0}}$ is a random walking speed (corresponding to the age and gender of each passenger at 0° of heel and Suit-0) generated from a distribution that is specified by the IMO guideline for evacuation analysis (IMO, 2016).

During the evacuation of a passenger ship, the passengers will be walking on an angle of trim if they change their direction 90° while walking on heel. Because the experiments revealed that survival suits have an effect on walking speeds of individuals at different angles of heel (Azizpour et al., 2022a), it is reasonable to assume that survival suits have an effect on walking speeds at an angle of trim as well. Because there was no data available at the time of writing this thesis to represent the combined impact of trim and survival suits on walking speeds, it was necessary to make assumptions to approximate this impact. The methodology for implementing the donning time and impact of survival suit on walking speeds at different angles of heel and trim are explained in detail in Annex V and VI (Paper III and supplementary material for paper III).

5.3.3. Description of the hypothetical passenger ship

The modified version of mEX was used to simulate the evacuation of a hypothetical passenger vessel based on the MS Roald Amundsen's layout (MSRA) (see Figure 27). MSRA, is a passenger ship designed and certified for operation in polar waters. While the analysis uses the vessel's overall layout, some of the internal layout and specifications have been changed, so the model used in the simulations is not an exact replica of the MSRA. The MSRA has a length and beam of approximately 114 m and 20 m, respectively, and meets the requirements for ice class 1B. The ship has cabin capacity for 530 passengers and 151 crew members. The ship has four main vertical zones spread across 11 decks, eight of which are accessible to passengers (decks 4 to 11). The cabins are on decks 4, 5, 7, 8, and 9, while the dining rooms and social areas are on decks 6, 9, and 10. All three assembly stations in MSRA are located on deck 6. The embarkation station (location of the four lifeboats - two on the port and two on the starboard side) is also on deck 6, so passengers don't need to walk up and down the stairs to get into the lifeboats from the assembly stations. A more detailed description of the layout of MSRA is presented in Annex VI (supplementary material for paper III).

5.3.4. Results of evacuation modelling

The evacuation of MSRA was modelled in two main benchmark scenarios of day and night case. The public space was occupied by 903 passengers during the day, while the cabins were occupied by 656 passengers during the night. For Suit-0 and Suit-2, the day case evacuation scenario was simulated for three angles of heel, namely 0°, 10°, and 20°, while the night case evacuation scenario was simulated only for 0° of heel. Each simulation scenario was repeated 50 times, and the 95% longest case was chosen as the representative result for the corresponding case.

By analysing the simulation output and looking into the impact of donning the Suit-2 during the assembly phase, it was revealed that at 0° of heel, compared to the base case (Suit-0 at 0°), the assembly time during the day was increased by 65% (465.6 s to 769.4 s). When the heel angle was increased to 20°, compared to the base case, the assembly time in the day case scenario increased by 77 % due to the combined effect of walking on the heel and donning the Suit-2 at the assembly station. Similarly, in the night case scenario, where the number of passengers in the model was smaller, donning the Suit-2 at the assembly station increased assembly time by 38% (from 779.3 s to 1.75.4 s) compared to the corresponding base case scenario (Suit-0 at 0°) (see Table 7).

The simulation revealed that, in our case study, the arbitrary safety factor of 25% (IMO, 2016) is clearly insufficient to account for the impact of wearing the TPIS at 0° during the assembly phase. The percentage of increase in assembly time as a result of deploying the TPIS is dependent on the duration of travel time for all passengers to the assembly station, however, it should also be noted that the implemented donning time for Suit-2 does not take heel angle into account, so the donning time at all heel angles were identical to the donning time for Suit-2 at 0°. The floor's orientation/movement may have a significant impact on passengers' donning performance (S.C Mallam, Small, & MacKinnon, 2014). Furthermore, the required distribution time for the TPIS is not implemented in the simulations. Therefore, in reality the actual impact of donning the TPIS during the assembly is expected to be greater than the findings in our study.

During the abandonment, passengers must walk from the assembly station to the location of the life-saving appliances (LSA) (embarkation station). Passengers will also need some time to get into the LSA once they arrive at the embarkation point. Based on the provided data (Azizpour et al., 2022a) the simulation confirmed that wearing the TPIS can affect the time it takes to walk to the lifeboat. At 0° heel, the abandonment time for 903 passengers in Suit-0 was about 211 seconds. This time is increased by 71% (361 s) if passengers walk at 20° of heel while wearing Suit-2.

The impact of wearing a TPIS, which can reduce freedom and convenience of movement, can also influence the embarkation time. When the ship is at an angle of heel or in motion (rolling), boarding the lifeboat becomes even more difficult and time-consuming. The presence of disabled people and children who require extra assistance to board the LSA may also prolong the process of abandonment. The time of embarkation into the LSA and launching of the LSA was not simulated because, to the best of our knowledge, no comprehensive research exists to shed light on the actual time required for passenger to board an LSA while wearing TPIS (i.e., Suit-2). It needs to be noted that since the maximum time for abandonment should not exceed 30 minutes (IMO, 2016), any increase in travel time to the LSA means less time available for embarkation and launching of the LSA.

Table 7 presents the results of the 95% (longest simulation) cases for assembly and abandonment time of MSRA during day and night case scenarios.

Table 7: 95th percentile times for the Day and Night assembly and abandonment scenarios at various angles of heel and with and without TPIS (Azizpour et al., 2023b)

<table>
<tr><th>Primary Scenario</th><th>Phase</th><th>Heel Angle</th><th>95% Time (s) Suit-0 (Min-Max Time)</th><th>Suit-0 % Increase compared to Suit-0 at 0°</th><th>95% Time (s) Suit-2 (Min-Max Time)</th><th>Suit-2 % Increase compared to Suit-0 at 0°</th></tr>
<tr><td rowspan="6">Day case</td><td rowspan="3">Assembly</td><td>0°</td><td>465.6
(343.9-469.4)</td><td>N/A</td><td>769.4
(631-780.8)</td><td>65%</td></tr>
<tr><td>10°</td><td>477.2
(349.6-485.7)</td><td>3%</td><td>791.3
(641.5-793.1)</td><td>70%</td></tr>
<tr><td>20°</td><td>490.2
(344.5-510.2)</td><td>5%</td><td>822.5
(697-835)</td><td>77%</td></tr>
<tr><td rowspan="3">Abandonment</td><td>0°</td><td>210.8</td><td>N/A</td><td>224.1</td><td>6%</td></tr>
<tr><td>10°</td><td>243.3</td><td>15%</td><td>280.1</td><td>33%</td></tr>
<tr><td>20°</td><td>274.2</td><td>30%</td><td>361.0</td><td>71%</td></tr>
<tr><td rowspan="2">Night case</td><td>Assembly</td><td>0°</td><td>779.3
(714.84 – 789.16)</td><td>N/A</td><td>1075.4
(933.08 – 1099.92)</td><td>38%</td></tr>
<tr><td>Abandonment</td><td>0°</td><td>118.7</td><td>N/A</td><td>127.6</td><td>7%</td></tr>
</table>

According to Table 7, the result of the evacuation simulation (assembly time) of MSRT with the inclusion of the donning of the TPIS (Suit-2) did not exceed the maximum allowed assembly time (IMO, 2016), but for ships with a larger size and a larger number of passengers on board, the increase in assembly time could be quite significant, possibly exceeding the 60-minute threshold. Furthermore, the simulation assumes that all passengers are aware of how to get to the assembly station and will most likely take the shortest route. Obviously, in real-life passengers may look for family members or children before proceeding to the assembly station. As a result, during real-life accidents, a longer assembly time can be expected.

According to the findings of this study, which highlighted the insufficiency of the arbitrary 25% safety factor suggested by the guideline of evacuation analysis (IMO, 2016), in certification analysis for passenger ships intending to sail in polar waters, it is critical to include the impact of required time to don the TPIS within the assembly time. Several approaches are suggested to approximate this impact:

1. Increase the safety factor to at least 50%.
2. 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.
3. Include TPIS donning in the modelling of the assembly process as demonstrated in this study (see Annex V and VI). 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 (Suit-2) used in this study could be used (see Annex I and II).

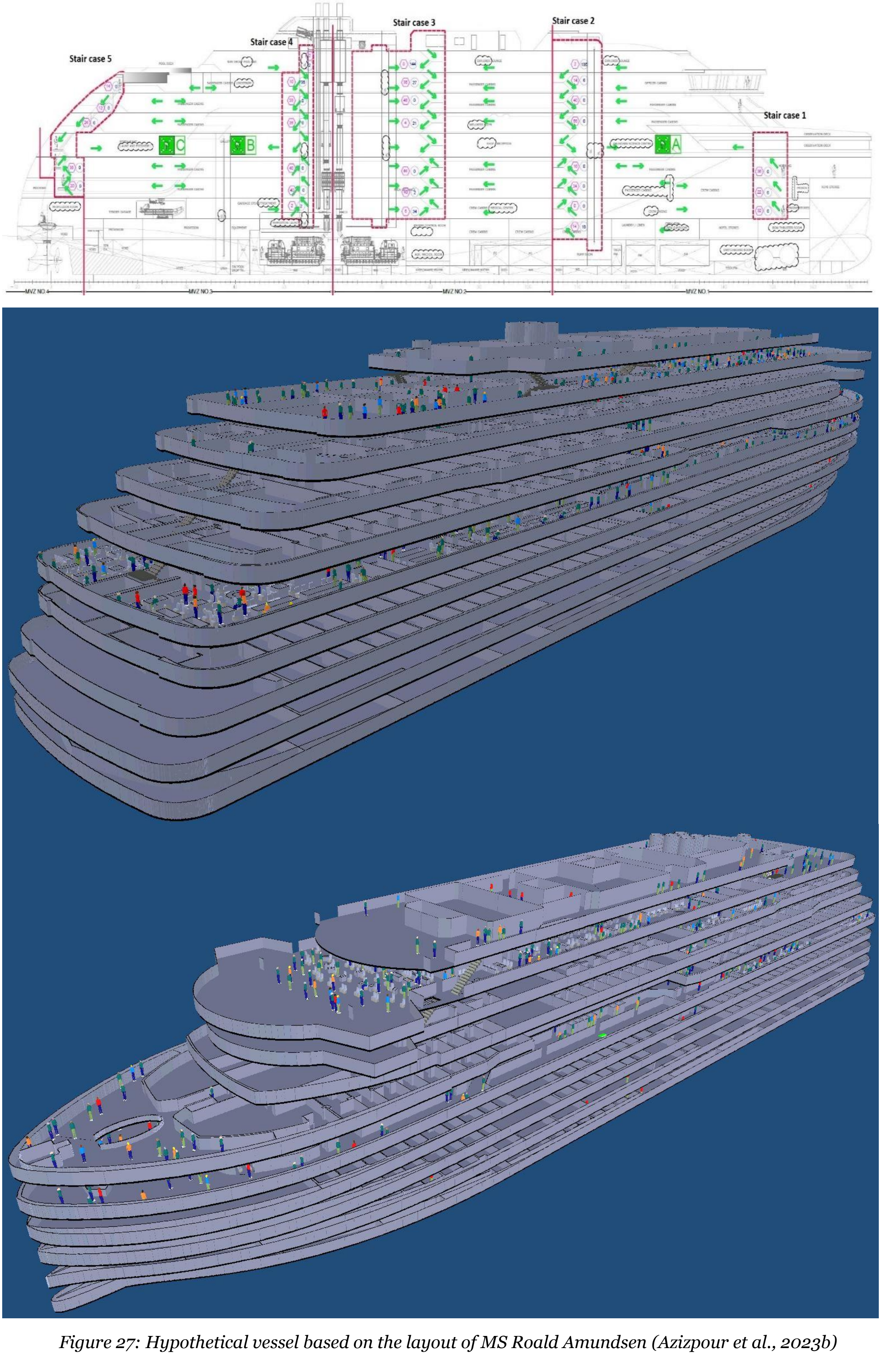

Figure 27: Hypothetical vessel based on the layout of MS Roald Amundsen (Azizpour et al., 2023b)

Chapter 6: Discussion and conclusion

This chapter presents a brief discussion of the findings (data collection and modelling). The detailed discussion of the finding in each study is presented in the corresponding papers and associated supplementary material. This chapter also discusses the contributions of these studies as well as limitations and future research directions.

6.1. Discussion

The safe evacuation of passenger ships is always a challenging operation, especially in the harsh climate of polar region. According to the IMO guidelines for evacuation analysis for passenger ships (IMO, 2016) all passenger ships must be certified for compliance with the maximum acceptable evacuation time of 60 to 80 minutes, depending on the number of main vertical zones in the passenger ship. Due to a perceived lack of generally available reliable human performance data and perceived limitations of evacuation simulation software, the IMO guidelines specify a simplified ideal benchmark evacuation scenario for certification analysis of passenger ships. This ideal benchmark scenario ignores the impact of adverse vessel orientation (i.e., assumes, 0° of heel), ignores dynamic motions and the presence of smoke, heat and toxic gases. The evacuation analysis guidelines suggests that an arbitrary safety factor equal to 25% of total assembly time is sufficient to account for the impact of the aforementioned factors on passenger evacuation performance during the assembly phase.

The Polar Code (IMO, 2017) requires that, in the event of a ship abandonment and the potential of passenger immersion in polar waters, thermal protective immersion suits (TPIS) should be deployed (made available to all passengers and crew) on all vessels operating and sailing in polar waters. The primary requirement is that the TPIS be designed to be worn unaided in less than 120 seconds (IMO, 1998) and not reduce average walking speed by more than 25% (ISO, 2012). Compliance with this requirement is demonstrated by determining the donning time and walking speeds produced by six test subjects wearing the TPIS and walking over 30 m under the condition of 0° of heel (IMO, 1998; ISO, 2012). Clearly, the results from the performance of six test subjects (donning and walking with TPIS) cannot represent the actual performance observed in a larger cross section of society. While international standards limit the time it takes to don the TPIS and the impact it may have on walking speeds on a level deck (IMO, 2004; ISO, 2012), there is no evidence that these standards-imposed limitations are appropriate for passenger ship evacuation in harsh conditions, specifically in polar condition.

During a passenger ship evacuation in polar waters, passengers may be required to don the TPIS during assembly and walk to the lifesaving appliance (LSA) while the vessel is at an angle of heel. Clearly, the distribution and donning of the TPIS and walking while wearing the TPIS can have an impact on the assembly and abandonment time of a passenger vessel. Therefore, it is critical to assess and understand the impact of deploying TPIS on the assembly and abandonment process of a passenger ship, particularly with respect to the IMO's 25% arbitrary safety factor (IMO, 2016).

The primary motivation for this thesis was to provide reliable data on the actual time required to correctly don a TPIS and to assess the potential impact of wearing the TPIS on walking speeds of individuals at different angles of heel ($0°, 10°, 15°$ and $20°$). Furthermore, by utilising the collected data in a ship evacuation model, this thesis aimed to provide insight into the impact of deploying the TPIS on passenger ship assembly and evacuation time and determine whether this needs to be explicitly included in IMO guideline (IMO, 2016), for certification analysis of passenger ships intending to operate in polar waters.

To quantify the donning time of a TPIS, a typical commercially available thermal protective immersion suit that is certified for use in polar conditions was chosen for data collection. The chosen TPIS (Viking YouSafeTM Blizzard) (Suit-2) is a universal size immersion suit with integrated buoyancy elements and a layer of thermal insulation. The rugged design and bulkiness of the suit were believed to make donning and walking difficult and thus provide a conservative result. The donning experiment was planned to be conducted in a controlled environment in which participants attempted to don the suit on a flat floor without being influenced by adverse environmental stressors such as dynamic motion of the floor, static heel, etc.

The results of measuring the donning time of 108 participants revealed that the TPIS's Net Donning Time ranged from 65 to 341 seconds, with over 90% of the participants requiring a total donning time of more than 120 seconds (IMO, 1998). The analysis revealed that different factors such as age, gender, previous experience, and correct procedure of donning can have a profound impact on donning times of the TPIS. An equation for predicting the donning time of TPIS based on the age, gender, and previous donning experience of individuals was suggested (see Chapter 5.1, Eq. (6) and Paper I).

According to the results, for example, for a female/male, without prior experience aged 25 years and 65 years, the donning time is predicted to be 228.7/180.3 seconds and 282.7/221.2 seconds respectively. Thus, the older person, the greater the expected donning times. The donning times, in particular for older persons, will naturally have an impact on assembly times. The impact of age on individual donning time clearly indicates that on polar expedition vessels particularly with a large number of elderly passengers (since a longer donning time can be expected for most of the elderly passengers), the impact of the donning time on the assembly process cannot be ignored.

In addition to the donning data, the impact of the TPIS on walking speeds at various angles of heel was also measured in trials involving 210 volunteers (see Chapter 5.2 and Paper II). During the trials, participants were instructed to walk (as fast as they could) through a 36-meter-long corridor at different angles of inclination (0°, 10°, 15° and 20°). The data was collected for two different types of TPIS, a lightweight sea pass passenger suit (Suit-1) and a bulky thermal protective immersion suit (Suit-2). The participants wore either their regular clothing (Suit-0) or one of the two types of provided TPIS. The findings revealed that individual walking speeds were significantly influenced by age, gender, and environmental factors such as the angle of heel and the type of survival suit. The impact of the aforementioned factors on walking speeds was presented in the form of an equation that determined a walking speed reduction factor appropriate for the type of survival suit and angle of heel, as well as age and gender (see Chapter 5.2, Eq. (10) and Paper II). The calculated reduction factor predicts that in the most severe cases, (i.e., 20° heel angle, Suit-2, for a 65-year-old female) walking speeds will be reduced by up to 38%.

The impact of TPIS donning time (see Chapter 5.1 and Paper I) and walking speed reduction while wearing a TPIS (see Chapter 5.2 and Paper II) on passenger vessel assembly and abandonment time was investigated by utilising the newly collected human performance data within a maritime evacuation model to simulate the evacuation of a passenger vessel in polar conditions (see Chapter 5.3 and Paper III). The geometry of a hypothetical passenger ship based on the layout of MS Roald Amundsen was used and the evacuation of the vessel was simulated for two of the IMO stipulated evacuation scenarios, i.e., the primary day and night scenarios (IMO, 2016). Passengers were distributed in public areas in the day case, while in the night case passengers were located in their cabins. For each assembly scenario, the assembly process is considered to be completed once the passengers have entered the assembly station and donned the

TPIS. When donning is required, the assembly time in the day scenario, with the vessel at 0° of heel, and assuming Suit-2 is used, is increased by at 65% (see Chapter 5.3 and Paper III) compared to the situation without donning the TPIS. In the night scenario, under similar conditions, the assembly time is increased by 38% (it is noted that there are far fewer passengers in the night scenario compared to the day scenario). Clearly, the increase in assembly time due to donning the TPIS greatly exceeds the 25% and the arbitrary safety factor suggested by IMO is insufficient to account for all adverse factors in addition to the impact of the donning process.

The modelling results also demonstrated that walking with the survival suit could adversely affect the abandonment time. Clearly, this effect is dependent on the distance that passengers must walk while wearing the TPIS and whether they must traverse stairs on their way to the LSA. As the available time for abandonment (time required to walk to the LSA, board the LSA and launch the LSA) is limited to a maximum of 30 minutes, the longer the passengers require to travel to the LSA, the less time is available for boarding and launching the LSA. Needless to say, wearing a TPIS may affect the time it takes for each passenger to board the lifeboat, reducing the lifeboat's boarding rate. Since at the time of writing this thesis there is no data available for quantifying the impact of wearing the TPIS on the boarding rate of a lifeboat, this impact was not considered in the simulation.

While there is a wide range of survival suit types currently commercially available, in the evacuation simulation analysis presented in this thesis only a single type of survival suit (Suit-2) was considered. As shown in this thesis, the impact of the type and design of survival suit will have a significant effect on walking speeds (see Chapter 5.2 and Paper II). Furthermore, depending on the design and material of the suit, the average time required to don a survival suit may vary. As a result, the donning times and walking speeds presented in this thesis cannot be generalised for all types of survival suits. The ship operators may also prefer to equip their vessels with a type of thermal protective suit that requires the minimal storage space and is less expensive than a TPIS (i.e., Suit-2). It needs to be noted that, in a real-life evacuation scenario, in addition to the time required to don the suit, there will be a time delay for distribution of the suit, and passengers may have to wait in line at the distribution points. Furthermore, in an emergency, the ship may be in a condition of heel or trim or in dynamic rolling motion, with a number of elderly passengers and passengers with disabilities. The aforementioned factors are very likely to increase the donning time of the survival suits.

Hence, until very specific data for the distribution and donning of each particular type of polar approved survival suit becomes available, it is recommended that the donning time of a suit that provides the most conservative result (e.g., Suit-2) be used in the certification analysis of passenger ships intended to operate in polar waters.

The impact of wearing a survival suit on waking speeds can vary depending on the type and design of the suit. Suit-1 and Suit-2 are examples of survival suits at either end of the spectrum of available polar survival suits. One is light, relatively easy to don and relatively easy to walk in (Suit-1) while the other is heavier, less easy to don and less easy to walk in (Suit-2). This thesis demonstrated that the lightweight survival suit (Suit-1) appeared to have less of a detrimental impact on individual walking speeds when compared to the bulky TPIS (Suit-2). While the ship evacuation simulation revealed that walking with Suit-2 increases travel time to the lifeboats, some passenger ship operators may distribute a very light weighted survival suit among the passengers during the abandonment. Although it can be argued that wearing a lightweight survival suit has a less negative impact on passenger walking speeds during the evacuation, it should be noted that the impact of the survival suit is not limited to walking speeds. Most light-weight survival suits, like the Suit-1, do not provide thermal protection or have integrated buoyancy elements. As a result, before donning the suit, passengers must first put on warm clothing and then don the suit. This process takes some additional time. Furthermore, passengers must wear the life jacket on top of the light weighted immersion suits. Clearly, the time it takes to put on the life jacket while having donned the light weighted survival suit, must be added to the speculated total time it requires to don the suit. As a result, the total time required to deploy a light weighted survival suit is greater than the time required to don the suit alone.

Wearing life jackets over a survival suit may also cause discomfort when passing through the doors of the lifeboat, and passengers wearing survival suits may board at a slower rate. Hence, until specific data on the impact of each type of polar survival suit on individual walking speeds and boarding rate to life-saving appliances becomes available, it is recommended that the impact of Suit-2 on walking speeds (which provides a conservative result) be used in evacuation models for simulation of vessel abandonment in polar waters.

This thesis has demonstrated that the IMO imposed arbitrary safety factor of 25% for assembly time predictions is inadequate to accommodate the potential negative impact of donning a TPIS, let alone accommodating all the other adverse factors currently excluded in passenger ship certification assembly analysis.

Thus, for evacuation certification analysis for vessels operating in polar waters, this thesis has suggested three approaches for incorporating the impact of the TPIS into evacuation analysis. These are, (i) increasing the safety factor from 25% to 50%, (ii) retaining the 25% safety factor but add 300 s to the predicted assembly time or (iii) include TPIS donning in the evacuation modelling of the assembly process, as demonstrated in Chapter 5.3 and Paper III (see Annex V and VI).

6.2. Contribution

The content of this thesis addressed quantification and analysis of the emergency evacuation of passenger ships operating in polar regions. The study aimed to shed light on a highly demanding, complex and poorly understood problem - how survival suits impact evacuation of passenger ships operating in polar waters. Within this thesis, this issue was addressed by collecting human performance data relating to donning times and walking speeds associated with TPIS, through a series of land-based trials and utilising this data in an evacuation simulation tool (maritimeEXODUS) to evaluate the evacuation of a passenger ship in polar waters. The results of the thesis which are published in three journal papers contribute to improving the safety of passenger ships in polar region in different aspects:

- **Enhancement of design and ergonomics of survival suits**
  The issues identified in the data collection regarding the challenges of donning and walking with the survival suit can be used by the regulator to revise the requirement for design and performance testing of survival suits. The insights provided by the donning experiments can also be used by manufacturers to improve the design and ergonomics of survival suits.
- **Evidence-based data for certification analysis of passenger ships intending to operate in polar waters**
  The certification of passenger ship evacuation capabilities necessitates advanced computerised evacuation simulation to assess and confirm the vessel's compliance with the requirements of MSC.1/Cir.1533 (IMO, 2016). The simulation of evacuation of a passenger vessel intending to operate in polar waters requires reliable data to quantify passenger evacuation performance while wearing cold weather gear (i.e., donning time and walking speeds at 0° of heel

and other angles). The evidence-based findings presented in this thesis (Paper I and paper II) can be used in the leading maritime evacuation simulation software to model human performance in polar evacuation. This capability can be used to predict the total assembly and abandonment time for a vessel designed to operate in polar waters, allowing for the development of tested intrinsically safe evacuation procedures during the design phase.

- **Providing knowledge for improving the evacuation options**
  The ability of evacuation simulation software to simulate human performance in polar conditions can also be used to evaluate changes to existing vessel evacuation plans (if intending to operate in polar region). The maritime industry can benefit from this capability of the simulation tool by testing (through simulation) the potential improvements in ship designs and various emergency procedures with the goal of lowering the risk for operation of passenger vessels in polar waters.
- **Demonstrating the insufficiency of safety factor and giving input into IMO**
  The simulation of evacuation of a passenger vessel certified to operate in polar waters revealed that the imposed arbitrary 25% safety factor (IMO, 2016) is insufficient to account for the impact of time required for dispatching and donning the survival suits during the assembly phase of passenger ship. This evidence-based study can provide information for IMO Ship Design Committee (SDC) and regulatory authorities (i.e., flag states and class registries) to update the associated guidelines and regulations.

6.3. Conclusion

Assessing the impact of deploying survival suits during the evacuation of passenger ship while operating in polar waters requires data characterising the performance of individuals in donning and walking while wearing a survival suit. The performance of individuals wearing a thermal protective immersion suit (Suit-2) and the effect of two different types of survival suits (Suit-1 and Suit-2) on individual walking speeds was investigated as part of this thesis through a series of data collection trials. The results showed that the total donning time (including unpacking a new suit) of the TPIS (Suit-2) ranged from 75 to 431 seconds, with over 90% of the individuals requiring a donning time of more than 120 seconds. Walking with Suit-1 resulted in a reduction in individuals' walking speeds ranging from 0% at 0° of heel to 13% at 20° of heel. The reduction in walking speeds associated with Suit-2 ranged from 6% to 23.5% for heel angles ranging from 0° to 20°. The required donning time for Suit-2 was implemented within the assembly time of a hypothetical passenger ship by modifying a maritime evacuation simulation model (maritimeEXODUS). The results suggested that at 0° of heel during the day case scenario and donning Suit-2 (once passengers reached the assembly station) the assembly time was increased by 65%. In the corresponding night case scenario, the assembly time was increased by 38%. Clearly, this increases in assembly times in both day and night case scenarios are not accommodated within the 25% arbitrary safety factor introduced by IMO in the guideline for evacuation analysis of passenger ships.

Because there is no requirement in the Polar Code for the use of a specific type of survival suit, the type of survival suit on board different passenger vessels may vary. Regardless of the type of survival suit, there will be a time delay associated with the distribution of the survival suits during an evacuation scenario, and depending on the number of available distribution points, passengers may have to wait in line to receive their survival suit. This will undoubtedly cause a delay in the assembly process. Furthermore, the movement and heel of the passenger vessel could have an effect on the distribution and donning of the survival suits. While there is no data to show the effect of rolling or heel of the vessel on distribution and donning of TPIS, it is suggested that the measured donning time for Suit-2, which provides a conservative result, be used for simulation of evacuation in a passenger ship intended to operate in polar waters.

The simulation of a passenger ship evacuation also demonstrated that walking with the survival suit increases the travel time during the abandonment. Using a survival suit may also affect the boarding rate to a lifeboat. Passengers wearing the survival suit may require extra space in the lifeboat and encounter difficulty moving around to make room for other passengers who enter the lifeboat. There is currently no data available to shed light on the potential impact of wearing a survival suit on lifeboat embarkation, but obviously the increasing in the travel time of the passengers results in having less time for embarkation and launching the lifeboats. Therefore, having the shortest practicable travel distance from the assembly station to the lifeboats can enhance the evacuation performance of the passenger vessel.

6.4. Limitations and further work

As with any experimental study involving human test subjects, there are limitations associated with the work which should be considered when reviewing the results. The limitations of the experimental works in this thesis and possibilities of further research are identified as follows:

- In order to conduct the research in an ethical manner and to reduce the risk of injury to the participants, the experiment was conducted in a controlled environment and experimental protocol eliminated some factors, such as stress, darkness, slippery surfaces, dynamic motion, etc. which could have a detrimental impact on donning and walking performance of individuals. Furthermore, the physical space available to the participants during the donning trials was representative of the floor area per passenger required by international regulation. It is possible that in actual emergency situations, passengers may be in environments with less physical space which makes the donning difficult. Measurement of the donning and walking performance of the individuals while wearing a survival suit in an encumbered space and under the influence of motion or angle of inclination of the floor (i.e., positive and negative trim) is an interesting topic that requires further research.
- Prior to the start of the trial, participants were instructed to remove excessive clothing such as winter jackets, scarves or heavy jumpers. In reality, such extra warm clothing may be worn by passengers in real situations, not only making donning of the TPIS more difficult but also introduce some delay to the start of the donning by the individuals.
- All trial participants (who were aged from 18 to 72 years old) were in good health and physical condition. Thus, the sample population used in the trials may not be considered fully representative of the target population of a passenger vessel. While further research is required to include a wider cross-section of the public, the donning times measured in these trials and the impact of survival suits on the walking speeds may be considered to be optimistic. Therefore, the quantified donning time and reduction factors suggested in this thesis should be considered as minimum values until further research can be undertaken.
- As the trials (walking through the corridor) were conducted by a single participant at a time, the impact of group behaviours or contra-flows were not considered. This research focused on the collection of unimpeded walking speed data similar to that currently used in the guideline of evacuation analysis. Thus, the impact of group behaviours, while of importance, was considered beyond the scope of the current project and is left for further research.

Admittedly, 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. 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 modelling work in this thesis are identified as follows:

- The modelling scenarios investigated 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 in this thesis, the impact of the TPIS was identical regardless of whether the trim was positive or negative. However, in the simulations presented in this thesis, 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.
- 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. In reality, 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 distribute the TPIS.

- 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^{o} and 20^{o} of heel. As a result, only the walking time from the assembly station to the LSA was directly measured in the abandonment analysis. Thus, the impact of wearing TPIS on the abandonment phase can only partially be addressed. Quantifying the impact of wearing TPIS on the boarding rate of the LSA is suggested for further research.
- 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.

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Annex I – Paper I

Factors influencing the time required to don thermal protective immersion suits correctly

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Factors influencing the time required to don thermal protective immersion suits correctly

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A R T I C L E I N F O

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A B S T R A C T

The cold environment in polar regions introduces additional challenges when abandoning passenger vessels and offshore facilities. The International Maritime Organization Polar Code requires vessels operating in polar regions to be equipped with approved thermal protective immersion suits (TPIS) that can be donned unassisted within 120 s. As time is critical during an evacuation, quantifying the Net Donning Time (NDT) is important as this may need to be factored into passenger ship evacuation analysis. Furthermore, an incorrectly donned TPIS may be ineffective in providing the required thermal protection, so in addition to NDT, it is important to understand the factors that impact donning correctness. In this study, we present the results of a series of trials that quantified participants' performance while donning a TPIS with integrated buoyancy. Analysis of data from 108 participants revealed that NDT ranged from 65 to 341 s, with over 90 % requiring a total donning time of greater than 120 s. The mean NDT was dependent on a complex relationship between, age (increases by 6.6 % for each 10 years), gender (increases by 33 % if female), experience (decreases by 17 % with experience), method of instruction (increases by 21 % with video instruction) and failure to remove shoes (increases by 26 %). Furthermore, the method of instruction significantly impacted the number of donning errors, with instruction by video producing an average of 1.5 errors while written instruction producing 2.3. Finally, a donning time distribution is suggested for use in evacuation modelling analysis.

1. Introduction

Decreasing sea ice coverage in polar regions in recent times has resulted in a growth in the popularity of adventure cruises involving large passenger ships sailing in polar waters (Luck et al., 2010; Maher, 2017). The increase in ship traffic inevitably results in a higher probability of accidents or incidents involving these vessels in these challenging conditions (Khan et al., 2020). In light of this, and acknowledging the inadequacy of existing safety provisions for passenger ships operating in polar waters, the International Maritime Organization (IMO) introduced the Polar Code in 2017 (Polar Code, 2017). The Polar Code requires that passenger ships operating within polar waters are required where appropriate, to provide thermal protective clothing and 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 time required to gather the passengers in the assembly stations, the time required by passengers to don their TPIS, or the time available to move passengers from the assembly station to the life safety apparatus (LSA) and consequently abandon the vessel. Given that emergencies may occur on passenger ships in polar waters, and that passengers and crew are likely to be encumbered by TPIS it is important to know how the TPIS is likely to impact time-critical procedures and operations. In particular, how long does it take to don TPIS, and how does the wearing of TPIS impact the movement rates of passengers and crew? An essential design requirement of TPIS is that they can be quickly donned during an emergency. According to IMO (SOLAS) and International Organization of Standardization (ISO) requirements, TPIS must be unpacked, properly donned and secured without assistance within 120 s in ambient temperatures of $20 \pm 2^{\circ}C$ (ISO, 2012; SOLAS, 1998). Within this paper, the total time required to don the TPIS is referred to as the

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Total Donning Time (TDT). This includes the time associated with opening all packaging, removing the suit from the packaging and donning the suit. It is further noted that it is essential that the TPIS is correctly donned. A TPIS that is incorrectly donned can impact the effectiveness of the thermal protection and buoyancy offered by the suit and may also adversely impact the ability of the wearer to walk efficiently.

In most cases, apart from anecdotal information, or information from marketing materials, a rigorous evidence base characterising the impact of TPIS on human performance within maritime environments does not exist. Furthermore, quantifying TPIS donning time is critical for three reasons: (1) developing achievable evacuation procedures for passenger ships operating in polar waters, (2) enhancing the design of TPIS, and (3) modelling evacuation performance using ship-based evacuation models (Galea et al., 2013; Gwynne et al., 2003; Vassalos et al., 2002; Pradillon, 2004).

Since 2002 the IMO has published a set of guidelines for evacuation modelling associated with new and existing passenger ships (IMO-MSC/Circ., 1033). The human performance data specified in these guidelines are based on research associated with land-based scenarios such as walking speed data collected from the built environment, such as rail stations. As such, the human performance data implemented within maritime evacuation models do not incorporate the performance of individuals under conditions associated with maritime emergencies such as adverse vessel orientation (heel or trim) or conditions associated with extreme weather such as may be encountered in polar regions. However, within the guidelines the IMO invited the Member States to collect and submit information and data resulting from research and development activities on human behaviour associated with ship evacuation (IMO-MSC/Circ., 1533).

Implicit within the intent of the IMO Polar Code (Polar Code, 2017) and the associated ISO standards (ISO, 2012) is the requirement that the TPIS should not adversely impact passenger ship 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 normal walking speeds (ISO, 2012). However, thus far there is a lack of a substantive evidence base quantifying the impact of various types of TPIS on these parameters, and there is little understanding of the impact that the TPIS may have on evacuation performance within a maritime environment.

From the mid-1990s, the first ship evacuation models started to appear in the literature (Vassalos et al., 2002; Galea and Owen, 1994; Galea et al., 1998; Galea, 2000), and 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 protective clothing, such as lifejackets on walking speeds and passenger response times (Galea et al.). Interest in quantifying the performance of people resulted in two significant land-based studies with a major focus on the impact of the maritime environment on walking speeds. Both studies attempted to reproduce key aspects of the maritime environment using land-based simulators. Both studies occurred independently and at around the same time, 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). The TNO study made use of a modified shipping container on hydraulics to represent a ship corridor at various angles of heel and trim while the Canadian study made use of a purpose-built facility called SHEBA (Ship Evacuation Behaviour Assessment Facility) that could be heeled at various angles.

The SHEBA facility allowed measurements of human performance and behaviour in a typical ship passageway and stairway. Tests were conducted with participants with and without life jackets. While the SHEBA trials involved participants wearing lifejackets and collected data on donning of lifejackets (Glen, et al., 2003), none of the studies considered the impact of TPIS on the performance of individuals. More recently, several other lifejackets donning trials have been reported providing useful data concerning lifejacket donning times for infants and adults in full-scale studies (Brown et al., 2008; MacDonald et al., 2011).

One of the few studies concerning the donning of TPIS was conducted by Mallam et al. (2012). Their trials involved 32 test subjects (18 male and 14 female) with an average age of 22.9 ± 2.0 years, donning two different types of TPIS in both static and dynamic environments. The dynamic environment was created using an electric motion platform (2m $\times$ 2m) with six degrees of freedom. The two types of TPIS were randomly distributed among both genders such that each type of suite was donned by nine males and seven females. Each participant repeated the trials seven times using the same type of suit. Each participant received verbal instruction on how to don the TPIS and was also allowed 300 s to read the instruction sheet prior to attempting to don the suit. Participants could also read the instructions again during the rest period between each subsequent donning trial. Thus, the participants can be expected to be well briefed as to the donning procedures prior to the start of the trial. The average donning time, determined by analysis of video recordings, was found to vary between 90.1 s and 115.9 s depending on the type of suit. A key finding of this work was that there was a significant learning effect associated with repeated donning of the TPIS. However, unfortunately, the donning times and the correctness of donning for the first donning attempt of each suit was not reported, and so it is uncertain how long a time was required for the first donning of each suit or what level of correctness that was achieved. Furthermore, there are a number of other limitations associated with these trials that reduce the usefulness of the findings. For example, all the participants were in the early twenties and so unrepresentative of the broad cross-section of the population that may need to utilise the TPIS, the sample size was very small, participants were instructed to tie back long hair prior to the trial so as not to interfere with the donning process and finally, the TPIS used in the trials were not representative of the type of survival suit approved for evacuation in polar waters (Mallam et al., 2012; Mallam et al., 2014).

In another donning study, the effect of learning and training on the correctness of donning survival gear (immersion suits) was investigated using 536 seafarers (290 officers and 246 ratings). Less than 1 % of the donning trials involved an error relating to the correctness of donning. In this experiment, all participants had received the necessary safety training required to serve at sea (Sanli et al., 2019). As the participants in this study were trained professional seafarers, the results do not shed light on the performance of typical cruise or adventure cruise passengers.

To address this lack of maritime relevant data and amass an evidence base that can be used to assess the impact of TPIS on evacuation performance in polar regions, Wester Norway University of Applied Science (HVL) and The Arctic University of Norway (UiT) embarked on the ARCtic EVACuation (ARCEVAC) project. As part of the AREVAC project, two different types of TPIS were used in a series of experiments to assess their impact on walking speeds and quantify donning times and the factors that influenced donning times. The two TPIS differed significantly, one was a lightweight survival suit produced by Hansen Protection (Sea Pass passenger suit) (Brünig et al., 2021) and the other was an immersion suit with fully integrated buoyancy and thermal insulation produced by Viking (Yousafe Blizzard PS5002). The impact of TPIS on walking speeds of individuals along a corridor at four different angles of the heel (0°, 10°, 15° and 20°) has recently been reported in Azizpour et al. (2022).

The aim of this paper is to systematically explore TPIS donning time and correctness and the factors that influence these parameters. To explore these issues a series of donning trials are conducted with over 100 volunteers donning a buoyancy integrated immersion suit produced by Viking (Viking TPIS, see Fig. 1). In addition, the paper provides a quantification of the TDT for the Viking TPIS that can be used in evacuation modelling analysis for passenger ships in polar conditions.

(a) Viking TPIS (b) TPIS carry bag with instructions placard (c) TPIS in sealed plastic bag

Fig. 1. The Viking TPIS and its packaging.

2. Experimental procedure and data collection

To identify the factors influencing donning times and the correctness of donning and to quantify the TDT for the Viking TPIS a series of trials were conducted with volunteers recruited from the local community. This section describes the recruitment of participants, the TPIS used in the trials and the experimental procedures employed.

2.1. Trial participants

Trial participants were recruited through the local media, social media, word of mouth etc. Recruited participants were asked to complete a pre- and post-trial questionnaire that included questions related to demographical information and potential previous experience in donning TPIS. In total 108 volunteers (71 male and 37 female) aged between 18 and 72 years of age were recruited. Older participants were not allowed in order to reduce the risk of injuries if slipping. Other recruitment criteria were that participants should be in good health without any serious condition that could impair their movement or vision. The total number of participants in different age groups for males and females is presented in Table 1. Of the 108 participants, 59 stated that they did not have prior experience of donning TPIS. The rest of the participants (49 people) either claimed to have a previous experience with donning a survival suit or had donned another type of survival suit (Hansen TPIS (Brünig et al., 2021) prior to the trial (see Table 1). The average height and weight of the male group were 1.83 m (Standard Deviation (SD) = 0.06 m) and 84.1 kg (SD = 11.9 kg), respectively. The female group had an average height and weight of 1.67 m (SD = 0.05 m) and 68.3 kg (SD = 10.5 kg), respectively.

2.2. TPIS

The TPIS used in this study was supplied by Viking and is a buoyancy integrated immersion suit equipped with a thick layer of thermal insulation, satisfying the thermal requirements of the Polar Code (2017). This TPIS is a one size fits all suit, accommodating a wide array of body types and heights. The suit consists of integral foot coverings and a hood with non-integral but attached gloves. Rubber seals around the face and wrists are intended to prevent water ingress into the suit. The foot covering was equipped with rubber soles requiring the suit to be worn without shoes (Fig. 1.a). A total of 25 Viking TPIS were used in the trials, of which 14 were new (previously unused) and 11 were previously used, at least once. Each TPIS was stored in a zipped carry bag provided with the suit (see Fig. 1.b). The zipper of the carry bag extended over three sides of the carry bag. In addition, unused suits are sealed within a plastic bag within the carry bag (see Fig. 1.c). Once used by the first participants, suits were folded and placed inside the carry bags without the sealed plastic bag, ready for the next group of participants. We define the Net Donning Time (NDT) to be the time required to open the carry bag, extract the TPIS and don the suit (see Eq. (4) and Eq. (5) for details).

2.3. Trial procedures

The donning trials were conducted at two shore-based facilities, the ARCOS safety centre in Tromsø) and the ResQ safety centre in Haugesund. In total, 84 volunteers participated at the ARCOS safety centre and

Table 1
Arithmetic mean, minimum, and maximum NDT (s) for the different age groups of participants given their previous donning experience and method of instruction (number of participants shown in brackets).

		Mean, Min-Max and (Number of participants)						
Method of Instruction	Experience	18 – 19 Years of age		30 – 50 Years of age		≥51 Years of age		Total number
		Male	Female	Male	Female	Male	Female	
Written Instruction (WI)	No Experience (NE)	149.1 90.6–208.4 (25)	202.9 135 –335 (12)	221.4 164.4–341.1 (4)	185.6 142.6–210.6 (3)	201.7 125.4–278.1 (2)	187.2 187.2–187.2 (1)	47
	Experience (E)	122.7 64.7–265.6 (14)	145.7 110.6–224.6 (4)	139.4 77.4–249.3 (13)	198.4 106.9–235.4 (7)	109.4 93.2–125.6 (2)	209.7 167.9–251.5 (2)	42
Video Instruction (VI)	No Experience (NE)	156 101.9–221.3 (7)	315.5 315.5–315.5 (1)	N/A	177.5 172.4–182.6 (2)	165.1 165.1–165.1 (1)	365 365–365 (1)	12
	Experience (E)	N/A	179.8 179.8–179.8 (1)	170.3 146.7–193.9 (2)	185.8 111.8–259.7 (2)	112.3 112.3–112.3 (1)	201.7 201.7–201.7 (1)	7
Total number		46	18	19	11	6	8	108

24 at the ResQ safety centre. Full details concerning the trial procedures can be found in the Supplementary Materials (see *Sec*. S1), here we present a summary of the key details. Upon the arrival of the participants at the trial location, participants went through a registration process which included completing the pre-trial questionnaire and consent form, and participants were then given a group safety briefing. Participants were also instructed to remove coats and jackets and to leave all personal belongings behind prior to being escorted to the trial area.

The TPIS within its carry bag was placed on the floor in front of each participant. Participants were instructed to imagine that they were at sea on board a passenger ship sailing in polar waters and the evacuation alarm had just been sounded. The participants were told that they had to don the suit as quickly and as correctly as possible so that they would be ready to safely evacuate the vessel. The task would start once the instructor yelled “GO” and the end point was defined as the time that the participant raised their arms above their head.

Prior to starting the trials, a sub-group of randomly selected participants were shown a two-minute instructional video demonstrating the correct donning procedure. In total 19 participants were shown the video demonstration. This sub-group consisted of 10 male and 9 female participants aged between 18 and 72 years.

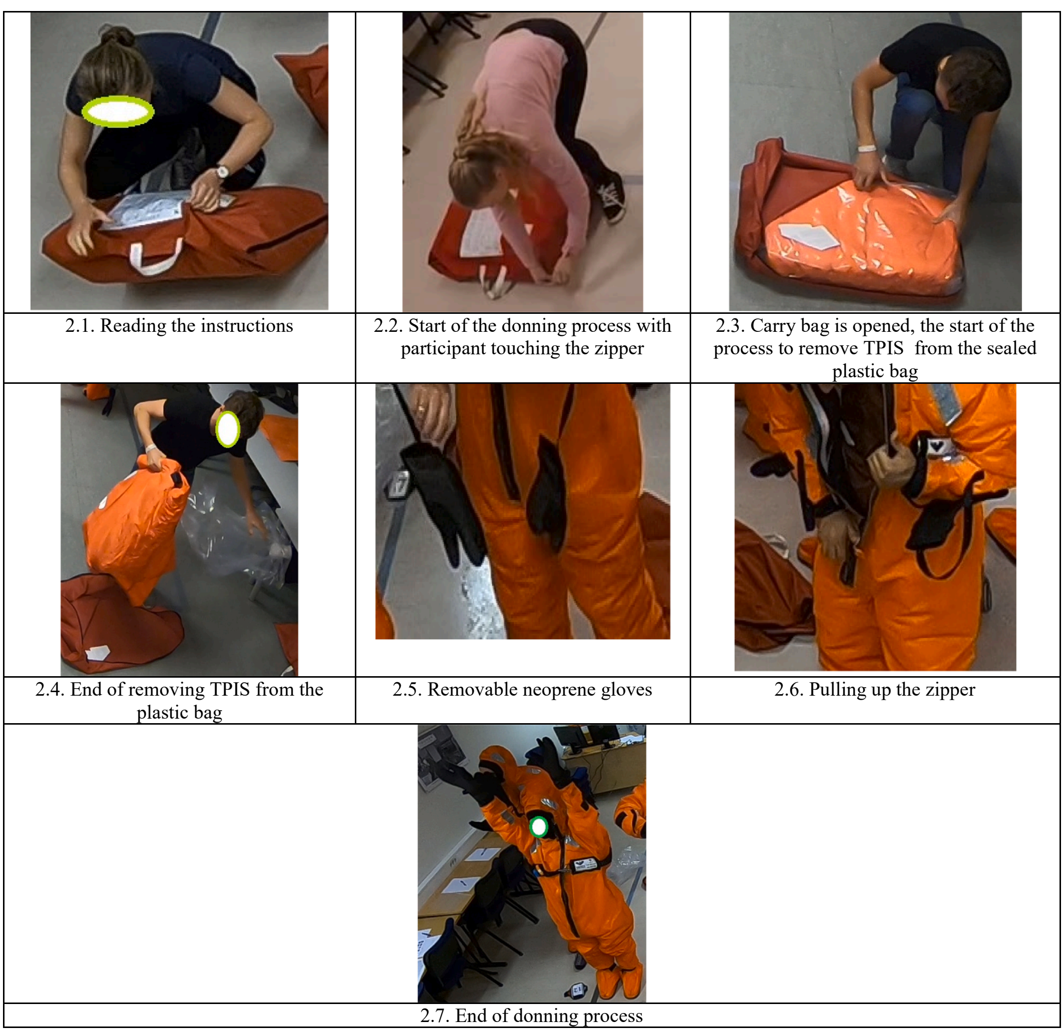
In addition, written instructions (provided by the manufacturer) were available to all participants through a laminated sheet located prominently on the suit carrying cover (Fig. 1.b and Supplementary Material *Sec*. S2). Participants were not permitted to read the instructions prior to the start of the trial. The participants’ donning performance was recorded throughout the donning trial using two GoPro Hero cameras (frame rate of 25 FPS). A range of quantitative and qualitative data was collected during the trials through video footage and questionnaires (see Supplementary Material *Sec*. S3). Quantitative data concerning donning correctness and speed of donning was collected through analysis of the video footage.

Presented in Fig. 2 are example frames extracted from the trial video footage highlighting important behaviours noted during the donning trials (additional information can be found in Supplementary Material Figure S2). The images demonstrate examples of participant behaviour as they read the instructions (Fig. 2.1), unpack the TPIS (Fig. 2.2 to Fig. 2.4) and attempt to don the suit (Fig. 2.5 to Fig. 2.7).

Prior to the start of the experiments, an application for ethical approval for the research was sent to the Norwegian Centre for Research Data (NSD). All appropriate measures were taken to ensure the safety and anonymity of participants. Participation in the trials was completely voluntary and the participants could withdraw from the trials at any time.

3. Results

In this section the main results from the data collection are summarised. This consists of data extracted from the video analysis supported by data extracted from trial questionnaires.



2.1. Reading the instructions

2.2. Start of the donning process with participant touching the zipper

2.3. Carry bag is opened, the start of the process to remove TPIS from the sealed plastic bag

2.4. End of removing TPIS from the plastic bag

2.5. Removable neoprene gloves

2.6. Pulling up the zipper

2.7. End of donning process

Fig. 2. Examples of key participant behaviours during donning trials.

3.1. Definition of variables

The controlled variables of primary interest consisted of:

- Demographic: primarily age and gender
- Experience: no previous donning experience (NE) or previous donning experience (E)
- Instruction method: written instruction only (WI) or video plus written instruction (VI)

Information relating to Demographic and Experience variables were quantified through analysis of the pre- and post-trial questionnaires. For the Experience variable, participants were asked if they had previously donned a TPIS. If they answered yes, they were considered experienced, irrespective of how long ago or how often they had undertaken the task. Participants were placed in one of the two Instruction categories at the start of the trial. As a main purpose of the trial was to establish a donning time distribution that could be used in evacuation modelling analysis, it was decided to focus on the minimum instructional method associated with just written instructions, and so most of the participants were placed in this category.

Observational parameters derived from the video analysis included; net donning times (NDT), preparation time (PT), extraction time (XT) and donning errors. These terms are further defined in this and subsequent sections. The process by which observational parameters were reliably and consistently extracted from video footage relied on the specification of a data dictionary and the precise definition of key parameters that were to be quantified. The definitions of key timed events as defined in the data dictionary are as follows:

(1) **Trial Start/End:**
(a) **Trial start time:** Time at which 'GO' command is heard on audio track (t_s).
(b) **Trial end time:** Time at which the participant has raised both hands to the highest level they could reach, indicating they were finished (see Fig. 2.7) (t_e).
(2) **Preparation phase:**
(a) **Start preparation:** Trial start time (see Fig. 2.1) (t_{sp}, note by definition, $t_{sp} = t_s$).
(b) **End preparation:** Time at which the participant disengaged from the preparation phase and engaged in the donning process by touching the zipper tracker in order to open the cover (see Fig. 2.2) (t_{ep}).
(3) **Extraction phase:**
(a) **Start extraction process:** Time at which the participant first touches the plastic bag with the intent to open it (once the cover is opened). (See Fig. 2.3) (t_{xs}).
(b) **End extraction process:** Time at which the participant has fully extracted the TPIS from the plastic bag (see Fig. 2.4) (t_{xe}).

Having defined these parameters, it is possible to determine the time required by each participant to undertake various tasks. These are defined as follows:

During the preparation phase, it is anticipated that participants will take some time to read the donning instructions which are available on the face of the package in the form of a large placard (see Fig. 1.b and Supplementary Material *Sec.* S2) prior to attempting to don the TPIS. The time spent during the preparation phase (PT) for each participant is defined as the time interval from the start of the trial (i.e., 1a) to the end of the participants preparation process (i.e., 2b), see Eq. (1).

$$PT = t_{ep} - t_s \tag{1}$$

The time required to extract the TPIS from the plastic bag (XT) for each participant is defined as the time interval from the start of the extraction process (i.e., 3a) to the end of the extraction process (i.e., 3b), see Eq. (2).

$$XT = t_{xe} - t_{xs} \tag{2}$$

The NDT for a participant with a used TPIS (NDT_{used}), i.e., suit not in a sealed plastic bag, is defined as the time interval from the end of their preparation phase (i.e., 2b) to their trial end time (i.e., 1b). The NDT_{used} can be determined for 94 participants and is given by Eq. (3).

$$NDT_{used} = t_e - t_{ep} \tag{3}$$

The NDT for a participant with a new TPIS (NDT_{new}), i.e., suit in a sealed plastic bag, is defined as the time interval from the end of their preparation phase (i.e., 2b) to their trial end time (i.e., 1b) less the XT time. The NDT_{new} can be determined for 14 participants and is given by Eq (4).

$$NDT_{new} = \left(t_e - t_{ep}\right) - XT \tag{4}$$

The Total Donning Time (TDT) for a participant with a used TPIS (TDT_{used}) is defined as the time interval from the trial start time (i.e., 1a) to their trial end time (i.e., 1b) plus the XT time. The TDT_{used} can be determined for 94 participants and is given by Eq. (5).

$$TDT_u = (t_e - t_s) + XT \tag{5}$$

Thus, the TDT includes the preparation time and a representation of the extraction time. Depending on the nature of the intended application, the XT can be represented by the mean XT, maximum XT or the XT distribution within Eq. (5).

The Total Donning Time (TDT) for a participant with a new TPIS (TDT_{new}) is defined as the time interval from the trial start time (i.e., 1a) to their trial end time (i.e., 1b). The TDT_{new} can be determined for 14 participants and is given by Eq. (6).

$$TDT_n = (t_e - t_s) \tag{6}$$

As the TDT_{new} inherently includes a measure of the actual extraction time achieved by each participant, there is no need to add the XT term to Eq. (6).

Finally, it is important to note that the NDT is a combined measure of two parameters, the time required to extract the TPIS from the zippered carry bag and the time required to don the TPIS. Thus, the NDT does not simply measure the inherent ease or difficulty associated with donning the TPIS. This is particularly important to keep in mind when attempting to compare the inherent donning performance of the TPIS described in this analysis with another TPIS design.

Throughout the video analysis, other behavioural data such as donning errors were quantified and recorded in the form of binary variables (Yes = 1, No = 0) (see *Sec.* 3.4). A randomly selected set of footage was analysed by two raters using the definition of variables provided in the data dictionary. The analysis was undertaken independently by the two raters to quantify key observational parameters (e.g., donning times, instruction times, opening times, etc.) and behavioural parameters. As part of the inter-rater assessment, video footage for 20 participants was analysed by the two raters and the results were compared using inter-rater analysis methods (McGraw and Wong, 1996; McHugh, 2012). Interclass Correlation Coefficient (ICC) was used to compare the measurements of durations and Kappa statistics were used for comparison of quantified behavioural variables. Results showed excellent agreement between raters with an average ICC value of 0.99 and a Kappa value of 0.85, respectively, for duration measurement and behavioural data. Analysis of the video footage for the Viking TPIS required approximately 63 person-hours of effort, 5076 data points were collected.

3.2. Net donning time

The donning data from 108 participants were collected from two different locations (see *Sec.* S1) thus, the possible influence of location on the NDT was assessed using a Mann-Whitney test. Results from the test did not indicate that the location of trials influenced the NDT (P-value = 0.23). Therefore, data from the two different locations were merged into one dataset. Descriptive statistics for NDT according to the different age groups, gender, experience and method of instruction are presented in Table 1.

Across all categories, the NDT for males varied from 64.7 s to 341.1 s (see Table 1), with an overall mean of 147.5 s while for females the NDT varied from 106.9 s to 364.9 s (see Table 1) with an overall mean of 198.9 s. Taken across all categories, this suggests that males were on average quicker in removing the TPIS from the zippered carry bag and donning the TPIS.

A distribution identification test, based on the Anderson-Darling goodness-of-fit test (Stephens et al., 1986), suggests that the NDT for both males and females was best represented by log-normal distributions. The Anderson-Darling test gave P-values of 0.42 and 0.64 for the male and the female group, respectively. As presented in Fig. 3, NDT can be represented by log-normal distributions with location (μ) and scale (σ) of 4.94 and 0.334 respectively for males and 5.25 and 0.297 respectively for females. The influence of age, gender, experience, and method of instruction on NDT is examined in detail in Section 4.3.

3.3. Preparation and extraction times

By definition, all participants spent some time during the preparation phase as defined by Eq. (1). This is the time interval between the trial start time and the participant purposefully touching the zipper to open the carry bag. Among all participants who did not receive the video instruction (i.e., the 89 participants in the WI group, see Table 1) the average time spent in the preparation phase prior to beginning to open the carry bag was 2.5 s ($SD = 5.2s$) with a range from approximately 1 s to a maximum of approximately 35 s.

For the 89 participants in the WI group, it is reasonable to assume that some or all of the 'preparation time' is spent reading the donning instructions. While there is a large amount of text on the instructions placard, the actual donning instructions consist of eight short bullet points and associated pictograms (see Supplementary Material *Sec*. S2). Thus, once the appropriate text is identified on the placard, the donning instructions would not require much time to read but may require more time to correctly interpret. The time spent in the preparation phase (PT) for the 89 participants in the WI group is distributed as shown in Fig. 4.a. A Mann-Whitney test did not show significant differences in PT time based on gender (P-value = 0.62).

As can be seen in Fig. 4.a. some 14 (16 %) participants had an extended preparation time (i.e., greater than 2 s). Given this large tail, it is difficult to represent the PT distribution using a continuous mathematical expression. Thus, two expressions are used to describe PT distribution. The long tail of the PT distribution is reasonably well described using a log-normal distribution (P-value = 0.75) with the location (μ) and scale (σ) respectively 2.35 and 0.56.

By taking an average preparation time of 1 s for participants without extended preparation time and assuming that the additional time for those with extended preparation time (16 %) follows a log-normal distribution, the PT distribution for the 89 participants in the WI group can be approximated by Eq. (7).

$$PT = 1 + U * X \tag{7}$$

where $U \sim \text{Bernoulli}(0.16)$ and $X \sim \text{Log-normal}(2.35, 0.56)$

Using this formulation, each person is allocated a 1 s PT and 16 % have an additional PT derived randomly from the log-normal distribution (X).

Finally, as 14 new suits were available during the trial, 14 (eight males and six females) participants were engaged in the extraction phase, where the TPIS had to be removed from the sealed plastic bag. The duration of the extraction phase (i.e., XT as defined by Eq. (2)) varied from 9.8 s to 31.5 s, with a mean of 19.4 s (SD = 7 s). A Mann-Whitney test did not show that the mean XT was significantly different between the male and female groups (P-value = 0.33). The XT was not significantly different from the log-normal distribution (P-value = 0.06) and should be a reasonable choice for modelling purposes (though a distribution fit is in any case deemed to be uncertain with such small sample size). The time spent in the extraction phase (XT) by the 14 participants who had new suits is distributed as shown in Fig. 5. The XT distribution can be approximated by a log-normal distribution and is given by Eq. (8).

$$XT = Log - normal(2.9, 0.39) \tag{8}$$

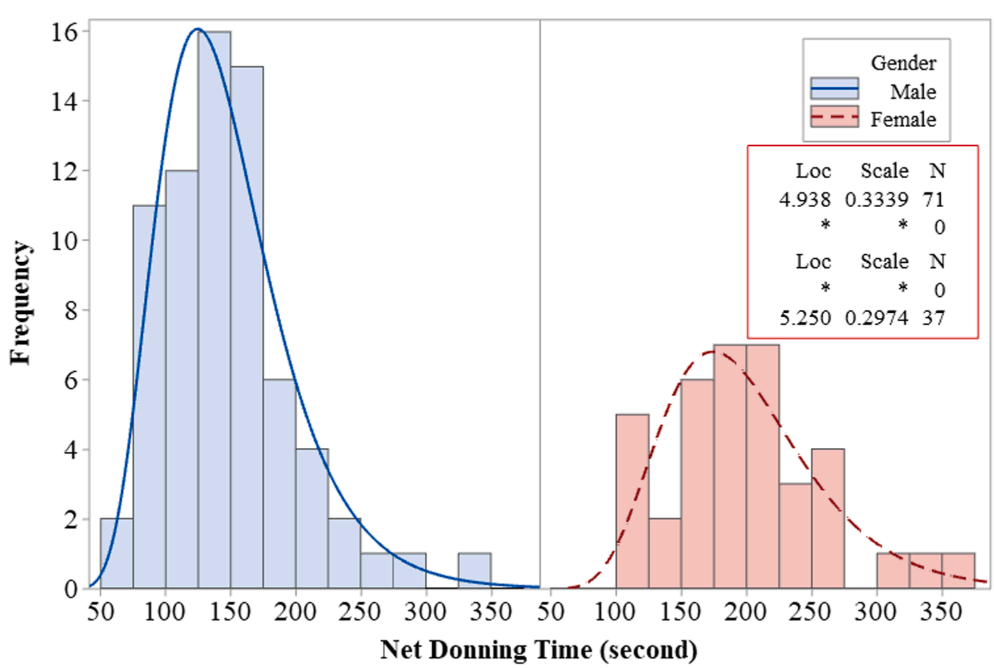
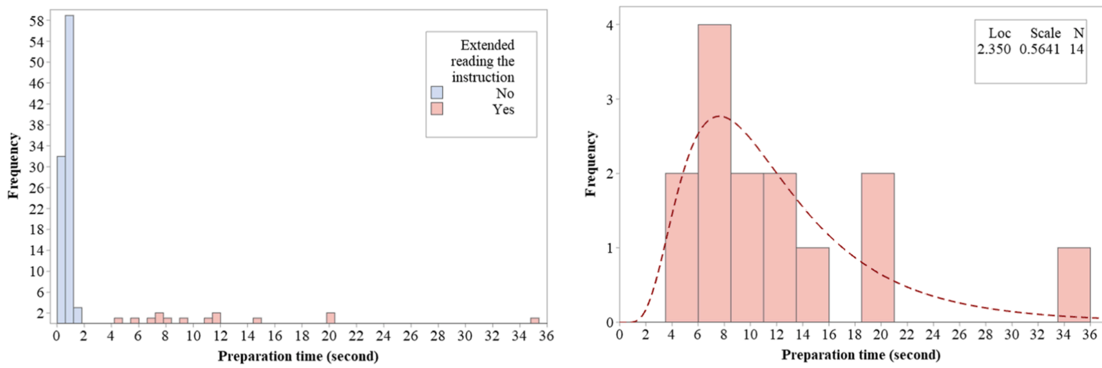


Fig. 3. Distribution of NDT for both male and female groups.



(a) PT distribution (89 participants)

(b) PT distribution for participants with extended preparation times (14 participants)

Fig. 4. Preparation of all (a) and preparation with extended reading (b) time distribution.

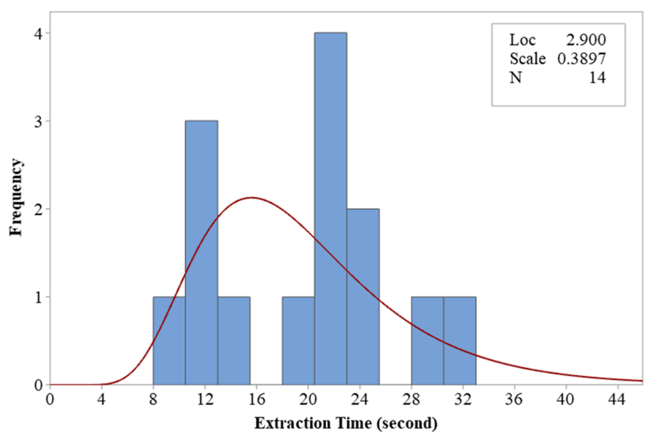


Fig. 5. Extraction time (XT) distribution (14 participants).

3.4. Donning errors

The number of donning errors incurred by each participant was also evaluated. A donning error was defined as a key feature of the donning process that was not correctly completed by the participant. These features were based on the checklist of features identified by the TPIS manufacturer and indicated on the laminated instructions appearing on the suit carry case (see Fig. 1.b and Supplementary Material *Sec.* S2). Donning errors are associated with seven key donning features as shown in Table 2. To be classed as a donning error, the donning feature must be in a final state other than the correct final state identified in Table 2.

Throughout the video analysis, correctness of donning of all items listed in Table 2 was checked/quantified for each participant using a binary variable (Incorrect/No = 0, Correct/Yes = 1). The Error Count (number) for each participant was defined as a metric to investigate the correctness of donning. An 'Error Count' of zero indicates that the participant donned the TPIS correctly with no errors, while an 'Error Count' of seven denotes that the participant made seven errors during donning. The error metric did not distinguish between the different types of errors listed in Table 2.

Table 2
List of key donning features and their correct final state.

#	Key donning feature	Definition of correct state
1	Shoes	Shoes should be removed prior to donning suit
2	Hood (see Fig. 1.a and Fig. 2.7)	Hood should be pulled over the head covering the entire head
3	Ankle straps (see Fig. 1.a)	Both ankle straps should be securely fastened
4	Interior length straps	Both interior length straps should be adjusting to ensure suit legs are not to baggy
5	Zipper (see Fig. 2.6)	The zipper should be pulled up all the way past the chin
6	Chest buckle	The chest buckle must be fastened
7	Gloves (see Fig. 2.5)	Both gloves should be worn

As shown in Table 3, the 108 participants incurred a total of 234 donning errors, 158 by male (of which there are 71) and 76 by female (of which there are 37) participants. On average, males incurred 2.2 donning errors while females incurred 2.0, and experience and video instruction decreased the mean number for donning errors. Presented in Fig. 6 is a pie chart showing the frequency of each donning error.

The least number of donning errors was associated with the hood and gloves, representing only 0.4 % (1) and 0.9 % (2), respectively, of the total number of errors (see Fig. 6). Only 0.9 % and 1.8 %, respectively, of the population donned these suit components incorrectly. Participants with very long hair appeared to require longer time to ensure that their hair was within the hood, and this was confirmed by participants in their post-trial questionnaire (see Supplementary Material *Sec.* S3).

The next most frequent donning error concerned the fastening of the ankle strap, representing 6 % (14) of the total number of errors (see Fig. 6). Given the universal size (one size fits all) of the TPIS, the ankle strap is necessary to secure that the shoe of the TPIS remains in place on the wearers foot. In total 13 % (9) of men and 14 % (5) of women failed to fasten the ankle straps. The next most frequent donning error, representing 8.1 % of the total number of errors, involved the zipper (see Fig. 6). When the zipper is correctly pulled up over the chin it creates a waterproof seal, however participants struggled with pulling the zipper above the neck and chin. Approximately 11 % (8) of males and 30 % of females (11) struggled with this task.

The third most frequent donning error, representing 22.6 % of the total errors (see Fig. 6) concerned the lifting harness (chest buckle). This is designed to aid the retrieval of an individual from water. If the lifting harness is not buckled up it is more difficult to rescue passengers that have fallen into the water. Only 46 % (33) of males and 59 % (22) of females had buckled up their lifting harness when donning was completed. The second most common donning error, representing 23.1 % of the total errors (see Fig. 6), was associated with failing to remove shoes prior to donning. More than half the males (54 % i.e., 38) and 43 % (16) of females failed to remove their shoes. The most frequent donning error, representing 38.9 % of the total errors (see Fig. 6), was failure to adjust the length straps. These straps are intended to compensate for the universal size of the TPIS. The length straps, one located on each side, adjust the length of the TPIS, lifting the gusset and bunching up excess fabric in the legs and upper body area. Some 88 % (63) of men and 76 % (28) of women failed to adjust these.

Presented in Fig. 7 is the distribution of the number of donning errors incurred by participants from the male and female groups. For each

Table 3
Descriptive statistics for donning errors according to different methods of instruction and experience.

Method of Instruction	Experience	(Number of errors) / (Number of people)	Average number of errors / person	Mode of errors per person	Number of occurrence of mode	Min number of errors per person	Max number of errors per person	Number of people
Written Instruction (WI)	No Experience (NE)	118/47	2.5	3	18	0	5	47
	Experience (E)	87/42	2.1	2	17	0	4	42
Video Instruction (VI)	NoExperience (NE)	19/12	1.6	2	7	1	2	12
	Experience (E)	10/7	1.4	1	4	1	2	7
Total		**234/108**	**2.2**	**2**	**44**	**0**	**5**	**108**

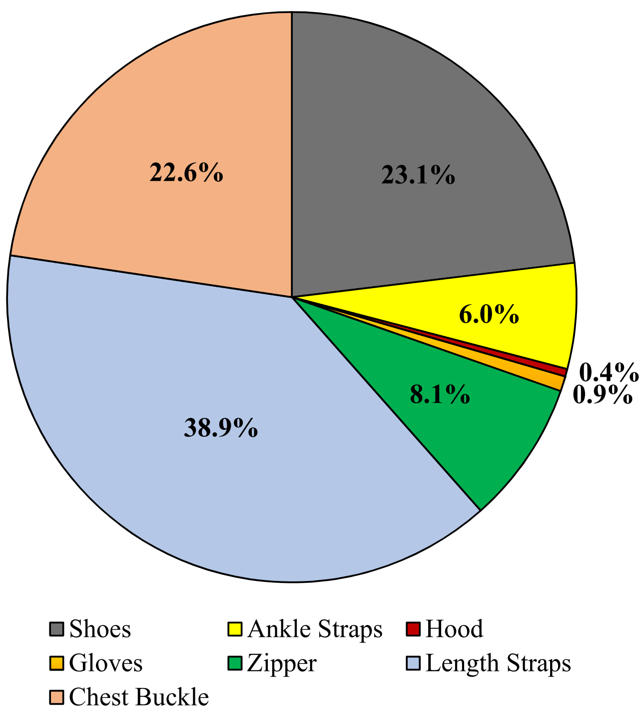


Fig. 6. Frequency for each type of donning error.

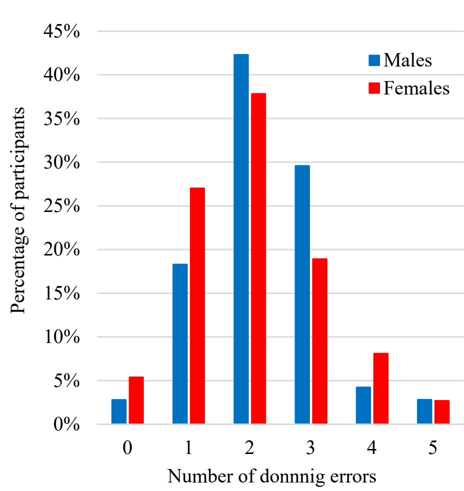


Fig. 7. Percentage of male and female participants committing a given number of donning errors.

participant the number of donning errors varies from 0 to 5 for both males and females, with the most common number of errors being 2 for both males and females.

4. Identification of factors impacting number of donning errors and NDT using regression modelling

In this section a regression model is developed to explore which parameters are most influential in impacting NDT and the number of donning errors and the nature of the interaction. All the regression analysis was performed using Minitab (version 19.2) and a significance level of 0.05 is used in all statistical inferences.

4.1. Regression models

4.1.1. Poisson regression

Poisson regression (Hoffmann, 2016) can be used to predict a dependent variable that are counts (e.g., number of donning errors) following a Poisson distribution given one or more independent variables or predictors. Let $Y \sim \text{Poisson}(\mu_Y)$ denote the number of donning errors following a Poisson distribution with expected number of donning errors given by μ_Y. In order to avoid negative values of μ_Y, one assumes that there is a log-linear relationship between μ_Y and the predictors x_i, $i = 1, \dots, n$, in the following way:

$$Ln(\mu_Y) = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n \tag{9}$$

By exponentiation of Eq. (9) we have:

$$\mu_Y = e^{a_0} * e^{a_1x_1} * e^{a_2x_2} * \dots * e^{a_nx_n} = A_0 * A_1^{x_1} * A_2^{x_2} * \dots * A_n^{x_n} \tag{10}$$

In the Poisson regression model, each 1-unit increase in the predictor x_i multiplies the expected value of Y by $e^{a_i} = A_i$. Here A_i can be interpreted as a growth factor, and $A_i - 1$ gives the relative increase in expected number of donning errors per unit increase of x_i (all other factors being kept constant).

4.1.2. Log-linear regression

The potential impact of various predictors on the NDT was investigated using a log-linear regression model by log transforming the NDT (as a response factor) in a general linear regression model (Levine et al., 2001). If the response variable (i.e., NDT) is log-transformed, the effect of any predictor in a linear regression model would be a percentage-wise reduction or increase in the NDT. A log-linear multiple regression model for response variable Z (i.e., NDT) and predictors x_i can generically be represented as follows:

$$Ln(Z) = b_0 + b_1x_1 + b_2x_2 + \dots + \varepsilon, \varepsilon \sim Normal(0, \sigma) \tag{11}$$

By exponentiation of Eq. (11) we have:

$$Z = e^{b_0} * e^{b_1 x_1} * e^{b_2 x_2} * \cdots * e^{\varepsilon} = B_0 * B_1^{x_1} * B_2^{x_2} * \cdots * \widetilde{\varepsilon}, \quad \widetilde{\varepsilon} \sim Log - normal(0, \sigma) \tag{12}$$

In the log-linear regression model, each 1-unit increase in the predictor x_i multiplies the expected value of Z by $e^{b_i} = B_i$. Here B_i can be interpreted as a growth factor, and $B_i - 1$ gives the relative increase in NDT per unit increase of x_i (all other factors being kept constant).

4.2. Factors influencing the number of donning errors

A Poisson regression analysis (see *Sec.* 4.1.1) was undertaken to explore the impact of predictor parameters on the expected average number of donning errors (ADE $= \mu_Y$). The predictor parameters explored in the regression analysis are preparation time (x_1), method of instruction (x_2), experience (x_3), gender (x_4) and age (x_5). The definition and state of the predictor variables are presented in Table 4. Note that video instruction (VI) is an abbreviation of video with written instruction, i.e., these participants had access to both forms of instruction.

In addition to the predictor parameters identified in Table 4, potential interactions between the parameters were also considered through the introduction of interaction terms such as method of instruction and donning experience ($x_2 \times x_3$). According to the results of the stepwise Poisson regression, only the x_1, x_2 and x_3 predictor parameters were found to be significant, while none of the interaction terms turned out to be significant ($R^2 = 25.4$ %). As a result, the expected average number of donning errors can be estimated by:

$$ADE = 2.81 * 0.96^{x_1} * 0.59^{x_2} * 0.73^{x_3} \tag{13}$$

Presented in Table 5 are the coefficients, standard errors and P-values for the significant predictor parameters in Eq. (13). Also presented is the expected change in predicted ADE per unit increase in predictor parameter.

From Table 5, 'method of instruction' (x_2) is predicted to have the greatest impact on the ADE, followed by 'experience' and then 'PT'. From Eq. (13), a group of people exposed to written instruction only ($x_2 = 0$), without previous donning experience ($x_3 = 0$) and a PT of 0 s (i.e., no time to read instructions) are expected to incur an average of 2.8 donning errors (ADE $= 2.81 * 1 = 2.81$ from Eq. (13)). However, if the same group has a PT of 10 s (i.e., has more available time to read the instructions), then they are expected to incur an average of 1.9 donning errors (ADE $= 2.81 * 0.96^{10} = 1.9$). Thus, for inexperienced persons exposed only to written instructions, the average number of donning errors is predicted to decrease by approximately 33 % for every 10 s of preparation time.

Presented in Fig. 8 is a plot of the expected ADE (Eq. (13)) for participants with different types of instruction as a function of preparation time. However, it should be noted that only a single participant had a PT as high as 35 s, but any test intended to confirm how representative this data point is would be very uncertain due to the small sample size. If this PT is considered an outlier and excluded from the analysis, then the P-value for PT increases from 0.02 (i.e., a significant result) to 0.09 (i.e., not a significant result). Thus, while it may be argued that intuitively it would be expected that PT would exert a significant impact on the expected number of donning errors, the analysis presented here is not conclusive and would benefit from additional data.

Table 4
Definition of predictor parameters examined in the regression analysis.

Predictor Parameter	Definition	State	
x_1	Preparation Time (s)	0 – 35 s	
x_2	Method of Instruction	1 = Video Instruction (VI)	0 = Written Instruction (WI)
x_3	Experience	1 = Yes (E)	0 = No (NE)
x_4	Gender	1 = Female	0 = Male
x_5	Age (years)	18 to 72 years	

Table 5
Contributing factors and change in the ADE given one unit increase in each of the influencing variables (when all other variables are fixed).

Variable	Coefficient	Standard Error of Coefficient	$A_i = e^{a_i x_i}$	Change in the ADE per unit increase of x_i	P-value
x_1	−0.044	0.02	0.96	Approximately −4% per second preparation time	0.023
x_2	−0.52	0.2	0.59	−41 % with receiving video instruction	0.009
x_3	−0.32	0.15	0.73	−27 % with having previous donning experience	0.03

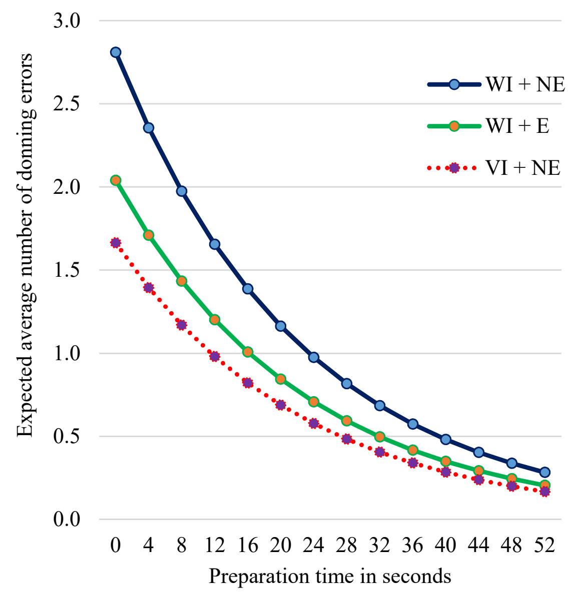


Fig. 8. Predicted average number of donning errors as a function of preparation time for various methods of instruction and experience.

As can be seen from Fig. 8, for a given preparation time those with WI and no experience always produce more errors on average than those with VI and no experience. The WI and experience group fall between the two. To produce an average of one donning error, those with WI and no experience require a preparation time of 23 s, those with WI and experience require on average a preparation time of 16 s, while those with VI and no experience require a mean preparation time of 12 s. When interpreting Fig. 8, it should be noted that the maximum recorded preparation time was approximately 35 s. Furthermore, for the VI group none of the participants has a preparation time of greater than 2 s and so the curve is essentially a model extrapolation (hence shown as a dashed line).

4.3. Factors influencing NDT

As with the donning errors, a variety of parameters such as age, gender, method of instruction, etc may influence donning performance of individuals. Here, we explore the potential impact of the control variables (i.e., age, gender, height, weight, previous donning experience, video instruction) (see *Sec.* 3.1) and a selection of the observed variables (such as taking the shoes off prior to donning, number of donning errors including and excluding the error associated with the taking off the shoes at the beginning, duration of preparation time) on the NDT (response variable) using a log-linear regression model. The purpose of the modelling in this section is not to predict or quantify the NDT for modelling application, but to analyse the postulated impact of all aforementioned factors on donning performance of individuals. More generally, the regression analysis is used to understand the interrelation between the different variables. A recommended expression to predict NDT for modelling application is presented in Section 5.4.

As in the donning errors analysis (see *Sec*. 4.2), the five predictor parameters of preparation time (x_1), method of instruction (x_2), experience (x_3), age (x_4), and gender (x_5) were considered (see Table 4). In addition, the observational variable, 'failure to remove shoes prior to donning' (x_6) was included. This parameter was included in the analysis as it was noted from the video analysis that if participants did not remove their shoes prior to donning the suit, they tended to struggle with their inserted foot getting stuck in the suit's thigh, thereby extending their donning time. If $x_6 = 1$, i.e., YES, then shoes were not removed and if $x_6 = 0$, i.e., NO, then shoes were removed prior to donning.

First, the donning data from the participants without previous experience (59 people) was considered within the regression model. Thus, the parameters investigated were those identified above, excluding the x_3 parameter, and we call this Model 1. As in the donning error analysis, potential interactions between the parameters were also considered.

The regression analysis suggests that gender (x_4) strongly impacts the average NDT, with being female increasing the expected average NDT by 29 %. However, apart from gender (x_4), none of the parameters were found to significantly influence the average NDT (see Table 6) producing a model with an R^2 of 25.5 %. While not significant, age (x_5), preparation time (x_1) and video instruction ($x_2 = 1$) were found to potentially increase the average NDT. The result concerning preparation time and video instruction may appear surprising as it is expected that having more preparation time and having video instruction would better equip the participants to don the suit faster and so we could expect that the average NDT would decrease rather than increase. However, as shown in *Sec*. 4.2, both preparation time and video instruction tend to decrease the number of donning errors. If participants perform fewer donning errors, it is possible that the NDT increases (as suggested by the regression models) as participants correctly undertake all the tasks required to correctly don the suit. The one exception is the donning error associated with (not) removing shoes prior to donning. As stated previously, from analysis of the video footage, participants who did not remove their shoes prior to donning struggled with the donning process increasing their NDT. Thus, as noted in the regression model if $x_6 = 1$ (shoes not removed), the average NDT increases by approximately 16 % (see Table 6). The positive correlation between age (x_5) and expected average NDT is to be expected. The regression analysis suggests that expected average NDT increases by 6 % for every 10-year increase in age. Donning the suit is a strenuous physical activity requiring a certain amount of flexibility and so it is expected that donning time will generally increase with age.

To increase the power of the analysis, the data associated with the experience parameter (x_3) was included in the regression model, which we call Model 2. This increased the number of data points from 59 to 108. With the increased data set, all the parameters, with the exception of preparation time (x_1) are now found to significantly impact the average NDT (see Table 7). Furthermore, the impact of each variable on the expected average NDT has also increased. However, the results show that only experience (x_3) significantly reduces the expected average NDT. Having previous donning experience reduced the expected average NDT by about 17 %. Thus, these results are consistent with earlier findings (Mallam et al., 2012) that suggest that experience tends to reduce the expected donning time. However, unlike the previous studies, the current study has quantified the potential impact of experience on donning time.

All other parameters tended to increase the expected average NDT, being female ($x_4 = 1$) by 33 %, failure to remove shoes ($x_6 = 1$) by 26 %, video instruction ($x_2 = 1$) by 21 %, preparation time (x_1) by 11 % for every 10 s and age (x_5) by 6.6 % for each 10 years increase in age. However, it is noted that preparation time was not found to be significant, with a P-value of 0.07 (see Table 7). Other factors such as height, weight, and cross-product terms representing potential interactions between the parameters were not found to have a significant impact on the NDT.

The resultant log-linear regression model describing the NDT is presented in Eq. (14) and can predict approximately 37 % of the variation in the NDT ($R^2 = 37.0$ %). The parameters in Eq. (14) are defined in Table 7.

$$NDT = 105.2 * 1.011^{x_1} * 1.21^{x_2} * 0.83^{x_3} * 1.33^{x_4} * 1.0064^{x_5} * 1.26^{x_6} * \tilde{\varepsilon} \tag{14}$$

where $\tilde{\varepsilon} \sim Log\text{-}normal.(0, 0.29)$

5. Discussion

The analysis presented in *Sec*. 4 identified the main factors influencing the number of donning errors (ADE, see *Sec*. 4.2) and the net donning time (NDT, see *Sec*. 4.3). In this section the impact of these relations is discussed.

5.1. Factors influencing the number of donning errors

Donning errors (see *Sec*. 3.4) can have a range of detrimental effects on the safety of the person wearing the TPIS. Some donning errors (related to hood, zipper and gloves) can reduce the effectiveness of the thermal protection provided by the suit, reducing the survival time offered by the TPIS. Some donning errors (related to ankle and interior straps) may make it more difficult to walk, increasing the time required to reach a place of safety or potentially causing trips and falls. Some donning errors (related to shoes) may make it more difficult to don the TPIS, reducing the time available to reach a place of safety. Thus, multiple donning errors have an accumulative effect on reducing safety and so should ideally be eliminated completely, or at the very least, reduced in frequency by the population and absolute number incurred by individuals.

Table 6
Model 1: Definition of contributing factors and change in the NDT of the inexperienced participants, given one unit increase in each of the influencing variables (when all other variables are fixed).

Variable	Definition (Unit)	Coefficient	Standard Error of Coefficient	$A_i = e^{a_i}$	Change in the mean NDT per unit increase of x_i	P-value
x_1	Preparation time (seconds)	0.0054	0.0073	1.005	About + 5 % for every 10 s of preparation	0.46
x_2	Method of instruction $x_2 \in \{VI = 1, WI = 0\}$	0.13	0.11	1.14	About + 14 % with receiving VI	0.23
x_4	Gender $x_4 \in \{Male = 0, Female = 1\}$	0.25	0.076	1.29	About + 29 % longer donning time for females	0.002
x_5	Age $x_5 \in (18 - 72\,\text{year old})$	0.0060	0.0032	1.0060	+6% per every 10-year increase in age	0.07
x_6	Failure to remove shoes prior to donning $x_6 \in \{Yes = 1, No = 0\}$	0.15	0.092	1.16	About + 16 % increase in donning time with NOT removing shoes prior to donning	0.11

Table 7
Model 2: Definition of contributing factors and change in the NDT given one unit increase in each of the influencing variables (when all other variables are fixed).

Variable	Definition (Unit)	Coefficient	Standard Error of Coefficient	$A_i = e^{a_i}$	Change in the mean NDT per unit increase of x_i	P-value
x_1	Preparation time (seconds)	0.011	0.0061	1.011	About + 11 % for every 10 s of preparation	0.07
x_2	Method of instruction $x_2 \in \{\mathrm{VI}=1, \mathrm{WI}=0\}$	0.19	0.085	1.21	About + 21 % with receiving VI	0.03
x_3	Experience $x_3 \in \{\mathrm{Yes}=1, \mathrm{No}=0\}$	−0.19	0.060	0.83	About −17 % reduction in donning time with having previous experience	0.002
x_4	Gender $x_4 \in \{\mathrm{Male}=0, \mathrm{Female}=1\}$	0.29	0.060	1.33	About + 33 % longer donning time for females	<0.001
x_5	Age $x_5 \in (18-72\,\mathrm{year\ old})$	0.0064	0.0025	1.0064	+6.6 % per every 10-year increase in age	0.01
x_6	Failure to remove shoes prior to donning $x_6 \in \{\mathrm{Yes}=1, \mathrm{No}=0\}$	0.23	0.066	1.26	About + 26 % increase in donning time with NOT removing shoes prior to donning	0.001

From Section 3.4 the number of donning errors incurred by an individual ranged from 1 to 5 with an average of 2.2 for the 108 participants. Clearly, it is desirable to reduce the average number of errors committed during the donning process, and so it is essential to determine the factors that influence donning errors. A Poisson regression model was used to investigate the potential influence of all the background (demographic, experience), randomized (instruction method), and observed (NDT, instruction reading times and extraction times) variables on donning errors.

Results of the Poisson regression suggest that of all the variables considered, three appeared to significantly impact the number of donning errors. These were, preparation time, method of instruction (see *Sec*. 4.3) and previous donning experience, producing P-values of 0.02, 0.009 and 0.03, respectively. Fig. 9 presents the histogram of donning errors for four groups of participants according to the type of instruction they received and their previous experience of donning. As shown in Fig. 9 and supported by Fig. 8, VI appears to be the most effective instruction methodology, producing an average of 1.5 donning errors amongst the 19 participants who had VI, compared to an average of 2.3 donning errors for the 89 participants who had WI. Furthermore, participants who received VI made a maximum of two donning errors while those that received WI made up to five errors (see Fig. 9). Of secondary importance, but still of significance is experience (E). As seen in Fig. 9 and again supported by Fig. 8, E also appears to reduce the number of errors. The average number of donning errors for those with no experience (NE), irrespective of instruction methodology, is 2.3 (59 participants) compared with 1.98 (49 participants) for those with E. Experience has a smaller impact on the propensity to generate errors than method of instruction. For those with WI, the maximum number of errors for those with NE and E decreases from 5 to 4 while the average decreases from 2.5 to 2.1. Similarly, for VI, the maximum remains unchanged at 2 and the average changes from 1.58 to 1.42 for NE and E. Thus, as with the expected donning time (see *Sec*. 4.3) these results are consistent with earlier findings (Mallam et al., 2012; Sanli et al., 2019) that suggest that experience tends to reduce the expected number of donning errors. However, unlike the previous studies, the current study has quantified the potential impact of experience on donning correctness.

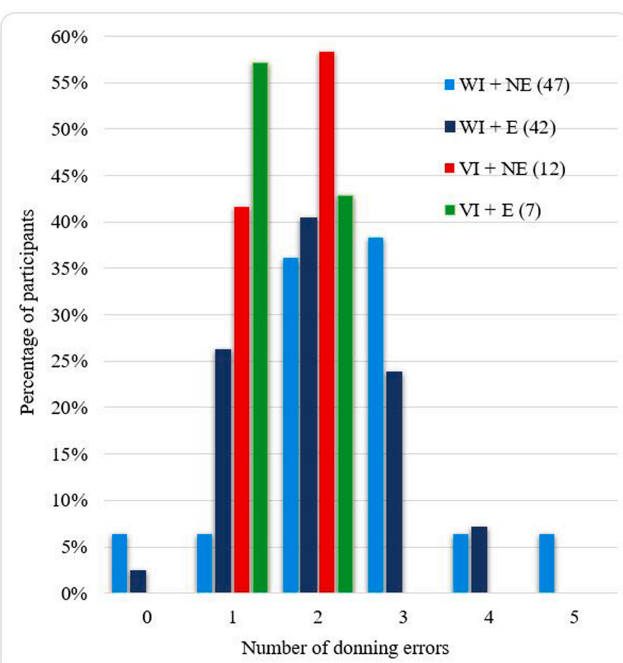


Fig. 9. Histogram of number of donning errors for participants according to instruction method and experience.

It is noted that the impact of experience in this study may be masked by how the experience was defined and measured. The quality, frequency and how recent the experience was gained is not represented in the current study. So, the experience claimed by participants could have been donning a similar TPIS, once 20 years ago, or once in the previous week, or every day throughout a person's sea going career. Furthermore, within this study, all would have been considered equivalent. These factors are likely to influence the effectiveness of the experience but are not considered within this study.

Thus, the impact of experience identified in this study can be considered indicative at best. In reality, experience may have a more profound effect depending on the nature of the experience. This is particularly important when considering utilising the presented data and correlations to represent the performance of mariners/crew regularly trained in donning TPIS. However, one of the prime motivations of this study was to determine the factors that impact donning correctness and time, and clearly experience is an important influential factor for both. However, another motivation of this study was to quantify the expected donning time for the TPIS, and this is further described in Section 5.5.2.

5.2. Importance of the donning error associated with shoe removal

The NDT is a key parameter of interest as the time required to don the TPIS may directly impact the amount of time available for passengers to reach a place of safety. In time critical evacuation situations, the longer it takes to don the TPIS, potentially the shorter is the time available to reach a place of safety. Thus, factors that tend to increase the NDT should be avoided and their number minimised. While most donning errors tend to decrease the NDT – as they usually result in some key donning function not being completed – neglecting to remove shoes prior to donning tends to increase the NDT due to the inherent difficulty of the resulting donning process while wearing shoes. From the video analysis it is known that 50 % of the participants (54 participants out of total 108) failed to remove their shoes prior to the first donning attempt (see Fig. 6). Furthermore, as shown in *Sec*. 4.3, failing to remove shoes prior to donning increases the average NDT by approximately 26 %.

The primary factors that influence this particular donning error are expected to be method of instruction and experience. Analysis of the donning video footage reveals that 100 % (19) of participants with VI and 52 % (22 out of 42) of those with previous experience in the WI group removed their shoes prior to the donning process. However, just approximately 30 % (14 out of 47) of those in the WI group with NE removed their shoes prior to the donning process. It is also expected that the duration of the preparation time is likely to impact whether or not the shoes are removed prior to donning, however, this cannot be determined easily from the basic frequencies. Nevertheless, it is important to identify procedural measures that can reduce the frequency of this donning error, in particular when dealing with those with NE and when relying on written instructions of the type associated with the tested TPIS.

To quantify the impact of background and randomised variables (see Table 4) on the probability of removing shoes (PRS), binary logistic regression (Hoffmann, 2016) was used (see Supplementary Material *Sec.* S4). The analysis reveals that only the preparation time, PT (x_1), method of instruction (x_2) and experience (x_3) were found to be significant. Furthermore, as previously suggested, VI had the most significant influence on PRS while E was the second most significant variable.

The PRS for the WI + NE group is considerably smaller than that for the VI + NE group with PT of up to 20 s. The PRS for the VI + NE group, even with PT = 0 s is 91 %, while that for the WI + NE group is just 22 %. If the PT is increased to 20 s, the PRS for the WI + NE group is just 85 %. While having experience improves the PRS for the WI group, the improvement is small and decreases as PT increases, furthermore, the impact of experience is even smaller for the VI group. Analysis also suggests that to achieve a 95 % probability of removing their shoes, the WI + NE group require a PT of at least 28 s, whereas the VI + NE group only require a PT of 4 s (for further details see Supplementary Material *Sec.* S4).

While the average time spent in the preparation phase may be considered short (2.3 s, see section 4.3), the actual donning instructions are rather short, consisting of only eight short bullet points and associated pictograms (see Fig. 1.b and Supplementary Material *Sec.* S2). It could therefore be argued that it should not require much time to read the instructions. However, the donning instructions are somewhat lost in a large amount of text, consisting of irrelevant text associated with care of the TPIS and various language options. Thus, it can take some time to actually locate the necessary information. Furthermore, the text font size is rather small, making it difficult for many to read. Indeed, based on the responses to the post-trial questionnaire (see Supplementary Material *Sec.* S5), many participants encounter these difficulties and state that they could not read the instructions. The 'extended preparation time' group (see Fig. 4.b) was identified as a sub-set of participants that spent more time in the preparation phase (approximately 4 s to 35 s) and so were more likely to have read the instructions, and thus more likely to note the requirement to remove shoes prior to donning. 71 % (10 out of 14) of the participants in the 'extended preparation time' sub-group took their shoes off prior to donning. This result is almost as good as the VI group, that achieved all 19 participants removing their shoes prior to donning.

The findings suggest that WI can also be an effective approach to providing donning instructions. However, it is essential that the instructions are short, accompanied by clear pictorials, written in large fonts, not combined with 'care' instructions, and simply focus on the essential items. According to the SOLAS (IMO-SOLAS, 2014), ship passengers must undergo a safety drill including assembling at lifeboat stations prior to or immediately following departure. It is likely that as part of the assembly drill passengers will be shown a video of the donning procedures, but it is unlikely that passengers will remember the correct donning procedures when required during an emergency. It is thus essential that clear, simple, short and unambiguous donning instructions are provided with the TPIS packaging.

5.3. NDT and donning errors

As stated in Section 4, NDT and donning errors are key parameters of interest as they each directly impact passenger survivability albeit in different ways. The longer the NDT, the less time is available for passengers to reach a place of safety, and donning errors have a cumulative impact on reducing overall safety by compromising thermal protection and possibly buoyancy. But how is NDT related to the number of donning errors? Presented in Fig. 10 is a graph of mean NDT across all participant control groups (108 participants) grouped according to the number of donning errors. It is clear that a simple direct correlation between number of donning errors and mean NDT does not exist. Furthermore, a Kruskal-Wallis test was used to investigate the impact of donning errors on NDT. The test did not find that NDT was significantly influenced by donning correctness (P-value = 0.49).

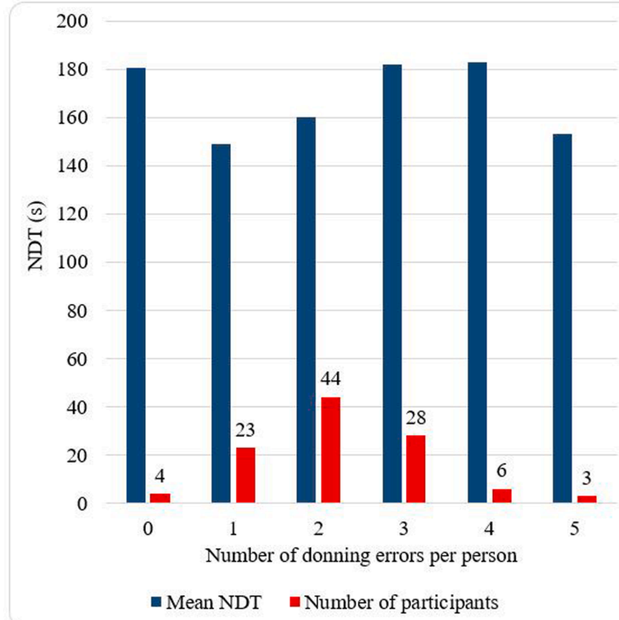


Fig. 10. Mean NDT as a function of number of donning errors.

Intuitively, this result may appear strange. It could be argued that most donning errors tend to decrease NDT through omission, i.e., neglecting to undertake an essential task. However, it is also possible that some participants may struggle with a particular essential task, such as pulling the zipper over the chin, only to eventually give up incurring a donning error while also having wasted time in the attempt, increasing their NDT. Thus, some donning errors may either increase or decrease average donning times, depending on the nature of the individual involved. In contrast, the donning error associated with the failure to remove shoes consistently increases donning time through the increased difficulty incurred in donning while wearing shoes. The donning error associated with shoe removal was the most common error, representing approximately 40 % of all errors committed and was committed by 50 % (54 out of 108) of the participants across all the trials (see *Sec.* 3.4). Thus, the relationship between the number of donning errors and NDT is inherently complex, with some donning errors increasing NDT for some participants and decreasing it for others, while other types of donning error tending to consistently increase NDT. This complex relationship explains the lack of correlation observed in Fig. 10.

5.4. Quantification of donning time for regulatory purposes

Here the quantification of the TPIS donning time is provided to assess regulatory compliance and for proposed use in evacuation simulation analysis used to demonstrate that proposed vessel design and procedures are appropriate.

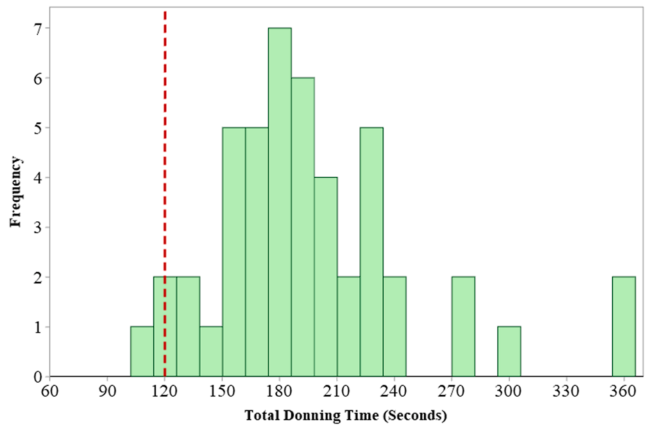


Fig. 11. TDT distribution (WI + NE group) highlighting the 120 s regulatory requirement.

5.4.1. Regulatory compliance

As discussed previously (see *Sec.* 1) it is an IMO regulatory requirement that TPIS can be unpacked and donned without assistance within 120 s (ISO, 2012; IMO-SOLAS, 1998). For the TPIS investigated we compare the TDT (derived from Eq. (5) and Eq. (6)) for inexperienced participants (59 participants) with the requirement. For the XT component in Eq. (5), we use the mean XT (19.4 s) derived from the trials involving the 14 new TPIS. Presented in Fig. 11 is a frequency plot of the 47 TDT's based on the data derived from the trials involving participants exposed to WI and who were inexperienced with the critical 120 s time indicated. As can be seen from Fig. 11, 95.7 % of the participants have a TDT in excess of the maximum permitted donning time of 120 s.

Even if only the NDT is considered (i.e., excluding the preparation time and the extraction time) 89.4 % of the participants fail to don the TPIS within 120 s. Clearly, the TPIS used in this study is not easy to don. This is also supported by the participants responses to the post-trial questionnaire (see Supplementary Material *Sec.* S5) where the majority of female participant responses (38 %) found the TPIS very difficult or difficult to don, while 18 % of the males found it very difficult or difficult to don. However, 80 % of the participants suggested that it would have been easier if there was a live visual demonstration during the donning process while 50 % said it would have been easier had there been some physical assistance during the donning process. While these types of interventions are not permitted during the regulatory assessment of the TPIS, these observations have important implications for the procedures adopted onboard vessels.

5.4.2. Evacuation modelling

The guidelines for evacuation analysis of passenger ships (IMO-MSC/Circ.,1533) specify population parameters that must be used in the evacuation analysis. These include parameters such as passenger response times, passenger deck walking speeds and passenger stair walking speeds. The walking speed data is provided as a function of age and gender. Furthermore, for evacuation modelling applications involving vessels operating in polar waters it may be appropriate to include the time required by passengers to don a TPIS. This could be significant in evacuation analysis as the donning times for TPIS can be up to 120 s (as required by IMO regulation) or more (see Fig. 15). However, currently there are no formulations characterising the donning times for TPIS that can be used in agent-based evacuation modelling applications, apart from simply assuming a uniform 120 s regulatory compliant donning time. To address this limitation, we use the data generated from the donning trials to specify a donning time relationship that can be used in agent-based evacuation modelling.

We define the Total Donning Time ($TDT_{modelling}$) for modelling applications by combining Eq. (1), (2) and (5), to produce,

$$TDT_{modelling} = PT + XT + NDT_{modelling} \tag{15}$$

where $PT = 1 + U * X,\ XT \sim Log - normal(2.9,\ 0.39)$

and $U \sim Bernoulli\ (0.16),\ X \sim Log - normal(2.35,\ 0.56)$

In Eq. (15), $NDT_{modelling}$ is defined by the log-linear regression model derived from the data-set for the group with WI, i.e., involving 89 participants. The data for the participants with VI are excluded in order for the NDT to be representative of the most conservative and likely situation on-board the vessel. The same type of log-linear regression model as in *Sec.* 4.3 is applied, except that the variables method of instruction and preparation time are excluded from the regression model. In this analysis, the background variables, age, gender and previous donning experience appear to have a significant influence on the NDT. Thus, $NDT_{modelling}$ is determined using these predicting factors in a log-linear regression model. The resulting model, as defined by Eq. (16), can predict $R^2 = 27.5\%$ of the expected variance of the NDT,

$$NDT_{modelling} = 130.3 * 1.006^{Age} * 1.32^{Gender} * 0.79^{Experience} * \tilde{\varepsilon}; \tag{16}$$

Where: $\tilde{\varepsilon} \sim Log - normal(0,\ 0.3)$

$Age \in (18 - 72), Gender \in \{Male = 0, Female = 1\}$

$$Experience \in \{People\ without\ donning\ experience = 0, People\ with\ donning\ experience = 1\}$$

As can be seen in Eq. (16), previous donning experience is one of the factors that can have a significant impact on the donning time. People with experience can perform approximately 21 % faster than their inexperienced counterparts. However, as noted in Section 5.1, given the vagueness of the definition of experience used in this study, it is suggested that the quantification of donning time for the inexperienced is more reliable and representative of expected performance than the quantification for the experienced. Thus, the predicted NDT for experienced should be used with care as it is likely to underestimate the performance of highly trained personnel such as crew.

Presented in Fig. 12 is the mean TDT as a function of age and gender. The mean TDT is calculated using Eq. (15), setting Experience to zero (excluding the standard deviations) in Eq. (16) and using the mean values for PT and XT. The mean donning time for the male group ranges between 166 s and 218 s, while the female mean donning time ranges between 211 s and 278 s. The donning time of both genders increases approximately 5.7 % for a 10-year increase in age. Furthermore, females

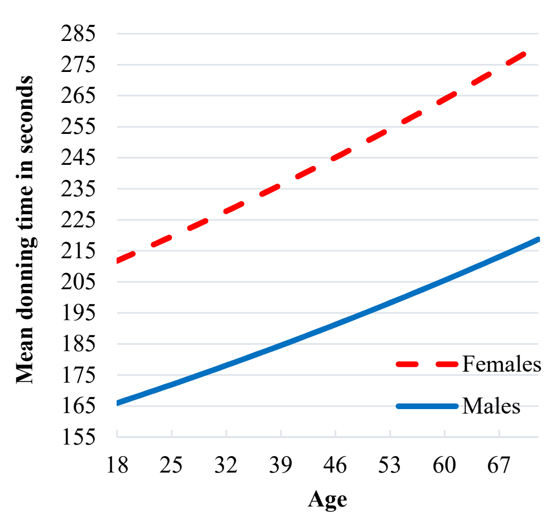


Fig. 12. Mean TDT for males and females as a function of age for people without experience (NE) using Eqs. (15) and (16).

at any age require on average over 32 % longer to don than their male counterparts of the same age. Nevertheless, there will always be a number of females who manage to don the TPIS faster than their male counterparts due to natural variations within each group (i.e., $\tilde{\varepsilon}$ in the regression model of NDT in Eq. (16) and the σ parameter in the log-normal distributions of PT and XT).

In addition to age, gender and experience, the type and ergonomics of the TPIS design and its packaging will also have an influence on the donning performance of individuals. Thus, the TDT presented in this paper is only intended to be representative of the particular TPIS examined. Furthermore, from analysis of the behaviour of participants during the donning trials and reflecting on their comments in the questionnaires, certain aspects of the TPIS design could be modified to improve donning performance. These aspects are discussed in the Supplementary Material (see Supplementary Material *Sec*. S5).

6. Limitations

As with any experimental study involving human test subjects, there are limitations associated with this work which should be considered when reviewing the results. The limitations of the current study are identified as follows:

- In order to conduct the research in an ethical manner and to reduce the risk of injury to the participants, the experiment was conducted in a controlled environment and experimental protocol eliminated some factors, such as stress, darkness, slippery surfaces, dynamic motion, adverse deck orientation, etc. which could have a detrimental impact on donning performance of individuals. Indeed, in the post-trial questionnaire, 95 % of the participants suggested that their donning times would be adversely impacted by dynamic motions or adverse deck orientation, with 48 % suggesting that their donning times could be doubled under such circumstances (see Supplementary Material *Sec*. S5).
- The TPIS used in the trials were new or in as good as new condition and perfect working order. In actual applications, it is assumed that the TPIS used by passengers will be well maintained and in good working condition as required by international regulations.
- While the physical space available to the participants during the trials was representative of the floor area per passenger required by international regulation, it is possible that in actual emergency situations, passengers may be in environments with less physical space. This may make donning more difficult.
- Prior to the start of the trial, participants were instructed to remove excessive clothing such as winter jackets, scarves or heavy jumpers. In reality, such extra warm clothing may be worn by passengers in real situations, making donning of the TPIS more difficult. Furthermore, in real situations, passengers may be instructed to remove such clothing prior to donning of the TPIS, increasing the number of preparation tasks and hence increasing the preparation time (PT) and hence the total donning time (TDT).
- All trial participants (who were aged from 18 to 72 years old) were in good health and physical condition. Almost 60 % of the participants were under the age of 20 years, with just 13 % of the participants being over the age of 51 years. Furthermore, the average Body Mass Index (BMI) for male and female participants was 25 (SD = 4) and 24 (SD = 3), respectively. The majority of participants in the trial were within the normal BMI range with none of the participants in the obese category. It is noted that in the UK and USA 27 % and 38 %, respectively, of the population are classified as obese (Gallagher et al., 2000). Thus, the sample population used in the trials may not be considered fully representative of the target population. While further research is required to include a wider cross-section of the public, the donning times measured in these trials may be considered to be optimistic.
- The video instruction was shown to the participants immediately prior to their participation in the trial. In real life situations, passengers may have viewed the video or undertaken an emergency assembly drill hours or days before the time of the actual emergency. Furthermore, during an actual emergency, passengers may not patiently concentrate and watch an instructional video prior to the donning. Further investigation is required to understand the impact of the duration of the time interval between receiving video instruction and actual donning on donning performance.
- For the participants in the written instruction group (WI), it is assumed that participants devote some time during the preparation phase to reading the donning instructions. However, in a real situation, it is possible that passengers may spend less (or more) time reading the instructions and so this may impact the NDT and the TDT.
- Concerning the validity of the statistical analyses, the participants performed the donning procedure in groups of up to 15 persons at the same time. Hence the individual donning errors (and donning time) could potentially have been influenced by the performance of the other participants in the same group. The statistical tests that have been performed is usually underpinned by that the individual samples are independent, and some caution should therefore be taken when considering the analysis of the factors that influence donning errors in particular.

7. Conclusion

Thermal Protection Immersion Suits (TPIS) are required by the IMO for all vessels operating in polar waters and must be designed so that they can be donned, unaided within 120 s. To meet this requirement, TPIS are typically designed as a universal one-size fits all. The one-size fits all approach has the advantage of reducing the time required to distribute the TPIS and the inevitable disadvantage of impacting the donning time, walking performance and general manoeuvrability of those individuals who are either very large or small in stature. The aim of this study was to explore the factors influencing the donning speed and correctness through an experimental trial involving 108 volunteers (71 males and 37 females) aged between 18 and 72 years old.

A key finding of this work is that the mean net donning time (NDT) was dependent on a complex relationship between, age (increases by 6.6 % for each 10 years), gender (increases by 33 % if female), experience (decreases by 17 % with experience), method of instruction (increases by 21 % with video instruction) and failure to remove shoes prior to commencing the donning process (increases by 26 %). The study is unique in that it identifies and quantifies, for the first time, the factors that influence donning time for the type of TPIS used in this study. This is important to ship operators as unnecessarily prolonging the time involved in donning the TPIS may mean that less time is available to safely abandon the vessel. With the insight that this information provides, ship operators can develop procedures to minimise the time required to don the TPIS. The information is also important to TPIS designers and manufacturers, as it identifies design issues that make it difficult to quickly don the TPIS.

Perhaps of greater importance than the donning speed is the donning correctness and the factors that influence correctness. Clearly, a TPIS that is incorrectly donned will impact life critical issues such as thermal protection and buoyancy. Thus, a further unique aspect of this study is that it identified that the number of donning errors is significantly impacted by the method of instruction, with video instruction (VI) producing an average of 1.5 errors while written instruction (WI) producing 2.3. This finding is again important to both ship operators and TPIS designers and manufacturers. For example, as part of the ship abandonment procedures, showing a live donning demonstration or playing a video of the donning process during an actual emergency may be more effective at reducing donning errors than relying on passengers to read the donning instructions. Nevertheless, project findings also suggest that WI can also be an effective approach to reducing the number of donning errors. However, it is essential that suit manufacturers provide instructions that are short, accompanied by clear pictorials, written in large fonts, not combined with 'care' instructions, and simply focus on the essential items.

In reviewing these results, it is important to note the limitations associated with the study. In particular, the study focuses on only a single type of TPIS, other suits may have different characteristics. This aspect is currently being examined in a related study involving a different type of TPIS. The majority (60 %) of the participants where under the age of 20 years, with just 13 % being over the age of 51 years and none of the participants being classed as obese. Furthermore, the trials were conducted in ideal environmental conditions. These limitations were a combination of practical and ethical considerations, the latter being intended to reduce the risk of injury to the participants.

Furthermore, it is interesting to note that the preparation time was not found to have a significant influence on NDT and a significant but weak influence on the expected number of donning errors. The later relationship was further weakened, to the point of insignificance, if the maximum preparation time data point was considered an outlier and removed from the analysis. Thus, it is suggested that the important relationship between preparation time and both NDT and number of donning errors requires further analysis.

The final key result, addressing an important aim of the paper was the specification of a donning time distribution that can be used in agent-based passenger ship evacuation analysis. Passenger ship evacuation analysis using modelling techniques, as required by IMO for all new builds, currently does not represent the time required by passengers to don the TPIS. As the time required to don the TPIS is a critical factor identified in the IMO (SOLAS), it is reasonable to assume that it may also be an important factor in evacuation analysis for passenger ships intended to operate in polar waters. The donning time distribution suitable for modelling analysis defined in this work allows engineers to assess whether the time required to don the TPIS critically impacts the evacuation process, and if it does, enables them to refine procedures to reduce the impact. This latter point is currently being pursued by the authors in a continuing study.

CRediT authorship contribution statement

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

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssci.2023.106064.

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Annex II – Supplementary Material for Paper I

Supplementary material: Factors influencing the time required to don thermal protective immersion suits correctly

Supplementary Material for: Factors influencing the time required to don thermal protective immersion suits correctly

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This document presents supplementary material for Azizpour, et al., [S1] relating to the experimental donning trials, the experimental methodology employed in the study, the packaging of the thermal protective immersion suit (TPIS), the participant questionnaire and the response to the participant questionnaire.

S1. The Trial Procedures

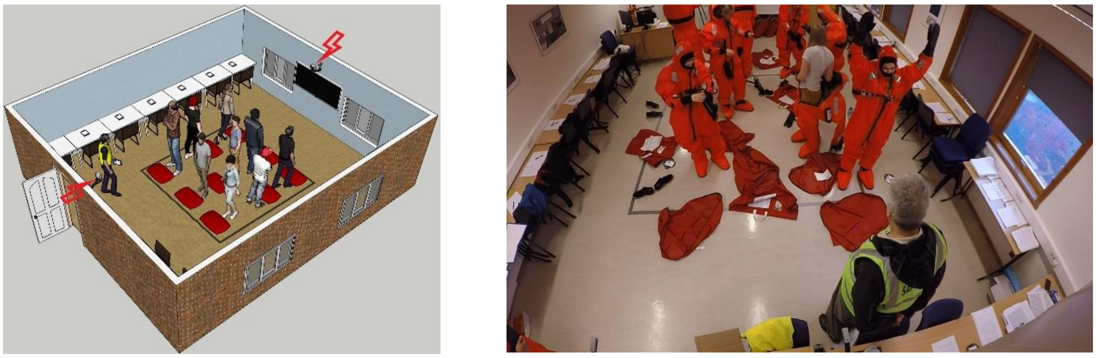
The donning trials were conducted at two shore-based facilities, the ARCOS safety centre in Tromsø and the ResQ safety centre in Haugesund. In total, 84 volunteers participated at the ARCOS safety centre and 24 at the ResQ safety centre. Upon the arrival of the participants at the trial location, participants went through a registration process which included completing the pre-trial questionnaire and consent form, and participants were then given a group safety briefing. At registration, each participant was issued a unique identification number which was used to track their performance. Participants were also instructed to remove coats and jackets and to leave all personal belongings behind, prior to being escorted to the trial area.

During the registration process, the air temperature within each test facility was noted and was found to be in the range of 18 ° to $22°C$. Once the registration process was completed, participants were escorted to the trial location and positioned within a square area of $3m \times 3m$ marked on the floor. To ensure that the minimum space requirement in SOLAS was met (0.35 m^2/person) [S2], a maximum of 15 participants were allowed to don the TPIS inside the aforementioned area although in practice, the number of participants in the square varied between 1 to 13 persons at a time (see Figure S1). The TPIS within its carry bag was placed on the floor in front of each participant. Once the participants were positioned, a member of the trial team set the scene for the trial and provided the trial instructions using a pre-defined script. Participants were instructed to imagine that they were at sea on board a passenger ship sailing in polar waters and the evacuation alarm had just been sounded. The participants were told that they had to don the suit as quickly and as correctly as possible so that they would be ready to safely evacuate the vessel. The task would start once the instructor yelled “GO” and the end point was defined as the time that the participant raised their arms above their head, indicating that they had completed the task and donned the suit as best as they could (see Figure S1b).

Prior to starting the trials, a sub-group of randomly selected participants were shown a two-minute instructional video demonstrating the correct donning procedure. In total 19 participants were shown the video demonstration. The donning process was undertaken by a professional instructor demonstrating how to unpack a brand-new suit and don it quickly and correctly. This sub-group consisted of 10 male and 9 female participants aged between 18 to 72 years.

In addition, written instructions (provided by the manufacturer) were available to all participants through a laminated sheet located prominently on the suit carrying cover (see Figure S3). Participants were not permitted to read the instructions prior to the start of the trial. The participant’s donning performance was recorded throughout donning trial using two GoPro Hero cameras (frame rate of 25 FPS). The cameras were positioned to capture the performance of participants in two opposite directions (see Figure S1). A range of quantitative and qualitative data was collected during the trials through video footage and questionnaires.

Demographic data and information relating to prior experience of the participants were collected through the pre-trial questionnaire while qualitative data concerning the participants perception of the ease of donning and suggestions to improve the TPIS design were collected through a post-trial questionnaire (see Figure S4). Quantitative data concerning donning correctness and speed of donning was collected through analysis of the video footage.



(a): Location of cameras and participants

(b): View from one of the cameras

Figure S1: Position of cameras and participants in the $3m \times 3m$ square in the room

Presented in Figure S2 are example frames extracted from the trial video footage highlighting important behaviours noted during the donning trials. The images demonstrate examples of participant behaviour as they read the instructions (Figure S2.1), unpack the TPIS (Figure S2.2 to Figure S2.4) and attempt to don the suit (Figure S2.5 to Figure S2.15).

Prior to the start of the experiments, an application for ethical approval for the research was sent to the Norwegian Centre for Research Data (NSD). All appropriate measures were taken to ensure the safety and anonymity of participants. Participation in the trials was completely voluntary and the participant could withdraw from the trials at any time.

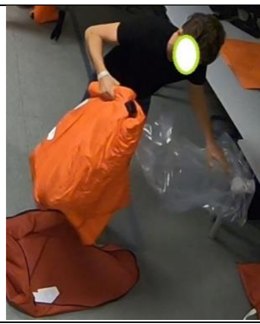
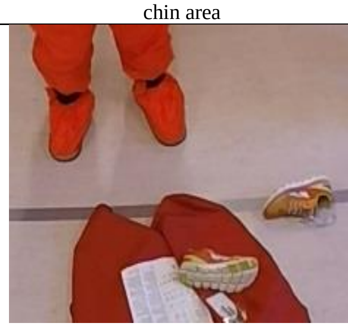
		
2.1. Reading the instructions	2.2. Start of the donning process with participant touching the zipper	2.3. Carry bag is opened, the start of the process to remove TPIS from the sealed plastic bag
		
2.4. End of removing TPIS from the plastic bag	2.5 Donning while seated on the floor	2.6. Participant looking at others for guidance while attempting to don
		
2.7. Participant preparing long hair prior to donning hood	2.8. Removable neoprene gloves	2.9. Adjusting internal length straps
		
2.10. Pulling up the zipper	2.11. A participant wearing glasses attempting to pull up the zipper over the chin area	2.12. Adjusting wrist straps
		
2.13. Chest buckle (undone)	2.14. Ankle straps correctly adjusted	2.15. End of donning process

Figure S2: Examples of participant behaviour during donning trials

S2. TPIS donning instructions

Presented in Figure S3 are the instructions for the TPIS which can be found on the packaging for the TPIS.

S3. Participant post trial questionnaire

On completion of the trial, participants were requested to complete a short questionnaire designed to identify their previous experience in donning TPIS and also their experience of donning the TPIS during the trial (see Figure S4).

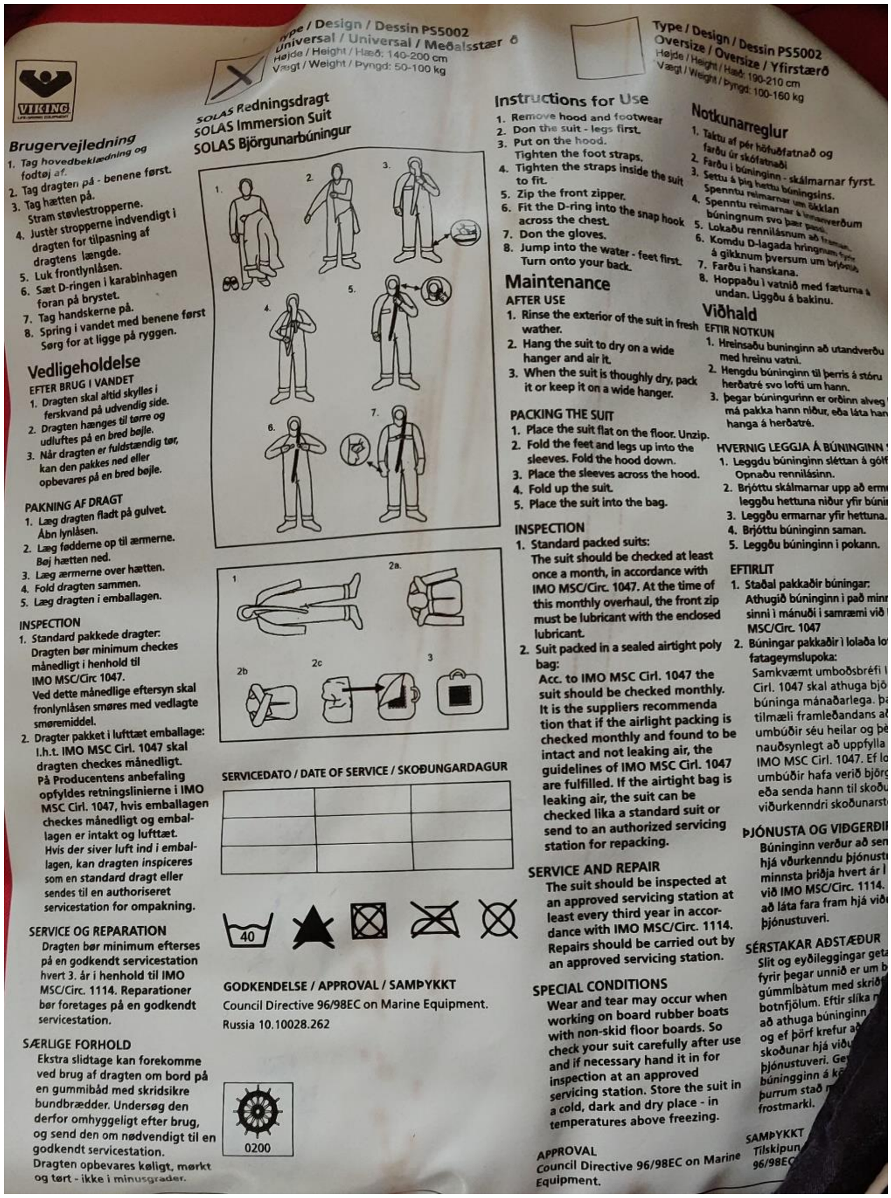
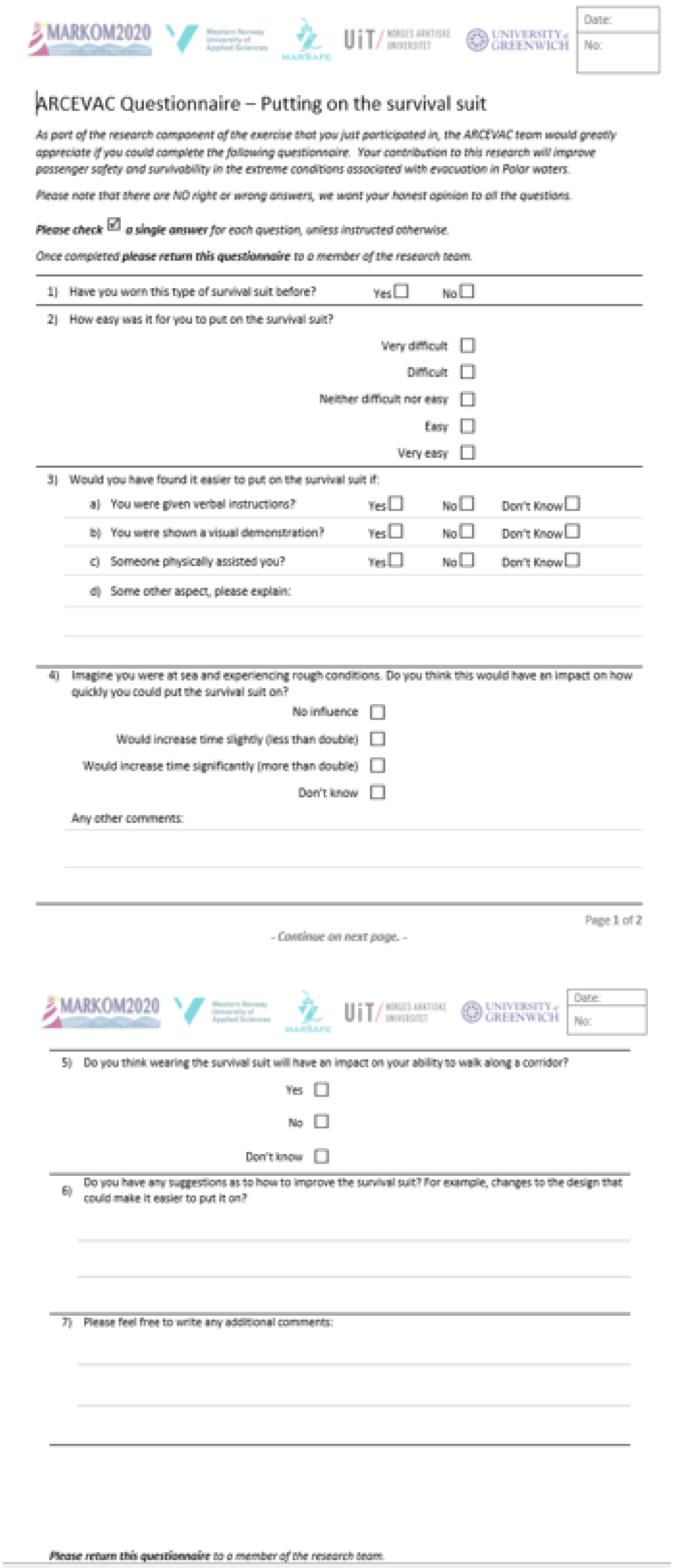


Figure S3: The donning instruction which was laminated on the suit carrying cover and available to all participants.


MARKOM2020 | Western Norway University of Applied Sciences | MARSAFE | UiT Norges arktiske universitet | University of Greenwich | Date: | No:

ARCEVAC Questionnaire – Putting on the survival suit

As part of the research component of the exercise that you just participated in, the ARCEVAC team would greatly appreciate if you could complete the following questionnaire. Your contribution to this research will improve passenger safety and survivability in the extreme conditions associated with evacuation in Polar waters.

Please note that there are NO right or wrong answers, we want your honest opinion to all the questions.

*Please check ☑ **a single answer** for each question, unless instructed otherwise.*

*Once completed **please return this questionnaire** to a member of the research team.*

1) Have you worn this type of survival suit before? Yes ☐ No ☐

2) How easy was it for you to put on the survival suit?
- Very difficult ☐
- Difficult ☐
- Neither difficult nor easy ☐
- Easy ☐
- Very easy ☐

3) Would you have found it easier to put on the survival suit if:
- a) You were given verbal instructions? Yes ☐ No ☐ Don't Know ☐
- b) You were shown a visual demonstration? Yes ☐ No ☐ Don't Know ☐
- c) Someone physically assisted you? Yes ☐ No ☐ Don't Know ☐
- d) Some other aspect, please explain:

4) Imagine you were at sea and experiencing rough conditions. Do you think this would have an impact on how quickly you could put the survival suit on?
- No influence ☐
- Would increase time slightly (less than double) ☐
- Would increase time significantly (more than double) ☐
- Don't know ☐

Any other comments:

Page 1 of 2

- Continue on next page. -

MARKOM2020 | Western Norway University of Applied Sciences | MARSAFE | UiT Norges arktiske universitet | University of Greenwich | Date: | No:

5) Do you think wearing the survival suit will have an impact on your ability to walk along a corridor?
- Yes ☐
- No ☐
- Don't know ☐

6) Do you have any suggestions as to how to improve the survival suit? For example, changes to the design that could make it easier to put it on?

7) Please feel free to write any additional comments:

***Please return this questionnaire** to a member of the research team.*

Figure S4: Post-trial questionnaire used in donning trials

S4. Importance of the donning error associated with shoe removal.

To quantify the impact of background and randomised variables (see Table 4 in [S1]) on the probability of removing shoes (PRS), binary logistic regression [S3] was used. Only the preparation time, PT (x_1), method of instruction (x_2) and experience (x_3) were found to be significant. Furthermore, as previously suggested, video instruction (VI) had the most significant influence on PRS while experience (E) was the second most significant variable. In addition, duration of the preparation time also appeared to have significant impact on the PRS. The result of the log-logistic regression ($R^2 = 23.5\%$) is presented in Eq. S1) while presented in Table S1 is the description and effect of the significant variables according to their corresponding coefficient in Eq. S1).

$$PRS = \frac{1}{1 + e^{\gamma}} \tag{S1}$$

where:

$$\gamma = 1.27 - (0.15 * x_1) - (3.7 * x_2) - (1.07 * x_3)$$

From Eq. (S1), a group of people exposed to written instruction (WI) ($x_2 = 0$), with no experience (NE) ($x_3 = 0$) and a PT of $x_1 = 0$ s (i.e., insufficient time to read instructions) will have a PRS of 22% ($PRS = \frac{1}{1+\exp(1.27)} = 0.22$ from Eq. (S1)). However, if the same group has a PT of 10 s (i.e., has more available time to read the instructions), then they are expected to have a PRS of 56% ($PRS = \frac{1}{1+\exp(1.27-1.5)} = 0.56$). Furthermore, to achieve a 95% probability of removing their shoes, the WI group with NE requires at least 28 s preparation time.

The variation of PRS with preparation time for various groups as determined by Eq. S1 is depicted in Figure S5. As can be seen from Figure S5, for a given preparation time those with WI and NE always have a lower PRS on average than those with VI and NE. For a PT of up to 20 s, the PRS for the VI and NE group is considerably larger than that for the WI and NE group. While having experience improves the PRS for the WI group, the improvement is marginal. The same caveats should be noted when interpreting S5 as those for Figure 8 in [S1]. Furthermore, for the VI group none of the participants has a preparation time of greater than 2 s and so the curve is essentially a model extrapolation (hence shown as a dashed line). However, Figure S5 shows the considerable advantage of VI for those with NE in terms of ensuring that participants remove their shoes prior to donning.

Table S1: Contributing factors and change in the PRS given one unit increase in each of the influencing variables (when all other variables are fixed)

Variable	**Coefficient**	**Standard Error of Coefficient**	**Increase in PRS per unit increase of x_i when all x_i initially set to 0**	**P-value**
x_1	-0.15	0.07	Approximately +3% per second preparation time	0.03
x_2	-3.7	1.1	+70% with Video Instruction	0.001
x_3	-1.07	0.46	+22% with donning experience	0.02

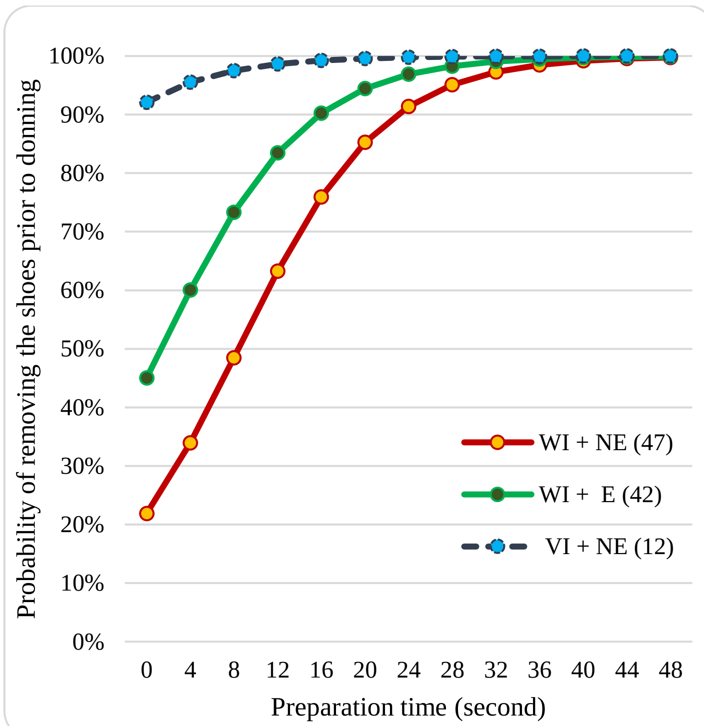


Figure S5: Probability of removing shoes prior to donning as a function of preparation time for various methods of instruction and experience

Concerning the impact of WI on the propensity for participants to remove their shoes prior to donning, it is assumed that participants will read the written instructions during the preparation phase. As described in Section 4.3 of [S1], the average time spent in the preparation phase was short, being only 2.3 s, with a range from 1 s to 35 s, with most participants merely glancing at the instructions placard prior to beginning to open the carry bag. Nevertheless, all participants had the opportunity to read the written instructions and so could have read the instructions prior to attempting to don the TPIS. Furthermore, we cannot judge the level of thoroughness of the reading, or the level of comprehension achieved by those who may have read the instructions. All that can be determined with certainty is the amount of time each participant spent during the preparation phase. It could be argued that this type of behaviour is typical of how many people tend to respond, with few attempting to thoroughly read instructions prior to operating a new device, especially if the operation of the device appears intuitive, e.g., putting on a pair of coveralls. Thus, the results relating to the performance of the 'written instruction' group could be argued to be representative of reality.

S5. Participant post trial questionnaire

Following the trials, 108 participants completed the post-trial questionnaire, representing a 100% completion rate. Question 1 related to establishing whether the participants had prior experience of donning a TPIS, the results of which are discussed in [S1]. Questions 2-5 were closed questions related to the experience of the participants while donning the TPIS while questions 6 and 7 where open questions.

The first question relating to the donning experience concerned the ease of donning (see question 2 in Figure S4). The vast majority of the male participants (47.9% or 34) said that the TPIS was Easy/Very Easy to don, with only 18.3% (13) suggesting that it was Difficult/Very Difficult (see Table S2). This is in contrast to the female participants, the majority (37.8% or 14) of which suggested it was Difficult/Very Difficult with only 18.9% (6) saying it was Easy/Very Easy (see Table S2). The difference between the male and female response was determined to be significant using a Kruskall-Wallis test (P-value = 0.004). These results are consistent with the observations that the net donning time (NDT) was related to gender, with males donning the TPIS some 29% quicker than females on average (see [S1], section 4.3). This is further supported through a Mann-Whitney test that showed that those who found the suit Easy/Very Easy to don manged to don the suit significantly faster than those who found it difficult to don (P-value < 0.001).

Table S2: Response to question 2 related to ease of donning

Influence / Gender	Very difficult	Difficult	Neither difficult nor easy	Easy	Very easy
Males	1.4% (1)	16.9% (12)	33.8% (24)	42.3% (30)	5.6% (4)
Females	2.7% (1)	35.1% (13)	43.3% (16)	16.2% (6)	2.7% (1)
Total	1.9% (2)	23.2% (25)	37.0% (40)	33.3% (36)	4.6% (5)

The second question relating to donning experience concerned the method of instruction and enquired if verbal, visual or physical instruction would have been helpful during the donning process (see question 3 in Figure S4). Approximately 80% (88) of participants felt that a (live) visual demonstration would have been helpful and almost two thirds (66.4% or 71) felt that verbal instructions during the donning process would have been helpful, while half (50% or 54) suggested that physical assistance would have been helpful (see Table S3). In each case, females were more in favour of the additional method of instruction than the males.

Table S3: Response to question 3 related to alternative methods of instruction

Method of instruction	Gender	Yes	No	I don't know
Verbal instruction	Males	64.8% (46)	21.1% (15)	14.1% (10)
	Females	69.4% (25)	16.7% (6)	13.9% (5)
	Total	66.4% (71)	19.6% (21)	14% (15)
Visual demonstration	Males	76.1% (54)	5.6% (4)	18.3% (13)
	Females	91.9% (34)	2.7% (1)	5.4% (2)
	Total	81.5% (88)	4.6% (5)	13.9% (15)
Physical assistance	Males	46.5% (33)	40.8% (29)	12.7% (9)
	Females	56.8% (21)	24.3% (9)	18.9% (7)
	Total	50% (54)	35.2% (38)	14.8% (16)

The high rate of request for additional methods of instruction reflects the inherent difficulty experienced by the participants in donning the TPIS. Furthermore, the higher proportion of females requesting the additional method of instruction reflects the greater difficulty experienced by females in donning the TPIS – which is reflected in the longer donning times experienced by females. This suggests that in practice passengers should not be left to their own devices to don the TPIS, additional instruction over that provided by the written and video instruction is desirable.

The donning trials were conducted in ideal laboratory conditions, without the impact of a pitching deck or adverse vessel orientation (heel or trim) that could be expected in an emergency situation. Participants were asked about their opinion of whether their donning performance would be likely to be negatively impacted by such adverse conditions (see question 4 in Figure S4). Virtually all the participants (95.3% or 103) thought that their donning time would be increased, with almost half (48.1% or 52) suggesting that their donning time would increase significantly, i.e., more than double (see Table S4). This opinion reflects the inherent difficulty that the participants experienced in donning the TPIS.

Table S4: Response to question 4 related to participant perception of impact of rough weather on the donning performance

Influence / Gender	Increase significantly (more than double)	Increase slightly (less than double)	No influence	I don't know
Males	40% (28)	53% (38)	4.3% (3)	2.7% (2)
Females	64% (24)	36.0% (13)	0% (0)	0% (0)
Total	48.1% (52)	47.2% (51)	2.8% (3)	1.9% (2)

Participants were also asked about their opinion concerning whether they felt that wearing the TPIS would impact their walking speed (see question 5 in Figure S4). Virtually all the participants (78.5% or 84) thought that the TPIS would impact their walking speed, with more females (86.5%) than males (74.3%) believing that the suit would have an impact (see Table S5). This is probably due to the ill-fitting nature of the one-size fits all TPIS and the poor fitting of the footwear associated with the suit (see response to questions 6 and 7 below). It is also worth noting that the perception of the participants is supported by experimental analysis, where wearing a TPIS of the type used in the donning trials reduced walking speeds by 6.1% at 0^{o} of heel, increasing to a reduction of 24% at 20^{o} of heel [S4]. Furthermore, females were more severely affected than males, with the reduction in walking speeds for females being 6.8% more severe than that for males at 0^{o} of heel [S4].

Table S5: Response to question 5, participant perception of the impact of the TPIS on walking speed

Gender	Yes	No	I don't know
Males	74.3% (52)	20% (14)	5.7% (4)
Females	86.5% (32)	8.1% (3)	5.4% (2)
Total	78.5% (84)	15.9% (17)	5.6% (6)

In addition, participants were requested to suggest how the TPIS design could be improved (see question 6 in Section S3) or if they had any other comments concerning the TPIS and the donning process (see question 7 in Section S3). Their responses are collated and summarised below. These comments provide useful insight into issues concerning the design of the particular TPIS tested that detrimentally impacted donning and which should be addressed to improve donning ease.

(a) Issues associated with the hood

The TPIS hood is designed to cover the whole neck and head including ears, forehead, cheeks, and jaw. The hood has a rubber seal which sits around the face. Female participants with long hair commented on the difficulty of tucking their hair into the hood while men commented on the difficulties with the face seal. 18.9% of females struggled with tucking their hair in the hood while this was not issue for any of the male participants.

b) Issues associated with the gloves

Many participants commented that they struggled putting on the gloves due to the friction between their skin and the inner layer of the gloves.

c) Issues associated with ankle straps and TPIS shoes

Due to the universal size of the TPIS design, the suit shoe is very large. The ankle straps are intended to keep the shoe in place. However, participants (particularly females) commented that as the shoe was too large, their feet would easily slip in the shoe while walking, creating a misstep hazard. Furthermore, participants commented that the Velcro fasteners were inadequate, often coming undone and getting entangled, potentially creating a trip hazard.

d) Issues associated with the zipper

While the zipper appeared to be a familiar and easy device to operate, it proved challenging for many of the participants particularly females. 19.7% of males struggled with pulling up the zipper while 37.8% of the females struggled with pulling up the zipper. Participants had difficulty in manipulating the zipper tracker and often had to bend at the abdomen to locate the tracker due to the bunching of the suit material. From the video analysis it appeared that participants had difficulty in pulling the tracker and sealing the suit when in this semi-bent position. Furthermore, video analysis suggested that participants experienced difficulty in pulling the tracker to seal the suit if the zipper threads where not aligned (see Figure S2.10). In addition, participants noted that it was difficult to pull the zipper over their chin due to the tight fit of the face seal (Figure S2.11).

e) Issues associated with the wrist straps

The wrist straps are required to tighten the rubber seal around the wrists. Two straps were provided on each sleeve. One for tightening the wrist rubber seal and the second to secure the gloves. Participants found it too complex as the Velcro on the straps kept tangling up, causing inconvenience during donning. Even though it was not clear in the written instruction that the hand straps needed to be fastened (see Section S2), many of the participants fastened the wrist straps by intuition. About 47% of males and 32% of females failed to fasten the wrist straps.

f) Issues associated with the inside straps

Due to the universal size of the TPIS design, the suit had two internal straps (located on each side) enabling the wearer to adjust the length of the suit. Participants who did not adjust the size of the suit using the internal straps, complained that the suit was too large which adversely impacted their mobility. Some of those who adjusted the length of the suit using the internal straps, commented that the bunched fabric around their gusset and thigh made walking difficult. Many of the participants also commented that the internal straps were not easy to see and in low light conditions would be almost impossible to locate. Participants suggested incorporating a reflective patch on the straps to make them more visible.

g) Issues associated with the donning instructions

Donning instructions were in Danish, English, and Icelandic together with instructions for maintenance, packaging, service, and repair as well as inspection, all on a large single page secured to the TPIS carry bag (see Section S2). Participants commented that the donning instructions were difficult to identify and read due to the small font size, small pictograms, and large amount of irrelevant material. They also noted that the need to remove shoes prior to donning was not highlighted and felt that this should be emphasised.

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[S3] J. M. Hilbe, Logistic regression models. Chapman and Hall/CRC, 2009.

[S4] H. Azizpour, E.R. Galea, S. Erland, B.M. Batalden, S. Deere, and H. Oltedal, "An Experimental Analysis of the Impact of Thermal Protective Immersion Suit and Angle of Heel on Individual Walking Speeds," Safety Science, vol. 152, no. 105621, 2022.

Annex III – Paper II

An experimental analysis of the impact of thermal protective immersion suit and angle of heel on individual walking speeds

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An experimental analysis of the impact of thermal protective immersion suit and angle of heel on individual walking speeds

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A R T I C L E I N F O

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A B S T R A C T

The cold environment of Polar Regions introduces additional challenges to maritime safety in situations where it becomes necessary to abandon a vessel. The Polar Code requires all vessels operating in Polar Regions to be equipped with approved thermal protective clothing suitable for immersion in polar waters (thermal protective immersion suit (TPIS)) for all passengers and crew. However, in addition to assessing thermal protection offered by TPIS, given the criticality of time in emergencies, it is essential to understand their impact on walking performance during evacuation and how this may be impacted by adverse vessel orientation. The ARCEVAC (ARCtic EVACuation) project examines the impact of two different types of TPIS (Suit-1 and Suit-2) on walking speed at 0°, 10°, 15° and 20° angles of heel. A test facility representing a 36 m long ship's corridor was developed and 210 volunteers recruited to participate in the trials. Project findings reveal that male performed considerably better than female counterparts and increases in age, weight and heel angle had significant adverse impact on walking speed while increase in height resulted in significant increase in walking speed. Furthermore, the specific nature of the TPIS had an impact on walking speed, with the most severe reduction in walking speeds being 38% for Suit-2 and 29% for Suit-1 at 20° of heel. Reductions in walking speed of this magnitude can have a profound impact on evacuation and so cannot be ignored from evacuation analysis.

1. Introduction

In recent years there has been a growing popularity of large passenger ships visiting polar waters (Luck et al., 2010) and thus the potential of an incident involving these vessels in these challenging conditions has increased. In light of this, and acknowledging that the existing safety provisions for passenger ships (IMO, 2014) may not be adequate, the International Maritime Organization (IMO) recently introduced the Polar Code (IMO, 2017). As part of this, passenger ship operators are required to provide approved thermal protective clothing and insulated immersion suits (referred to as TPIS in this paper), where applicable according to the weather condition (cold and wind) for each person on-board (IMO-SOLAS, 1998).

In many passenger ship emergencies, time is a critical factor, whether it be associated with the time required to abandon the vessel, the time required to gather passengers in assembly stations, the amount of time passengers are required to remain in assembly stations or the amount of time available to move from the assembly station to the life safety apparatus (LSA). Given that emergencies may occur on passenger ships in polar waters, and that passengers and crew are likely to be encumbered by TPIS, it is essential to know how the TPIS is likely to impact time critical procedures and operations (Kruke and Auestad, 2021; Kruke, 2021). In particular, how long does it take to distribute/collect TPIS, how long does it take to don the suit and how does the wearing of TPIS impact the movement rates of passengers and crew? In most cases, apart from anecdotal information, or information from marketing materials associated with TPIS, a rigorous evidence base characterising the impact of TPIS on human performance does not exist. Furthermore, quantifying the impact of TPIS on walking and behavioural performance of passengers is critical for developing achievable evacuation procedures for passenger ships in polar waters and for modelling evacuation performance using ship-based evacuation models (Galea et al., 2013; Gwynne et al., 2003; Vassalos et al., 2002; Pradillon, 2004).

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Since 2002 (IMO, 2002) the IMO has published a set of guidelines for evacuation modelling associated with new and existing passenger ships. As part of the guidelines movement speed data associated with walking speeds in corridors and on stairs were stipulated for use in modelling. The data is based on research associated with land-based scenarios such as data collected in rail stations and other buildings. However, the IMO invited Member States to collect and submit information and data resulting from research and development activities on human behaviour associated with ship evacuation. While the movement speed data used in the current guidelines (IMO, 2016) may be appropriate for passenger ship applications under 'normal' conditions, there is no evidence to support their appropriateness to maritime situations involving adverse vessel orientation, dynamic movements associated with sea-state and the wearing of protective clothing such as TPIS. Clearly, an evidence base quantifying how these conditions may impact walking speeds is required, even if it is to demonstrate that these factors are not significant.

The Polar Code (IMO, 2017) requires vessels sailing in polar waters to provide all passengers and crew with appropriate TPIS as specified by the IMO (IMO SOLAS, 2004). However, it is essential to understand the impact that TPIS will have on other IMO requirements associated with ship evacuation (IMO, 2014). As a result, it is essential to understand how donning TPIS, walking along corridors with TPIS and walking on stairs in TPIS will impact evacuation performance, particularly in scenarios involving adverse vessel orientation (Nicholls, et al., 2012; Glen et al., 2003). To the best of our knowledge, thus far there is no study published shedding light on these issues.

To address this lack of data and amass an evidence base that can be used to assess evacuation performance in Polar Regions, Western Norway University of applied Science (HVL) and The Arctic University of Norway (UiT) embarked on the ARCEVAC (ARCtic EVACuation) project. The aim of ARCEVAC is to develop an understanding of how ship evacuation is impacted by polar conditions and suggest improvements to regulations, ship design and ship operating procedures to improve passenger ship safety while operating in polar conditions.

Here we report results from a study to quantify the impact of TPIS on walking speeds at four different angles of orientation, 0°, 10°, 15° and 20°. A total of 210 volunteers, aged between 18 and 72 years of age participated. Walking speed trials were conducted with participants wearing normal clothing and two different types of TPIS (see Supplementary Material for details). To collect the data, two test facilities measuring 36 m in length were constructed, one in Tromsø and one in Haugesund (see Supplementary Material for details).

2. Previous research

Many studies quantifying the performance of human walking speeds have been undertaken over the past years (e.g., (Fruin, 1971; Predtechenskii and Milinskiĭ, 1978; Boyce et al., 1999; Hwang et al., 1991), however, these have focused on movement speeds within the built environment. From the mid-1990 s, the first ship evacuation models started to appear in the literature (Vassalos et al., 2002; Galea and Owen, 1994; Galea, 2000), and these publications highlighted the need for the collection of maritime specific walking speed data, to take into consideration maritime specific aspects such as heel, trim and dynamic motions. Around this time, interest started to develop in quantifying the performance of people in maritime environments (Galea et al., 2002; Bles et al., 2002; Glen et al., 2003; Koss et al., 1997; Brumley and Koss, 2000).

Two significant land-based studies into the impact of the maritime environment on walking speeds attempted to reproduce key aspects of the maritime environment through the use of land-based simulators. Both studies occurred independently and at around the same time, 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).

TNO developed the Ship Motion Simulator (SMS) to generate data related to the impact of the inclination of a vessel on passenger walking speeds. The facility was rectangular in shape (a shipping container) and fitted with dividers to form three small passages some 2 m in length that required test subjects to turn at the end to enter the next leg of the passage. The rig also provided a very limited staircase capability. This again was restricted by the size of the available space. The entire facility was placed on a hydraulic platform that allowed it to be tilted to various angles of heel (up to 15°) and trim ±20°). The TNO analysis focused on the parameters of age, angle of inclination and direction of travel. Sixty subjects participated in the corridor heel experiments ranging in ages from 18 to 63 years. The data generated from this facility should be viewed with caution as the environment does not allow the development of steady-state walking speed, with participants being forced to slow down after a few steps to take a turn. The TNO analysis also did not consider gender as a potential variable. The results from this study suggest that walking speeds can be reduced up to about 15% for angles of heel up to 15° (Bles et al., 2002).

Fleet Technology of Ottawa and Fire Safety Engineering Group (FSEG) of the University of Greenwich, with funding from the Canadian Transportation Development Centre developed a facility, known as SHEBA (Ship Evacuation Behaviour Assessment) (Glen et al., 2003). The SHEBA facility allows measurements of human performance and behaviour in a typical ship passageway and stairway. SHEBA comprised of a 7 m by 4 m cabin attached to a 10 m by 2 m passageway at the end of which is a stairway. This entire structure was mounted on hydraulic rams capable of tilting the facility to up to 21°. The steel structure reproduces a ship's corridor and stair, with/without handrails. Tests were conducted with participants using life jackets and without life jackets. In subsequent developments of the SHEBA facility, tests were undertaken with reduced visibility resulting from the introduction of non-toxic smoke and a limited range of dynamic motion was introduced. Trials involving 250 participants at fixed static angles of heel ranging from 0° to 20° suggest a significant impact of *age, gender and degree of heel* on walking speed (Glen et al., 2003). Results suggest that walking speeds generally reduce with increasing angle of heel above about 10°, females experience a greater reduction in average walking speed than males with increasing angle of heel, older participants experience a greater reduction in average walking speed with increases in angle of heel than younger participants and maximum reduction in average walking speed is about 12% at 20° of heel (Galea, 2003). The negative impact of heel and trim on walking speed of individuals is also confirmed in other studies which have been conducted in smaller scale in land-based facilities (e.g., (Lee et al., 2004; Sun et al., 2018; Wang et al., 2021; Aghabayk et al., 2021). The data from both the SHEBA and SMS trials have been incorporated into maritime evacuation models (for example (Galea, 2003).

While previous studies have provided useful insight into how angle of heel may impact walking speed of individuals, all these studies have involved test subjects walking over relatively short distances, not representative of the type of distance that may be encountered in maritime applications. Furthermore, while the SHEBA trials involved participants wearing lifejackets, none of the studies have considered the impact of TPIS on participant performance at angles of heel. The SHEBA trials did reveal that wearing encumbrances such as lifejackets had an adverse effect on walking speeds at angles of heel (Galea, 2003), and so it is possible that TPIS may have an impact on walking performance. Furthermore, other studies have shown that the wearing of protective clothing and footwear can influence walking performance (Kong et al., 2013; Park et al., 2011). The nature of footwear can have a direct impact on the amount of grip the wearer has with the floor and if this is reduced, may lead to increases in the number of mis-steps and trips which consequently reduce walking speed (Chang et al., 2012; Chang et al., 2013). Furthermore, the possible negative impacts of TPIS on walking performance may be intensified with adverse vessel angle of orientation.

Indeed, regulatory authorities accept that wearing TPIS may negatively impact performance of passengers and crew and have adopted standards describing minimum performance requirements. TPIS approved by the Polar Code (IMO, 2017) must satisfy the testing and evaluation criteria recommended by the IMO (IMO SOLAS, 2004).This requires that abandonment suits can be donned, unassisted within two minutes. Furthermore, the International Organization for Standardization (ISO), in their standard for testing of immersion suits, requires that speeds measured over a distance of 30 m while wearing the immersion suit, should not be reduced by more than 25% when compared with normal walking speed (Immersion Suits Test Methods, 2012). To satisfy the regulatory requirements concerning walking speeds requires test data from only six test subjects. Clearly, with data from such a small number of participants the reliability of the walking speed analysis is questionable.

3. Experimental set-up and procedures

The experimental set-up and procedures are described in full in the Supplementary Material (see Supplementary Material S1 and S2). Here we provide an overview of the experimental set-up and procedures.

The test facility consisted of a corridor structure measuring 1.7 m in width, 2.2 m in height and 36 m in length. The corridor could be orientated at four different angles of heel, 0°, 10°, 15° and 20°. Two test facilities were constructed, one at the ARCOS safety centre in Tromsø (see Fig. 1), constructed from construction site corridor containers, and one at the ResQ safety center in Haugesund (see Fig. 2) constructed from wood (see Supplementary Material S1.1 for details).

For each angle of heel three types of clothing conditions were explored in which the participants wore either their normal clothing, identified as Suit-0, or a lightweight survival suit produced by Hansen Protection (Sea Pass passenger suit) identified as Suit-1 or an immersion suit with fully integrated buoyancy and thermal insulation produced by Viking (Yousafe Blizzard PS5002) identified as Suit-2 as depicted in Fig. 3 (see Supplementary material S1.2 for details). Participants were instructed to wear flat shoes to the trials. Both suits are of a ‘one size fits all’ design. For Suit-1 shoes could be worn either inside or outside the suit while for Suit-2, shoes were not to be worn.

Participants were assigned into groups associated with a suit type (three groups) and into sub-groups associated with heel angle (10°, 15° or 20°). Each participant was required to walk through the corridor, one person at a time, as quickly as possible without running (see Supplementary material S2 for details). On completing their passage through the corridor, the next participant would repeat the process. Participants were not permitted to observe others attempting to walk through the corridor. On completing their first passage through the corridor, participants completed a questionnaire designed to explore their experience (see Supplementary material S3 for details). Once all the participants within a group had completed the questionnaire, they repeated the process at 0° of heel. Thus, each participant generated two walking speed data points. The behaviour and performance of the participants as they passed through the corridor was recorded by three GoPro cameras installed at three locations in the corridor, one positioned to record the starting time, one positioned to record the time at which they crossed the centre line and one to record the time at which they crossed the finishing line (see Supplementary Material S2.4 for details). The cameras were also used to record behaviour of the participants as they passed through the corridor (see Fig. 4). In total, four categories of data were collected during the experiment, demographical/registration, walking speed (video), behavioural (video and questionnaire) and perceptions (questionnaire).

In total 210 participants were recruited for the trials, 125 in Tromsø and 85 at Haugesund (see Supplementary Material S2 for details). The trial design partitioned participants into three age groups (AG),

Fig. 1. The Tromsø test facility heeled at 20^0.

Fig. 2. The Haugesund test facility heeled at 20^0.

Fig. 3. Hansen Protection (Suit-1) and Viking Immersion suit (Suit-2).

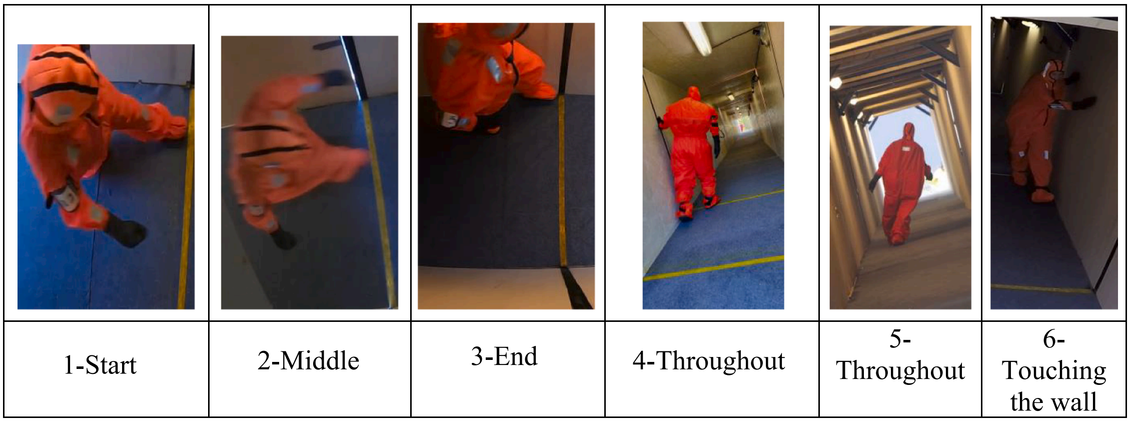


Fig. 4. Still images captured from trial video footage depicting the progress of participants at different stages of their movement through the heeled corridor.

Table 1
Total number of participants in each category including age groups (AG), following removal of disqualified participants.

Suit Type	Gender	0° Heel AG1/AG2/AG3	10° Heel AG1/AG2/AG3	15° Heel AG1/AG2/AG3	20° Heel AG1/AG2/AG3	Total (Excluding 0°)
Suit-0	Male	28/18/11	7/3/2	6/5/2	15/10/7	**57**
	Female	16/5/4	2/0/2	5/2/0	9/3/2	25
	Total	**44/23/15**	**9/3/4**	**11/7/2**	**24/13/9**	**82**
Suit-1	Male	10/3/13	6/2/3	0/0/0	4/1/10	26
	Female	6/10/3	1/4/2	0/0/0	5/6/1	19
	Total	**16/13/16**	**7/6/5**	**0/0/0**	**9/7/11**	**45**
Suit-2	Male	18/11/2	7/3/1	0/0/0	11/8/1	31
	Female	11/11/4	4/4/1	0/0/0	7/7/3	26
	Total	**29/22/6**	**11/7/2**	**0/0/0**	**18/15/4**	**57**
Overall Total		**89/58/37**	**27/16/11**	**11/7/2**	**51/35/24**	**184**

$AG1 \in (18-29)$, $AG2 \in (30-50)$ and $AG3 \in (50+)$. Attempts were made to have equal numbers in each age group and equal numbers of males and females however, this proved difficult. The distribution of age and gender within each suit and heel category is shown in Table 1. The data collection and data handling procedures were approved by the Norwegian Centre for Research Data (NSD) (see Supplementary Material S2.4 for details).

4. Results and data analysis

4.1. Data extraction

The process by which the walking speed data was extracted from the video footage is detailed in Supplementary Material S4. This involves extracting the time at which the participant crossed the start-line, the mid-point line and the end-line with times measured to an accuracy of $\pm$ 0.04 second. The number of times the participant touched the confining walls of the corridor was determined and in addition the number of missteps and falls was recorded (see Supplementary Material S4.1). Extraction of video data required approximately 190 person hours of effort.

Several participants were disqualified from the analysis for one of two reasons (see Supplementary Material S4.3 for details). During video analysis it was noted that a number of participants were 'running' even though they had been instructed to walk and not run. Running was defined as travelling at 3 m/s or greater (Glen et al., 2003; Koss et al., 1997; Brumley and Koss, 2000). The data from these participants were removed from the analysis. Furthermore, some participants were found to walk faster when at heel than at 0°. As heel is expected to have a neutral or negative impact on walking speeds, if the walking speed at 0° heel was found to be slower than 90% of their speed at heel, the data from these participants were also removed as it was considered that these participants were not fully engaged in the entire trial. Through this process data from 10 participants at 10°, 5 participants at 15°, and 11 participants at 20° were removed from the analysis. In total, data from 26 participants were removed, creating a data-set from 184 participants. The possible impact on results of analysis caused by removing aforementioned participants is discussed in Supplementary Material S4.3. Presented in Table 1 is a summary of the number of participants whose data contributed to the analysis.

Prior to the disqualification of 26 participants, a total of 18,480 data points were collected from the 210 registered participants, with 16,192 data points remaining following the removal of the disqualified participants.

4.2. Analysis of speed data and descriptive statistics

As data were collected at two sites (125 in Tromsø and 85 at Haugesund) the potential influence of trial location on mean walking speed was assessed to determine whether the two data-sets could be merged. A distribution identification test was conducted, and the Anderson-Darling test showed that the walking speed data derived from both sites were best represented by normal distributions with P-values of 0.36 and 0.14 for locations in Tromsø and Haugesund, respectively. Results from a

Table 2
Arithmetic mean and standard deviation of different groups according to suit type, gender and angle of heel.

Mean Speed (m/s) (Standard Deviation)		0° Heel	10° Heel	15° Heel	20° Heel
Suit-0	Male	2.32 (0.32)	2.53 (0.35)	2.20 (0.28)	2.11 (0.28)
	Female	2.22 (0.21)	2.10 (0.32)	2.02 (0.31)	2.01 (0.37)
Suit-1	Male	2.36 (0.34)	2.45 (0.33)	NA	1.71 (0.41)
	Female	2.12 (0.26)	2.16 (0.21)	NA	1.60 (0.22)
Suit-2	Male	2.26 (0.28)	1.92 (0.26)	NA	1.78 (0.39)
	Female	2.02 (0.24)	1.80 (0.28)	NA	1.41 (0.25)

Table 3
Definition and range of factors contributing to walking speed (according to the collected data).

Variable	Definition (Unit)
x_1	Age ($x_1 \in 18-72$ years old)
x_2	Gender ($x_2 \in$ Male $=0$, Female $=1$)
x_3	Angle ($x_3 \in 0^\circ$ to 20°)
x_4	Using Suit-1 ($x_4 \in$ Yes $=1$, No $=0$)
x_5	Using Suit-2 ($x_5 \in$ Yes $=1$, No $=0$)
x_6	Height ($x_6 \in 154-195$ cm)
x_7	Weight ($x_7 \in 48-123$ kg)

two-sample T–test showed that the influence of location of trial is not significant at a 5% significance level for mean speed values. Therefore, the two data-sets were merged. Furthermore, analysis showed that there was no significant difference between the average walking speed of individuals in first and second half of the corridor and so fatigue did not impact walking speeds (see Supplementary Material S4.2 for details).

In total 368 walking speed data points were collected from the 184 participants. Descriptive statistics (mean, standard deviation) for the data-set are presented in Table 2. The results suggest that, with the exception of a blip at 10° of heel, there is a general decrease in mean walking speed as the angle of heel increases. However, to determine how various factors such as age, gender and suit type impact walking speed as the angle of heel increases, requires the development of a regression model.

4.3. Regression model

Studies have shown that the correlation between walking speed (Y) and its predictors, such as age and gender of the individuals and angle of heel of the space is not necessarily linear (Glen et al., 2003). A method for handling non-linear relationships between variables is logarithmical (log) transformation of dependent and/or independent variables (Benoit, 2011). If the response variable (i.e., walking speed) is log-transformed, the effect of any predictor in a linear regression model would be a percentagewise reduction or increase in walking speed. Moreover, the potential for predicting negative walking speed is avoided. In our case, the log-transformation resulted in a more symmetrical distribution of the residuals, and an improved fit to the data, indicated by an increase in the value of R-squared. A log-linear multiple regression model for response variable *Y* (i.e., walking speed) and predictors x_i can generically be represented as follows:

$$\mathrm{Ln}(Y) = a_0 + a_1x_1 + a_2x_2 + \cdots + \varepsilon, \tag{1}$$

where $\varepsilon \sim \mathrm{Normal}(0, \sigma)$

By exponentiation of Eq. (1) we have:

$$\begin{aligned} &Y = e^{a_0} * e^{a_1x_1} * e^{a_2x_2} * \cdots * e^{\varepsilon}, (\text{if we take } e^{a_i} = A_i) \text{ Then :} \\ &Y = A_0 * A_1^{x_1} * A_2^{x_2} * \cdots * \tilde{\varepsilon}, \ \tilde{\varepsilon} \sim \mathrm{logNormal}(0, \sigma) \end{aligned} \tag{2}$$

In the log-linear regression model, each 1-unit increase in predictor x_i multiplies the expected value of Y by $e^{a_i} = A_i$. Here A_i can be interpreted as a growth factor, and $(A_i - 1)$is the relative increase in walking speed per unit increase of x_i (all other factors being kept constant). Y may be dependant not only on the predictors x_i but also on the interaction between predictors. The interactions between predictors can be represented by the terms $x_i * x_j$ with corresponding growth factor $A_{i \times j}$ in Eq. (2).

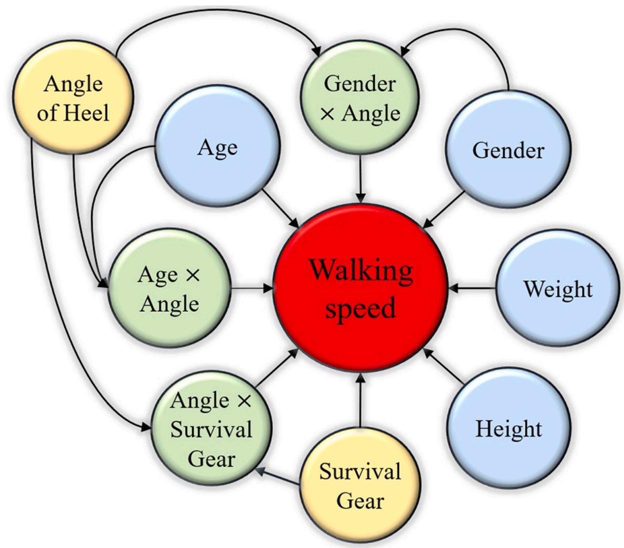


Fig. 5. Correlation between different factors in the log-linear regression model that significantly influence walking speed according to the collected data.

4.4. Impact of different variables – regression modelling

While there is a certain degree of randomness in walking speed of individuals, there is a number of personal factors that have been shown to have an impact on walking speed such as age, gender, height, weight and environmental factors such as angle of heel and trim (as discussed in (Park et al., 2011; Chang et al., 2012; Kim and Steinfeld, 2019; Shiwakoti et al., 2019; Lei and Tai, 2019; Heliövaara et al., 2012). In addition, we postulate that the nature of the TPIS worn by the individual – another environmental factor– may also impact walking speed. For the range of quantified variables presented in Table 3, the influence of each of the variables as well as the impact of their pairwise interaction on walking speed was investigated using stepwise log-linear regression (Rawlings et al., 2001), based on the regression model in Eq. (2). The regression analysis was performed using Minitab (version 19.2).

The result of the stepwise log-linear regression analysis for the estimation of walking speed can be represented by a Bayesian Belief Network (BBN) (Cooper and Herskovits, 1991). The BBN in Fig. 5 represents the causal relationships between the predicting factors which appeared to have significant influence on walking speed at a 5 % significance level. In the presented BBN model, walking speed is coloured in red while the impact of the personal and environmental variables is shown in blue and yellow respectively. Interaction terms, presented as green nodes, show that walking speed of different gender and age groups are not equally influenced by change in angle of heel. Furthermore, the negative impact of TPIS on walking speed changes with change in angle of heel.

According to the regression model presented in Section 4.3, multiple log-linear multiple regression was undertaken linking walking speed with the various influencing factors. According to the regression model, walking speed is presented as a product of different influencing factors and a random error term in Eq. (3).

$$Y = 1.5872 * 0.9982^{x_1} * 0.9323^{x_2} * 0.9999^{x_1 * x_3} * 0.9969^{x_2 * x_3} * 0.9928^{x_3 * x_4} * 0.9392^{x_5} * 0.9898^{x_3 * x_5} * 1.0037^{x_6} * 0.9975^{x_7} * \tilde{\varepsilon}, \ \text{where} \ \tilde{\varepsilon} \sim \mathrm{logNormal}(0, 0.1463). \tag{3}$$

Table 4
Change in walking speed given one unit increase in each of the influencing variables (when all other variables are fixed).

Variable	Definition	a_i	SE : a_i	A_i	Change in speed per unit increase	T-value	P-value
x_1	Age	−0.001815	0.000564	0.9982	−0.18% per year	−3.22	0.001
x_2	Gender	−0.0701	0.0289	0.9323	−6.8% for females	−2.43	0.016
x_5	Suit-2	−0.0627	0.0223	0.9392	−6.1% with Suit-2	−2.81	0.005
$x_3 \times x_1$	Angle × Age	−0.000112	0.000031	0.9999	−0.01% per degree ∗ year	−3.67	<0.001
$x_3 \times x_2$	Angle × Gender	−0.00309	0.001552	0.9969	−0.31% per degree for females	−1.99	0.047
$x_3 \times x_4$	Angle × Suit-1	−0.00721	0.00168	0.9928	−0.7% per degree with Suit-1	−4.3	<0.001
$x_3 \times x_5$	Angle × Suit-2	−0.01021	0.00188	0.9898	−1.0% per degree with Suit-2	−5.44	<0.001
x_6	Height	0.00372	0.00133	1.0037	0.37% per cm	2.79	0.006
x_7	Weight	−0.002489	0.000654	0.9975	−0.25% per kg	−3.8	<0.001

Note: SE = Standard Error (of the coefficient a_i).

Given the variables defined in Table 3, the log-linear regression model can predict the walking speed with $R^2 = 49.9\%$, which means that the model can explain about 50% of variation in walking speed. This degree of correlation is considered relatively high as there are many random effects that could influence the walking speed of an individual in a particular experiment. These also include, e.g., level of calf/quadriceps strength, hip flexion/abduction, impact of adrenaline, etc. (Inoue et al., 2017) which are challenging to quantify and were not measured in this experiment.

The predictors (Fig. 5), log-linear regression model coefficients (a_i), corresponding Standard Error (SE) terms, and the respective coefficients (A_i) in Eq. (3) are described in more detail in Table 4. The table presents how the walking speed is affected by the increase in each of the influencing variables by one unit when all other variables are held constant. Note that the only predictor that increases walking speed is participant height, i.e., an increase in height results in an increase in walking speed, whereas all the other predictors have a negative impact on walking performance. Similarly, synergies between age, gender, survival suit and angle of heel adversely affect walking speed (presented as green nodes in Fig. 5). All the aforementioned variables had a significant influence (at the 5% significance level as seen by the P-values in Table 4) on walking speed.

Table 4 also indicates that at 0° of heel, females walked on average 6.8% (i.e., $1 - A_2 = 1 - 0.9323$) slower than their male counterparts. Furthermore, females walk 0.31% ($1 - A_{3\times2} = 1 - 0.9969$) slower for each degree increase in angle of heel. This is represented through the Angle × Gender term which generates an additional reduction term for females when they walk on a heeled surface. The combined effect, e.g.,

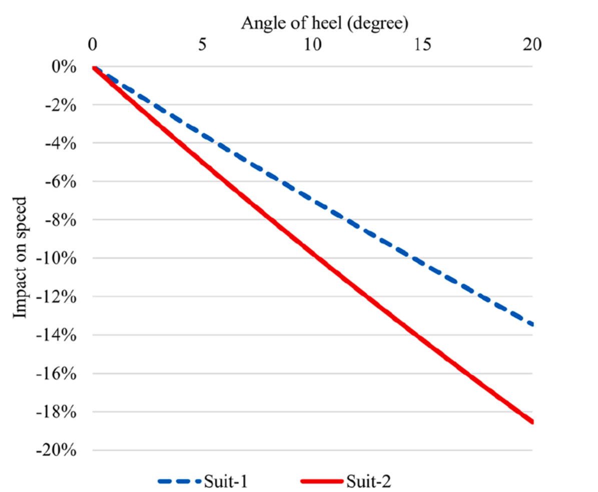
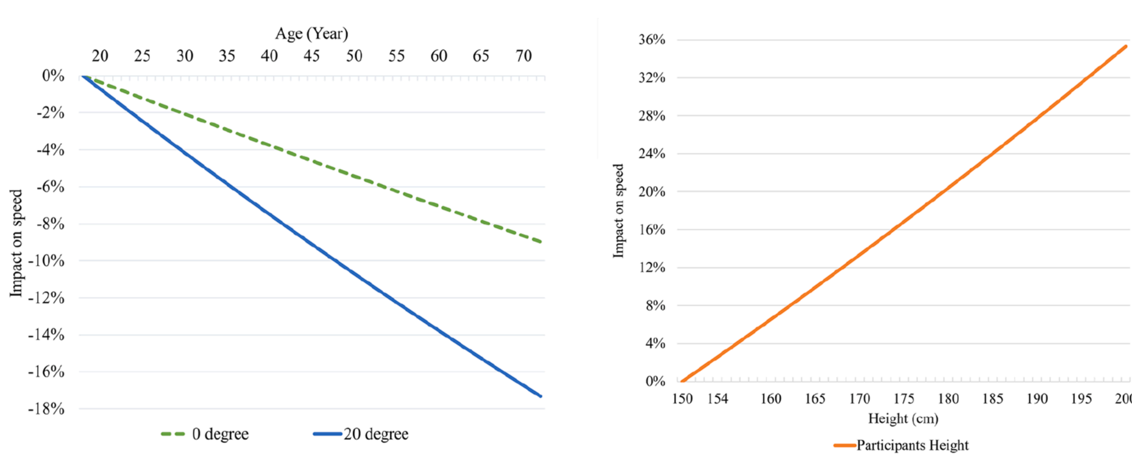


Fig. 7. Percentage of reduction in walking speed for different survival suit as a function of angle of heel.

at 10° heel, results in females walking approximately 9.6% $(1-(0.9323 \times 0.9969^{10}))$ slower than males of the same age, weight, height who are wearing the same TPIS.

The estimated effects of the continuous variables age and height on walking speed according to Eq. (3), are depicted in Fig. 6(a) and Fig. 6(b), respectively. As can be seen, as summing all other variables remain unchanged, at 0° of heel, increasing age from 18 to 72 years will reduce the walking speed by about 9% while at 20° of heel the reduction is



(a) Impact of Age on walking speed (b) Impact of Height on walking speed

Fig. 6. Impact of participants (a) age and (b) height on walking speed at 0° and20° of heel.

about 17%.

Note that the additional adverse effect of age that increases with higher angle of heel, is due to the interaction term Angle × Age. In contrast, an individual with height 190 cm would walk about 21% faster than a person of height 160 cm both at 0° and 20° of heel (since there is no significant correlation between height and angle of heel, this impact remains unchanged in different angles). Presented in Fig. 7 is the reduction in walking speed only as a function of angle of heel and suit type, without the interaction of other variables. Over the specified range of the continuous variables within the collected data, the maximum changes in walking speed are, an increase of over 31% due to increase in height and a maximum decrease in walking speed of about over 18% (at 20° of heel) due to interaction of Suit-2 and angle of heel.

Similar to age and weight, angle of heel and the wearing of survival suit produced a negative impact on walking speed. The effect of the interaction between angle of heel and the two different survival suits on walking speed (using Eq. (3)) is presented in Fig. 7. The impact of Suit-1 and Suit-2 increases significantly with angle of heel (see Fig. 7). However, Suit-2 had the greater impact decreasing walking speed by 18% at 20° compared to its performance at 0°. In contrast, Suit-1 decreases walking speed by 13%. The additional adverse effect of Suit-2 in 0° of heel is discussed in Section 5.

4.5. Analysis of behavioural data

Analysis of the video footage also revealed the number of times participants miss-stepped (slipped) and reached out with either one hand or both hands for support from the wall (hand wall contact or HWC) at least once during their journey along the corridor (see Supplementary Material S4.1 for details).

Presented in Table 5 is a summary of the percentage of participants who slipped/miss-stepped (slipped) or reached out for the support from the wall (HWC). As can be seen there is little or no slips for Suit-0 while for both Suit-1 and Suit-2 there are many slips with the frequency increasing with angle of heel. While at 20° of heel, both Suit-1 and Suit-2 result in approximately 90% of participants slipping, Suit-2 generates considerably more slips at lower angles of heel. It is noted that while Suit-1 produces no slips at 0° of heel, almost 20% of the participants in Suit-2 slip at 0° of heel.

$$Y = 1.5872 * 0.9982^{\mathrm{Age}} * 0.9323^{\mathrm{Gender}} * 1.0037^{\mathrm{Height}} * 0.9975^{\mathrm{Weight}} * 0.9392^{\mathrm{Suit-2}} * \widetilde{\varepsilon}, \text{ where } \widetilde{\varepsilon} \sim \mathrm{logNormal}(0, 0.1463) \tag{4}$$

Table 5 also shows that as the angle of heel increased, the frequency of participants who required to touch the wall for support also increased. This trend occurs for all three suit types but is more pronounced for Suit-1 and Suit-2 at high angles of heel (20°), suggesting that participants were less stable at high angles while wearing the protective clothing.

Participants answers to questions in the post-trial questionnaire reflecting their opinion concerning the influence of different environmental factors on their walking speed. The impact that different features of the TIPS had on walking performance was assessed using a five-point Likert scale (see Supplementary Material S3 and S3.1).

In total six factors that potentially impacted walking performance while wearing the suit were considered. These were: fit of the suit, ability to hear, ability to move with the suit, comfort of footwear, ability to see and weight of the suit. Collapsing the two negative ratings (very negative and negative) we find that Suit-2 scores consistently higher negative ratings than Suit-1 across all factors. For 'fit of the suit', Suit-2 had 1.6 times higher negative score than Suit-1 and this increased to a 18.5 times higher negative score of the factor 'weight of the suit'. The highest negative score was for 'comfort of footwear' with Suit-2 scoring 96%.

Table 5
Percentage of participants who slipped and who made hand-wall contact (HWC).

Suit Type	Angle of heel							
	0°		10°		15°		20°	
	Slip	HWC	Slip	HWC	Slip	HWC	Slip	HWC
Suit-0	0%	0%	0%	12%	0%	60%	2%	63%
Suit-1	0%	0%	18%	10%	NA	NA	89%	100%
Suit-2	19%	7%	45%	40%	NA	NA	92%	100%

5. Discussion

5.1. The impact of TPIS on walking speed

While the current IMO evacuation analysis guidelines (IMO, 2016) do not require the analysis of evacuation scenarios involving adverse angles of orientation, Eq. (3) provides a means for determining walking speeds as a function of orientation (angle of heel) and nature of protective clothing, for population specifics of age, gender, height and weight. Thus Eq. (3) incorporates two environmental factors (angle of heel and type of protective clothing) into the determination of walking speeds for maritime evacuation analysis. This capability is particularly useful when evacuation modelling is used to analyse accident scenarios.

However, the primary research question that this work addresses is to quantify the impact that TPIS has on movement speeds. This is of importance when undertaking passenger ship evacuation analysis. Clearly, if wearing TPIS significantly impacts movement speeds, this will need to be factored into evacuation analysis, where time is critical. Currently, evacuation analysis required by IMO (IMO, 2016) only considers the vessel at 0° of heel and so walking speeds within the IMO guidelines are only specified for this condition. If the angle of heel is set to 0° in Eq. (3) we have:

From Eq. (4) we note that Suit-1 does not impact walking speed at 0° of heel while Suit-2 does have an impact. If we compare walking speeds in Suit-2 with those of Suit-0 we find that walking speeds are reduced by a factor of 6.1% at 0° of heel. At 20° of heel, walking speeds are reduced by about 24%. Thus, if TPIS are worn by passengers from the start of the assembly process, walking speeds can be adversely affected, even at 0° of heel, which can have a negative impact on assembly times. Thus, when we consider the impact of TPIS, we have to consider the type of suit worn and the impact this may have on walking performance. The reason for the difference in performance of the two types of suit is complex, however, some insight into the causes of these differences may be found in the behavioural and survey responses.

From analysis of the video footage, 19% of participants who wore Suit-2 slipped (see Table 5) even at 0° of heel while none of the participants slipped in Suit-0 or Suit-1. Thus, the footwear provided by Suit-2 clearly impedes movement. As can be seen in Table 5, the proportion of participants slipping while wearing Suit-2 increases as the angle of heel increases reaching 92% at 20° of heel. While the slippage proportion for Suit-1 also increases as heel angle increases, it does so at a lower rate. These observations are consistent with the trends observed in Fig. 7 where Suit-2 generates lower walking speeds than Suit-1 at all angles and the degradation in performance increases as the angle of heel increases.

From observation of the video footage and the actual trials, the slippage caused by both Suit-1 and 2 is thought to be due to either to the foot/shoe of the participant slipping inside the boot of the suit or the sole of the suit footwear not providing sufficient grip to the floor surface. Participant foot slippage inside the suit is thought to be due to the 'one size fits all' concept resulting in the boot of the suit being too large for many people. This occurred even though all the participants had the ankle straps secured prior to the start of their journey down the corridor. The problem of the poor fitting boot became more apparent as the angle of heel increased.

In addition, replies to the participant questionnaire support the view that Suit-2 created a greater impediment to rapid movement compared to Suit-1. Suit-2 scored higher negative ratings on all measures dealing with how the suit impacted walking performance (see Supplementary Material S3.2). This scored poorly on matters concerning the 'weight of the suit' – 18.5 times higher negative score than Suit-1 and 2.1 times higher negative score for 'comfort of footwear'. Analysis of open comments in the survey showed that bulkiness of Suit-2 was another factor which negatively influenced walking speed of 73% of male and 70% of female participants. While some of these negative factors may be unavoidable due to the need to provide enhanced thermal protection, issues associated with the footwear are considered important as they can provide a significant impediment to safe evacuation and should be addressed through improved design.

5.2. Walking speed data-set suitable for IMO evacuation analysis

Within the IMO guidelines for evacuation analysis (IMO, 2016) unhindered mean walking speed for individuals at 0° of heel are specified as a function of two personal parameters, age and gender. The regression analysis presented in this paper consisted of an additional two personal parameters, weight and height. To make this regression analysis more compatible with the current IMO expectations, the regression analysis was repeated removing the two additional personal parameters. Thus, within the simplified IMO compatible walking speed model, four predictors are included, two personal predictors (age and gender) and two environmental predictors (angle of heel and suit type).

In the new (simplified) regression model, all parameters and introduced interactions were significant (at the 5% significance level) with the exception of the Angle × Gender interaction (P-value = 0.07). This is the result of omitting two of the significant factors (height and weight) that compromised the P-value for the interaction term Angle × Gender (which was significant in the original model). In the simplified model, the Angle × Gender interaction term has been retained and so the simplified model is given by:

$$Y = 2.55 * 0.9979^{\mathrm{Age}} * 0.9213^{\mathrm{Gender}} * 0.9999^{\mathrm{Angle}*\mathrm{Age}} * 0.9970^{\mathrm{Angle}*\mathrm{Gender}} * 0.9934^{\mathrm{Angle}*\mathrm{Suit-1}} * 0.9363^{\mathrm{Suit-2}} * 0.9901^{\mathrm{Angle}*\mathrm{Suit-2}} * \widetilde{\varepsilon}; \quad \text{where} \quad \widetilde{\varepsilon} \sim \mathrm{logNormal}(0, 0.1495) \tag{5}$$

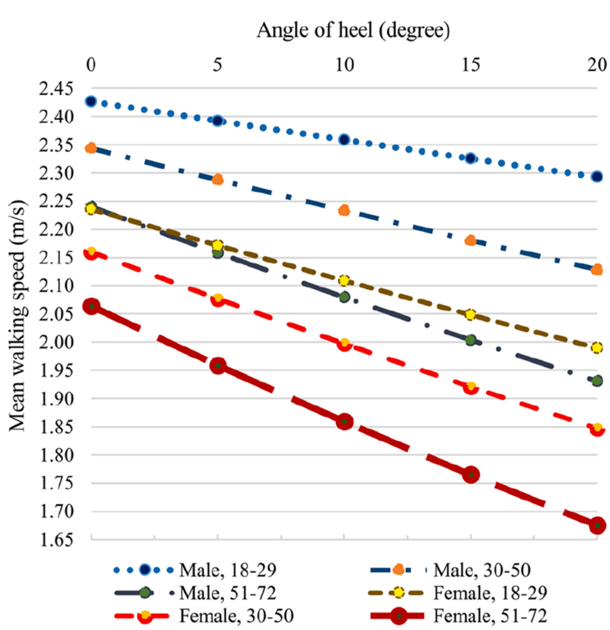


Fig. 8. Comparison of mean walking speed without TPIS generated by the simplified regression model (Eq. (5)) based on age, gender and angle of heel.

The simplified model given by Eq. (5) predicts the walking speed with $R^2 = 47.4\%$, which is close to the R^2 produced by the original model in Eq. (4) (49.9%). To obtain the mean walking speed for individuals not wearing suits, the terms for Suit-1 and Suit-2 in Eq. (5) were set to zero (i.e., Suit-1 = 0, Suit-2 = 0), and as a result, the last three factors are equal to 1. Based on this, the mean walking speed as a function of age, gender and angle of heel that is presented in Fig. 8, suggests that average travel speeds without TPIS generally decrease with increasing angle of heel for all age groups. Furthermore, for males the decrease in average walking speed from 0° to 20° of heel is 6%, 9% and 14% for age groups 18–29, 30–50 and 51–72 respectively. For females the reductions in average walking speed are 11%, 14% and 19% for the three age groups, respectively. We note that these results are in broad agreement with the SHEBA data-set (Galea, 2003; Lee et al., 2004), in particular, that walking speeds generally reduce with increasing angle of heel, females experience a greater reduction in average walking speed than males with increasing angle of heel, older participants experience a greater reduction in average walking speed with increases in angle of heel than younger participants and the maximum reduction in average walking speed in the SHEBA trials was about 12% at 20° of heel.

The walking speeds generated by the simplified model (Eq. (5)) for 0° of heel and Suit-0 generally agree with the walking speed data presented within the IMO evacuation analysis guidelines (IMO, 2016). In particular, mean travel speed decrease with increase in age and males are on average faster than females. However, within the guidelines, the unhindered walking speed ranges between a minimum 0.56m/s for females older than 50 years of age up to a maximum of 1.85m/s for males younger than 30 years of age. In comparison, the minimum walking speed determined by the simplified model is 1.74 m/s (female, age group 51–72 years of age, 0° heel, Suit-0), while the maximum walking speed is 2.85 m/s (male, age group 18–29 years of age, 0° heel, Suit-0). Thus, the mean walking speed predicted by the simplified model (based on the data collected in the trials) for all age groups for both males and females are bigger than the mean walking speed values specified in the IMO guideline document (Vassalos et al., 2002). Furthermore, the actual walking speed measured during the trials (at 0° of heel for Suit-0) ranges between 1.73 m/s and 2.99 m/s. Thus, the minimum and maximum walking speeds measured in the trials are about respectively 67% and 38% greater than the corresponding minimum and maximum walking speed specified within the IMO guidelines document (Vassalos et al., 2002).

Given that a there was a good mix of genders (62% male and 38% female) and a reasonable mix of ages (48% 18–29 years of age, 32% 30–50 years of age and 20% 51–72 years of age) it is not clear why the measured walking speeds are so much greater than those typically used in evacuation modelling. However, it is suggested that this could be due to all trial participants being recruited from a healthy and physically fit population. The vast majority of the participants were Norwegian (90%), with average height/weight of 181 cm/85 kg and 167 cm/68 kg, and average Body Mass Index (BMI) of 26 (SD = 4.08) and 24.29 (SD = 3.42) for male and females respectively. Furthermore, the majority of both males (75 %) and females (76%) claimed that they worked out two to five times a week. Thus, the trial group are not necessarily representative of the internal population or more specifically, of the general cruise or ferry passenger demographic.

Given the high values for walking speeds generated by the simplified model, this will result in shorter evacuation times and hence produce a less conservative safety analysis than would be expected if the currently accepted walking speed data-set is used. For this reason, it is suggested that the walking speeds predicted by the simplified model may not be appropriate to use directly within evacuation analysis. However, rather than use the predicted walking speeds directly in evacuation analysis, the model can be used to calculate walking speed reduction factors appropriate for various environmental conditions (heel and Suit type) for each gender and age group. The reduction factor is then applied to the walking speed specified within the IMO evacuation guidelines (Vassalos et al., 2002) to generate the appropriate walking speed for the angle of heel and suit.

The reduction factor (RF) is given by the ratio of the walking speed (WS) predicted by Eq. (5) for the specific condition of age, gender, angle of heel and suit type and dividing it by the predicted WS for the same age and gender for angle of heel 0° and Suit-0:

$$RF_{age,gender,angle,Suit} = \frac{Y_{Age,Gender,Angle,Suit}}{Y_{Age,Gender,Angle=0,Suit=0}} = 0.9999^{Angle*Age} * 0.9970^{Angle*Gender} * 0.9934^{Angle*Suit-1} * 0.9363^{Suit-2} * 0.9901^{Angle*Suit-2} \quad (6)$$

Thus, the walking speed reflecting the impact of the angle of heel and the nature of the suit worn is given by:

$$WS_{Age,Gender,Angle,Suit} = WS_{Age,Gender,Angle=0,Suit=0} \times RF_{Age,Gender,Angle,Suit} \quad (7)$$

where Walking Speed$_{Age,\ Gender,\ Angle=0,\ Suit=0}$ is given by the appropriate value from (IMO, 2016). The average reduction factors calculated using Eq. (6) for the identified age ranges, are presented in Table 6 for males and Table 7 for females.

Table 6
Reduction factors for mean walking speed for males walking at various angles of heel with various Suit types.

Suit type	Male group					
	Age group	Angle of heel				
		0°	5°	10°	15°	20°
Suit-0 (No Suit)	18–29	1	0.986	0.972	0.958	0.945
	30–50	1	0.978	0.956	0.935	0.914
	51–72	1	0.963	0.928	0.894	0.862
Suit-1	18–29	1	0.954	0.910	0.868	0.828
	30–50	1	0.944	0.892	0.842	0.795
	51–72	1	0.932	0.869	0.810	0.755
Suit-2	18–29	0.936	0.879	0.824	0.773	0.726
	30–50	0.936	0.868	0.805	0.747	0.692
	51–72	0.936	0.859	0.787	0.722	0.662

Table 7
Reduction factors for mean walking speed for females walking at various angles of heel with various Suit types.

Suit type	Female group					
	Age group	Angle of heel				
		0°	5°	10°	15°	20°
Suit-0 (No Suit)	18–29	1	0.971	0.943	0.916	0.890
	30–50	1	0.963	0.928	0.894	0.861
	51–72	1	0.949	0.901	0.855	0.812
Suit-1	18–29	1	0.940	0.883	0.830	0.780
	30–50	1	0.930	0.866	0.805	0.749
	51–72	1	0.918	0.843	0.775	0.711
Suit-2	18–29	0.936	0.865	0.800	0.739	0.684
	30–50	0.936	0.855	0.781	0.714	0.652
	51–72	0.936	0.846	0.764	0.690	0.624

An important observation concerning the combined impact of wearing TPIS as the angle of heel increases, is that walking speeds can be significantly decreased by the combined impact. The negative effect on walking speeds is not simply a linear combination of both factors. Based on the data presented in Table 6 and Table 7 the following general trends in walking speed reduction are noted:

- The walking speed of females are more severely impacted by heel than males in all age groups for all types of suit.
- The negative impact of heel on walking speeds increases as the angle of heel increases, irrespective of age or gender or suit type.
- At 0° of heel, males and females are equally impacted by wearing Suit-1 and Suit-2.
- At 0° of heel, wearing Suit-1 does not adversely impact walking speeds while wearing Suit-2 results in a 6.4% reduction in walking speed irrespective of age or gender.
- For males aged 18–29, the impact of wearing Suit-2 produces a reduction of 6.4% in walking speed at 0° angle of heel while 20° angle of heel results in 5.5% reduction in walking speed if the same group wear Suit-0. Thus, for this age group wearing Suit-2 has almost similar negative impact on walking speed as a 20° heel while wearing Suit-0. Note that the combined impact of wearing Suit-2 and 20° heel is a 27.4% reduction in walking speed, which is noticeable more than adding each individual impact.
- The negative impact on walking speeds of wearing Suit-1 or Suit-2 at positive (>0°) angle of heel increases with age for both males and females.
- The negative impact on walking speeds of wearing Suit-1 or Suit-2 increases as the angle of heel increases for both males and females.
- The negative impact on walking speeds of Suit-2 is more significant than that of Suit-1 for all angles of heel, across all age groups and genders.
- The most severe reduction in walking speeds occurs at 20° of heel for the oldest age group while wearing Suit-2. This results in walking speeds being reduced by 34% for males and 38% for females.

Currently, the ISO standard suggests TPIS that cause reductions in walking speeds of up to 25% are acceptable (Immersion Suits Test Methods, 2012) . However, it remains to be demonstrated the impact that this type of 'acceptable' reduction in walking speeds will have on evacuation analysis. While considered acceptable from an equipment acceptance criterion, its potential impact on evacuation analysis cannot be ignored and so should be factored into evacuation analysis. It is thus essential to identify the magnitude of walking speed reduction incurred by different types of TPIS. Furthermore, if adverse angles of heel are also considered in the evacuation analysis, this combined with the impact of TPIS can have a severe impact on walking speeds, producing reductions of up to 38% compared to walking speeds without wearing TPIS and at zero angles of heel.

It is noted that the regression model represents the impact of the critical factors on walking speed as a linear function (for example see Fig. 8). However, the trends in the actual data can deviate from linear behaviour, in particular at low angles of heel (see Table 2). This could be due, at least in part, to the low number of participants (and hence data points) in some of the cohorts (see Table 1). Finally, if the log-linear regression analysis is repeated with the previously excluded groups of disqualified participants (see Section 4.1) now included, the identified influencing factors remain significant, albeit with slightly different corresponding coefficients. Furthermore, inclusion of the additional data points reduces the R^2 value by 0.04 % points.

6. Limitations

As with any experimental study involving human test subjects, there are limitations associated with this work which should be considered when reviewing the results. The limitations of the current study are identified as follows:

- It is acknowledged that this experiment was carried out in a controlled environment in which all possible hazards were mitigated to assure the safety of all participants. This is clearly not the situation that would be experienced in a real-life emergency scenario (on-board a passenger ship). For example, in a real situation the floor surfaces may be wet making them slippery and so increasing the difficulty in walking. However, in order to undertake the research in an ethical manner it was necessary to exclude such factors.
- While angles of heel were incorporated within the experiment, dynamic motion as may be found on-board a vessel was excluded. The inclusion of dynamic motions is left for further research.
- As the trials were conducted by a single participant at a time, the impact of group behaviours or contra-flows were not considered. This research focused on the collection of unimpeded walking speed data similar to that currently used in evacuation analysis. Thus, the impact of groups behaviours, while of importance, was considered beyond the scope of the current project and is left for further research.
- The sequence of walking through the corridor at two angles (0° and heeled case) should ideally have been randomised for each participant. However, this was impractical due to the time required to change the angle of heel. Therefore, all participants consistently walked first through one angle of heel and subsequently 0° of heel.
- All participants walked through the corridor with it heeled towards their left. It is possible that walking performance could be influenced by the handedness of the participant. As this was not explored in these trials, this aspect is left for further research.
- The trial participants were all fit and healthy with many undertaking regular exercise two to five times per week. Within the experimental population, just 9% of the participants had BMI greater than 30 which is classified as obese. It is noted that in the UK and USA 27% and 38%, respectively of the population are classified as obese (Gallagher et al., 2000). Thus, the sample population used in the trials may not be considered fully representative of the target population. While further research is required to include a wider cross-section of the public, the walking speeds measured in these trials may be considered to be representative of upper limits. Furthermore, in order to be conservative, the reduction factors suggested in this paper should be considered as minimum values until further research can be undertaken.
- Only two types of protective suit were assessed. However, the results suggest that the design of protective clothing can have a significant impact on walking performance. Hence, it is essential that each unique concept in protective clothing is assessed for its impact on walking performance.

7. Conclusion

The safe evacuation of passenger ships is always challenging, particularly in arctic regions where extreme cold requires passengers to wear TPIS prior to abandoning the vessel. While the primary requirement is that the survival suit must provide thermal protection, it is also essential that it does not impede evacuation. To be considered appropriate for use, including cold conditions, the ISO standard requires that the wearing of TPIS must not reduce average walking speed by more than 25%. Compliance with this requirement is demonstrated by determining the average walking speed produced by only six individuals wearing the TPIS and walking over 30 m under conditions of 0° of heel. Currently, the acceptance requirements do not consider age or angle of heel as potentially important factors in influencing walking speeds and so these factors are ignored in the acceptance requirements.

To assess the impact of these variables on walking speeds, a unique study was undertaken that involved the development of a 36 m long test facility resembling a ships corridor. The facility could be orientated to four different angles of heel (0°, 10°, 15°, and 20°) enabling walking speeds to be evaluated for each orientation. In total walking speeds from 210 participants (males and females) ranging in age from 18 to 72 years were collected. Participants were instructed to walk through the corridor twice, first at 10°, 15° or 20° of heel and then at 0° of heel. Participants wore either normal clothing or one of two types of survival suit, Suit-1 or Suit-2, with Suit-2 being heavier and bulkier than Suit-1.

Results of the analysis demonstrate that gender, age, height, weight, angle of heel and the nature of the survival suit significantly influenced walking speed. For comparison purposes, the impact of heel and suit type on walking speed is assessed by comparison to the walking speed at 0° of heel while wearing normal clothing.

The analysis suggests that males consistently walked faster, on average, than females within all age groups and under all conditions. However, at 0° of heel, the reduction in average walking speed due to wearing the survival suit (i.e. Suit-1 or Suit-2) was the same for males and females and independent of age group. For Suit-1 there was no reduction in average walking speed, while for Suit-2, the average reduction in walking speed was 6.4%. Furthermore, at all other angles of heel and for all clothing states, the reduction in average walking speeds for females was greater than that for males and the reduction in walking speeds increased with age. The most significant reduction in walking speeds occurred at 20° of heel for Suit-2, resulting in a 38% reduction for the female 51–72-year age group while the corresponding reduction for Suit-1 was 29%. The reduction in walking speeds due to wearing protective clothing becomes more severe as the angle of heel increases and is clearly dependent on the nature of the protective clothing, with reductions due to Suit-2 being greater than Suit-1.

As reductions in walking speed due to the nature of the survival suit and the angle of heel can be significant, it is important to take these factors into consideration when undertaking evacuation analysis. For the two types of survival suit examined in this study, a method for calculating the appropriate reduction in walking speed as a function of age, gender, angle of heel and survival suit type has been provided.

As only two types of survival suit were assessed in this study and the results produced by both differed considerably, it is suggested that suit specific walking speed reduction factors should be specified by suit manufacturers. If walking speed reduction factors for a specific suit are not available, it is suggested that the most severe reduction factors provided in this study should be utilised in evacuation analysis.

CRediT authorship contribution statement

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

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssci.2021.105621.

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Annex IV – Supplementary Material for Paper II

Supplementary material: An experimental analysis of the impact of thermal protective immersion suit and angle of heel on individual walking speeds

Supplementary Material for An Experimental Analysis of the Impact of Thermal Protective Immersion Suit and Angle of Heel on Individual Walking Speeds

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This document presents supplementary material for Azizpour, et., al., [S1] relating to the design and construction of the experimental facility and the experimental methodology employed in the study.

S1. Experimental set-up

S1.1. Corridor set-up

The experimental facility consisted of a 36 m long corridor constructed in six sections each 6 m long. The cross-section of each corridor segment was 2.2 m in height and 1.7 m in width. To produce the desired angle of heel the side of each corridor section was raised to the appropriate height using a hydraulic jack and a set of support legs inserted beneath the raised side of the corridor section as shown in Fig. S1. The support legs were designed in order to maintain the desired angle of heel $(10°, 15° and\ 20°)$ and to withstand the load of the corridor sections and participants. A stability analysis for the corridor at the maximum angle of heel $(20°)$ demonstrated that the corridor was quite stable. However, as a safety measure, a set of counterweights, placed by the raised side of the corridor were lashed to the corridor to ensure that it would not topple over. The counterweights consisted of 220 litre drums filled with water at the Tromsø site and three 1000 litre tanks filled with water at the Haugesund site. Three persons were required to heel each corridor section to the desired angle, one involved in jacking the corridor and the others involved in positioning the legs (Figs. S2 and S3). It took approximately 4 minutes to jack up and secure each individual section or approximately 30 minutes to prepare the entire facility at the desired heel angle. Conversely, approximately 3 minutes were required to lower and secure each individual section back to 0° of heel, requiring about 20 minutes in total.

The Tromsø test facility was constructed using steel corridor containers. These are used for sheltering sidewalks in construction sites to prevent debris from falling on pedestrians Fig. S2. The interior walls and floor of each section were covered with plywood panels to seal the sides of each unit and to create flat smooth surfaces. The floor of each section was fitted with wall-to-wall carpeting to provide a similar surface to that typically found in passenger ships. Fluorescent lighting was mounted to the side walls to ensure a uniform well-lit illumination throughout the corridor. Luminosity measured one meter above the floor was on average 400 lux, which is four times more than the minimum average (100 lux) recommended by the appropriate standard [S2].

The test facility constructed at the ResQ safety center in Haugesund was essentially identical to the facility in Tromsø. The Haugesund facility was constructed entirely from wood with identical interior dimensions and identical finishes to the walls, floors, and identical interior lighting conditions. The process for heeling the Haugesund corridor was identical to that used in Tromsø (see Fig. S3).

S1.2. Survival suits

Two different types of TPIS(s) were used in the trials, a lightweight protection suit produced by Hansen Protection (Sea Pass Passenger Suit), identified as Suit-1, and a heavier and bulkier immersion suit produced by Viking (Yousafe Blizzard PS5002) identified as Suit-2 (see Fig. S4). Suit-1 came sealed in vacuum packages (one size fits all), did not have a thermal protection layer and shoes could be worn either inside the suit or on the outside over the suit. Suit-2 was provided in a reusable bag and was also a one-size-fits-all suit, with fully integrated buoyancy and thermal insulation. Suit-2 was worn without shoes.

a. A steel corridor section used in the construction of the Tromsø corridor at 0° of heel.

b. The Haugesund corridor fabricated from wood under construction and at 0° of heel.

c. Support legs for heeling the Tromsø corridor at 10° and 20° of heel.

d. Support legs for heeling the Haugesund corridor at 10° and 20° of heel.

S1: The Tromsø and Haugesund corridors under construction

S2:The Tromsø test facility heeled at 20°

S3:The Haugesund test facility heeled at 20°

S4:Hansen Protection and Viking Immersion suit

S2. Experimental procedure and data collection

The experiment was designed to collect human performance data relating to individuals walking at four different angles of heel, $0°, 10°, 15°, and\ 20°$ while wearing one of two different types of survival suits and normal clothing. The experiment was designed such that each participant walked first at one angle of heel and subsequently at $0°$ of heel (with the same type of clothing). This enabled a comparison of individual walking speeds at $10°, 15°, and\ 20°$ degree of heel with their walking speed at $0°$ of heel while wearing a particular type of clothing. As there were three different clothing states (Suit-0 (normal clothing), Suit-1 and Suit-2) and three angles of heel $(10°, 15°, and\ 20°)$, there were a total of 9 combinations of angle and clothing type in addition to the requirement for all participants to walk at $0°$ heel. In order to achieve a balanced number of participants with a similar distribution of age in each cohort, three defined age groups were defined (below 30, 30 to 50 and above 50 years of age) and participants were distributed in all the cohorts randomly and as equally as possible.

S2.1. Research ethics approval and recruitment of participants

Data collection required permission from the Norwegian centre for research data (NSD). According to the NSD requirements, it was necessary to conduct a risk analysis associated with the data collection and to adopt appropriate measures for personal data protection. The procedures adopted were documented and submitted to NSD, and when approval was granted (28.03.2018) recruitment of participants commenced. Participants were recruited through various means, including, social media, local newspapers, local TV channels, and leafletting in public places. Participants were also recruited through university networks. Members of the public interested in participating were requested to register online prior to the commencement of the trials. However, a number of volunteers turned up at the test facility on the day of the trials without prior registration. These volunteers were included and were required to complete the registration process at the test facility. In total 210 members of the public were recruited, with 125 people participating in six days of trials at Tromsø from 06/08/2018 to 12/08/2018. An additional series of trials were run at Haugesund for eight days from 05/04/2019 to 23/08/2019 in which 85 members of the public were recruited.

S2.2. Experimental procedure

Upon arrival, participants received a preamble describing the procedure of the experiment, safety instructions, and a consent form which they needed to sign before partaking in the trial. Those who had not registered online were required to complete the registration form. On completion of the registration formalities, participants wearing one of the survival suits were instructed to don the survival suit (Suit-1 or -2). The survival suit would be checked by a team member to ensure it was correctly donned, and the group would then be taken to the test facility.

When assembled outside beside the facility, participants were instructed that they were required to walk through the heeled corridor one person at a time. They were instructed to walk as fast as they could without running as if they were making their way to lifeboats in an orderly manner. Participants were not permitted to observe others making their way through the heeled corridor. Once participants walked through the heeled corridor $(10°, 15°\ or\ 20°)$ they completed the trial questionnaire. While participants were completing the questionnaire, the facility was adjusted to 0^o of heel ready for the next trial. On completing the questionnaire, and while still wearing the suit, the participants repeated the process at $0°$ of heel. The instructions were again given to each participant just prior to their second pass through the corridor. Participants then completed a second questionnaire, with an identical set of questions. On completion of the questionnaire, participants were free to leave. Cohorts consisting of 15 participants required approximately 90 minutes to complete the entire process. The performance and behaviour of participants as they walked through the test facility was recorded using four GoPro cameras installed within the facility (see Sec. S2.4). Four categories of data were collected during the experiment. These consisted of; demographical/registration data (see Sec. 2.3), walking speed and behavioural data extracted from the video footage, and personal experience data collected through the post-trial questionnaire (see Sec. S3). Table S1 presents the demography of recruited participants.

Table S1: Demographics of recruited population

Variable	Range
Age	18-72
Height	154-195
Weight	48-123
BMI	18-43
Nationality	Norwegian 90%, European 6%, Rest of the world 4%
Level of exercise	Less than one time to 7 times a week
Handedness	Right-handed 91%, Left-handed 9%

S2.3. Registration data

General demographical data such as gender, age, height, weight, sea experience, level of weekly physical exercise, etc. were collected through participant registration forms. Registration forms were completed up to two months prior to the trial, however, some participants completed the registration forms on the day of the trials. Late completion of the registration form made it difficult to ensure that a sufficient number of participants were recruited in all age and gender categories. During the process of registration, participants had access to the consent form which explained the nature of the experiment they would be engaged in. In addition, participants were instructed to wear a pair of flat walking shoes (e.g., not high heel shoes). As part of the registration process, applicants were asked if they had any temporary or long-term physical conditions that could impair their walking ability or ability to climb stairs. They were provided with examples such as respiratory condition, sporting injury, registered disability, etc. If they responded yes, they were excluded from participation.

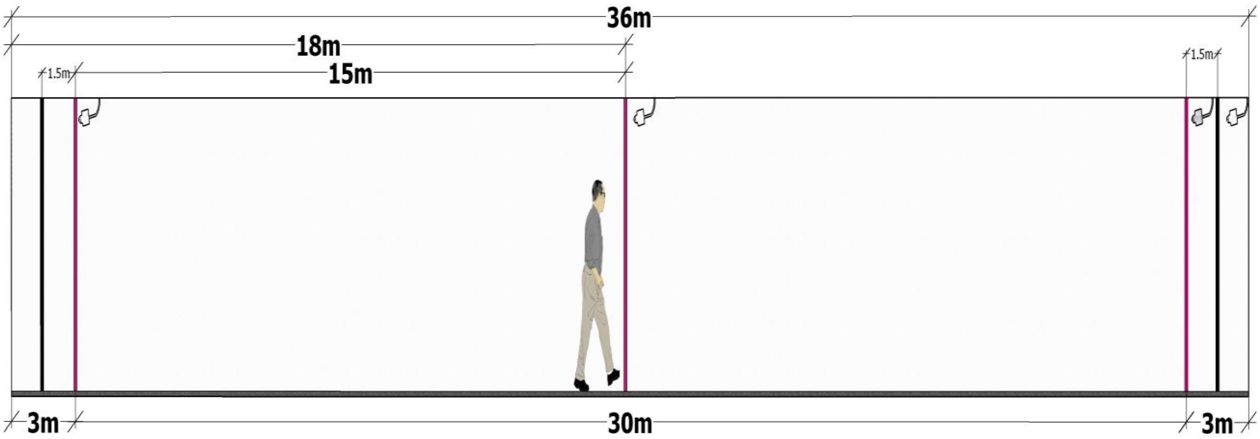
S2.4. Camera observations (speed & behavioural data)

Four GoPro Hero cameras were used to record the walking performance and behaviour of test participants. Cameras were positioned to capture the participants as they passed the start, middle, and end measuring lines and their movement throughout the corridor. Walking speed was determined over a distance of 30 m, with the start-line being off-set by 3 m from the entrance and the end-line being set-back 3 m from the exit to allow for participant acceleration and deceleration (see Fig. S 5). Acceleration and deceleration regions were split into two regions of 1.5 meters by additional lines marking 'false' start and end lines so that participants would not anticipate the start and end lines and hence modify their initial or final acceleration/deceleration. Participants walked through the corridor (at different angles) in a single direction (as shown in Fig. S 5) with the lower side of the corridor always on their left side. Three cameras were used to determine the walking speed of participants over the first half of the corridor (over 15 m), the second half of the corridor (over 15 m), and the entire length of the corridor (30 m). Cameras were synchronised by noting the time of a whistle blast at the start of each participant's passage through the corridor. Behaviour of participants as they passed through the corridor was also captured to quantify the count of miss-steps, trips, falls, contact with the wall, etc. (see Sec. S4.1). Presented in Fig. S 6 are examples of views from the various cameras. The two start-lines are visible in Fig. S 6-4, with the second yellow line marking the start of the walking speed measurement. Other behavioural performances of participants such as mis-steps and falls were quantified using cameras that captured throughout the corridor (Fig. S 6, insets 4-7).

S3. Participant Questionnaire

S3.1. Questionnaire data (participants experience)

In addition to recording the performance of participants, a questionnaire was developed to collect qualitative data on participant walking performance (see Fig. S7). The questionnaire was designed to explore participants opinion concerning the difficulty level of walking in the heeled corridor, the reason for stopping (if any), the influence of different corridor features (e.g., wall surface, angle of heel, type of floor, level of lightning, temperature and lack of handrail) on walking performance and the impact of the survival suit (e.g., fit of the suit, weight of the suit, ability to move, see or hear in the suit and comfort of footwear) on walking performance. All questions were presented in the form of multiple choice or Likert scale and there was an opportunity for participants to make additional comments. Once the questionnaire was designed, it was translated from English to Norwegian. The questionnaire was evaluated for intelligibility in both languages in a pilot study. During the pilot study, it was established that the volunteers could read, understand and answer all the questions in under 5 minutes (see Fig. S7).



S 5: Position of cameras and start and end line in the corridor

1-Start	2-Middle	3-End	4-Throughout	5-Throughout	6- Touching the wall	7-Falling in the corridor

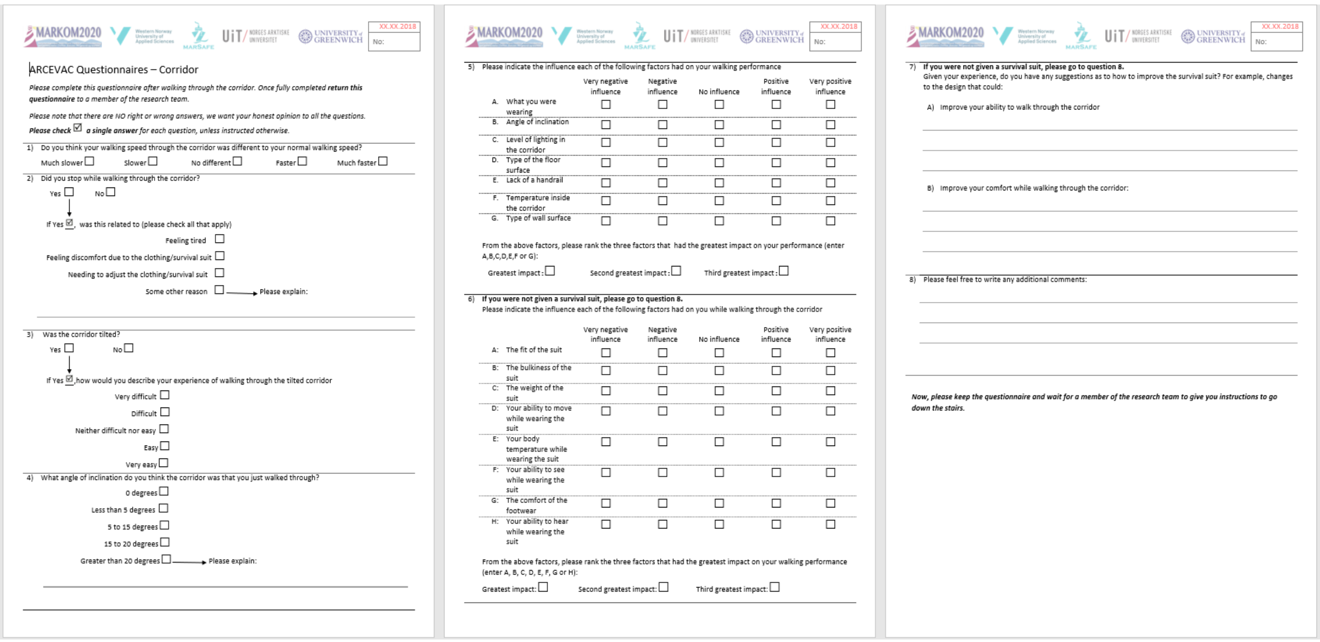
S 6: Still images captured from trial video footage depicting the progress of participants at different stages of their movement through the heeled corridor

S3.2. Questionnaire results

Once participants had walked through the corridor, they answered a questionnaire. The questionnaire was designed to survey the opinion of volunteers about the impact of various environmental factors on their walking performance. Over 90% of the participants believed neither of the ambient temperature, wall surface, floor covering, and level of lightning had any appreciable influence on their walking speed. The walls inside the corridor were not equipped with a handrail. About 47% of the participant commented that not having a handrail had a moderate to severe negative impact on their walking speed, while 2% believed that lack of handrail slightly improved their walking performance. The remaining 51% believed that lack of handrail did not impact their walking performance at all.

The questionnaire included a series of questions intended to establish the participant's opinion concerning specific suit features and how these may have impacted their walking performance. Answers to these questions were based on a five-point Likert scale ranging from a 'very negative' impact to a 'very positive' impact (see Table S2). To simplify the analysis of the replies presented here, the 'very negative' and 'negative' responses are collapsed into a general negative response as are the 'very positive' and 'positive' replies.

As both survival suits are intended to be immersion suits, they were equipped with a rubber seal around the face which prevents water ingress into the suit. This feature apparently influenced the hearing ability of individuals with 71.3% of participants wearing Suit-2 claiming that their walking performance was generally negatively impacted due to a reduction of hearing ability (see Table S2). In comparison, less than half (40.3%) of the participants wearing Suit-1 believed that their suit generally negatively their ability to walk due to loss of hearing, with 3.8% even suggesting it had a positive effect (see Table S2). The difference in the ability to hear while wearing the suit is thought to be due to the comparatively lighter weight of Suit-1 compared to Suit-2. Similarly, due to the lightweight nature of Suit-1, body temperature did not seem to be an issue, with only 8.6% of the participants wearing Suit-1 suggesting that it negatively impacted their performance. In contrast, 44.8% of participants wearing Suit-2 claimed that their elevated body temperature while wearing the suit adversely impacted their travel performance (see Table S2). The issue of elevated body temperature can potentially become a serious issue if passengers have to don their survival suit prior to walking to the assembly station, or if they



ARCEVAC Questionnaires – Corridor

Please complete this questionnaire after walking through the corridor. Once fully completed ***return this questionnaire*** *to a member of the research team.*

Please note that there are NO right or wrong answers, we want your honest opinion to all the questions.

Please check ☑ ***a single answer*** *for each question, unless instructed otherwise.*

1) Do you think your walking speed through the corridor was different to your normal walking speed?

Much slower ☐ Slower ☐ No different ☐ Faster ☐ Much faster ☐

2) Did you stop while walking through the corridor?

Yes ☐ No ☐

If Yes ☑, was this related to (please check all that apply)

Feeling tired ☐

Feeling discomfort due to the clothing/survival suit ☐

Needing to adjust the clothing/survival suit ☐

Some other reason ☐ → Please explain:

3) Was the corridor tilted?

Yes ☐ No ☐

If Yes ☑,how would you describe your experience of walking through the tilted corridor

Very difficult ☐

Difficult ☐

Neither difficult nor easy ☐

Easy ☐

Very easy ☐

4) What angle of inclination do you think the corridor was that you just walked through?

0 degrees ☐

Less than 5 degrees ☐

5 to 15 degrees ☐

15 to 20 degrees ☐

Greater than 20 degrees ☐ → Please explain:

5) Please indicate the influence each of the following factors had on your walking performance

	Very negative influence	Negative influence	No influence	Positive influence	Very positive influence
A. What you were wearing	☐	☐	☐	☐	☐
B. Angle of inclination	☐	☐	☐	☐	☐
C. Level of lighting in the corridor	☐	☐	☐	☐	☐
D. Type of the floor surface	☐	☐	☐	☐	☐
E. Lack of a handrail	☐	☐	☐	☐	☐
F. Temperature inside the corridor	☐	☐	☐	☐	☐
G. Type of wall surface	☐	☐	☐	☐	☐

From the above factors, please rank the three factors that had the greatest impact on your performance (enter A,B,C,D,E,F or G):

Greatest impact : ☐ Second greatest impact : ☐ Third greatest impact : ☐

6) **If you were not given a survival suit, please go to question 8.**
Please indicate the influence each of the following factors had on you while walking through the corridor

	Very negative influence	Negative influence	No influence	Positive influence	Very positive influence
A: The fit of the suit	☐	☐	☐	☐	☐
B: The bulkiness of the suit	☐	☐	☐	☐	☐
C: The weight of the suit	☐	☐	☐	☐	☐
D: Your ability to move while wearing the suit	☐	☐	☐	☐	☐
E: Your body temperature while wearing the suit	☐	☐	☐	☐	☐
F: Your ability to see while wearing the suit	☐	☐	☐	☐	☐
G: The comfort of the footwear	☐	☐	☐	☐	☐
H: Your ability to hear while wearing the suit	☐	☐	☐	☐	☐

From the above factors, please rank the three factors that had the greatest impact on your walking performance (enter A, B, C, D, E, F, G or H):

Greatest impact: ☐ Second greatest impact: ☐ Third greatest impact: ☐

7) **If you were not given a survival suit, please go to question 8.**
Given your experience, do you have any suggestions as to how to improve the survival suit? For example, changes to the design that could:

A) Improve your ability to walk through the corridor

B) Improve your comfort while walking through the corridor:

8) Please feel free to write any additional comments:

Now, please keep the questionnaire and wait for a member of the research team to give you instructions to go down the stairs.

S7: The participant post evacuation questionnaire used in the corridor trials

must walk a large distance indoors prior to reaching the embarkation station.

Analysis of open comments suggested that the bulkiness of Suit-2 was another factor that negatively influenced walking speed for 73% of male and 70% of female participants. This negative impact is also reflected in the response of participants to the specific question regarding their ability to move while wearing the suit, with 48.9% of the participants wearing Suit-1 and 86.5% of the participants wearing Suit-2 providing a generally negative response concerning their ability to move while wearing the suit (see Table S2).

S4. Walking Speed Data Extraction

S4.1. Video analysis

To ensure consistency in the video analysis, a data dictionary was developed containing precise definitions of the various parameters that were to be quantified through the video analysis. Two categories of parameters were defined, categorical and continuous. Continuous parameters were associated with the various time measurements derived from the video footage. These were the time at which a participant crossed one of the three defined lines (start, middle, or end).

Table S2: Influence of different features on survival suits (Suit-1/2) on the walking performance of individuals

Influence of different features of the suit	Suit type	Very negative influence	Negative influence	No influence	Positive influence	Very positive influence
Fit of the suit	1	7.2%	48.2%	40.8%	3.8%	0.0%
	2	30.9%	58.8%	10.3%	0.0%	0.0%
Weight of the suit	1	0.0%	1.9%	82.6%	11.7%	3.8%
	2	3.8%	32.6%	61.9%	1.7%	0.0%
Ability to move with the suit	1	0.0%	48.9%	42.7%	6.5%	1.9%
	2	15.1%	71.4%	11.8%	1.7%	0.0%
Body temperature in the suit	1	0.0%	8.6%	86.8%	4.6%	0.0%
	2	7.5%	37.3%	49.7%	3.6%	1.9%
Ability to see	1	0.0%	11.3%	82.1%	6.6%	0.0%
	2	3.6%	23.2%	73.2%	0.0%	0.0%
Comfort of footwear	1	5.3%	41.0%	43.4%	8.4%	1.9%
	2	68.2%	28.2%	1.7%	1.9%	0.0%
Ability to hear	1	4.6%	35.7%	55.9%	3.8%	0.0%
	2	23.7%	47.6%	28.7%	0.0%	0.0%

This was defined as the last video frame before the moment that the participants' foot crosses over the line. Examples can be seen in Fig. S 6:1-3. While the exact moment at which the participant crossed the line is difficult to determine, the measurements are within an accuracy of ± 0.04 s. Categorical variables such as touching the wall with one or both hands were defined in the following way: Never: if they never touched the wall, Occasionally: if they touched the wall less than 5 times throughout the corridor, and Frequently: if they touched the wall more than 5 times (Fig. S 6, insets 4 and 6). Other variables such as the number of mis-steps/stumble were defined as involuntary body movement which is the result of footing that is not normal for walking. Falling was defined as the situation in which any part of the body other than the feet comes into contact with the floor (Fig. S 6-7). Mis-steps/stumbles and falls were quantified by recording their respective frequencies, i.e., counting the occurrence of the event.

To ensure that the analysis was accurate and consistent with the definitions presented in the data dictionary an interrater test was undertaken. A selection of the video footage was used to assess whether raters were applying the definitions within the data dictionary in a consistent manner. The footage was analysed by two raters to quantify walking speed and behavioural variables. Analysis was carried out by two independent raters and the accuracy of measurements produced by the two raters were compared using Interrater analysis methods [S3, S4]. Interclass Correlation coefficient (ICCs) was used for comparing the speed measurement and Kappa statistics was used for comparison quantified of behavioural variables. Results showed excellent agreement between raters with an average Kappa value of 0.84 and ICCs value of 0.98, respectively for speed and behavioural data. The results for the interrater analysis confirmed the clarity of defined variables in the data dictionary and that the raters could accurately extract the required information with the given definition. The process of video analysis required approximately 190 person-hours of effort to complete.

S4.2. Walking speed analysis

Three walking speeds were determined for each participant, the walking speed over the first half of the corridor, the walking speed over the second half of the corridor, and the average walking speed over the entire length of the corridor. The walking speeds over each half of the corridor (15 m) were determined to investigate if there were any appreciable fatigue effects impacting walking speed. Comparison of the mean walking speed in the first and second half of the corridor showed that at a significant level of 0.05 there was no statistically significant difference in mean walking speed of participants. A two-sample T-test showed that, with P-value of 0.47 and 0.14, respectively, for 20° and 0°, there was no sign of a significant reduction in walking speed throughout the corridor (between the two half). The walking speed of participants in the first and second half of the corridor at 0° and 20° are compared in Table S3. As it was determined that fatigue did not significantly impact walking speed, the average walking speed over the entire corridor length is used in the analysis in Ref. [S1]. The average walking speed through the corridor was determined as follows:

$$speed\left(\frac{m}{s}\right) = \frac{30}{(T_E - T_W) - (T_S - T_W)} \qquad (1)$$

Here, T_E and T_S are the respective measures time for passing the start and end line, and T_W is the time of hearing whistle by each of the cameras.

Table S3: Average walking speed of participants in first and second half of corridor at 0°and 20°

Suit type	Age group	1st half on 20°	2nd half on 20°	1st half on 0°	2nd half on 0°
Suit-0	AG1 (18-29)	2.20	2.18	2.31	2.22
	AG2 (30-50)	2.02	2.04	2.39	2.07
	AG3 (51-72)	1.89	1.88	2.25	2.24
Suit-1	AG1 (18-29)	1.51	1.58	2.24	2.21
	AG2 (30-50)	1.85	1.80	2.17	2.14
	AG3 (51-72)	1.63	1.72	2.11	2.07
Suit-2	AG1 (18-29)	1.77	1.77	2.21	2.18
	AG2 (30-50)	1.56	1.57	2.20	2.12
	AG3 (51-72)	1.53	1.52	2.00	1.97

S4.3. Identification of disqualified participants

The data produced by some participants was considered to be inappropriate for analysis and was removed from the overall data set. The process by which certain data was excluded from the analysis is described in this section.

According to the IMO International guidelines for advanced evacuation analysis for passenger ships, unhindered walking speeds of individuals at 0° of heel is dependent on age and gender and varies from 0.56 m/s to 1.85 m/s [S6]. This range for walking speeds was derived from data concerning individual walking speeds within rail station environments [S5, S6]. In the experimental trials considered in this paper, the mean travel speed is greater than the maximum travel speed cited in the guideline [S6].

Prior to the start of each trial, participants were instructed to walk as fast as they could, but not to run. Even though participants were instructed not to run, some ignored the instruction and adopted a 'jogging' performance. A literature review [S7-S9] suggested that walking speeds greater than 3 m/s represent the start of the jogging/running phase of motion. Thus, those participants who walked at greater than 3 m/s were considered to be running and so were disqualified and their data excluded from analysis.

Another issue impacted the suitability of the data produced by some participants. Studies have shown walking over heeled surfaces can negatively impact walking speed, or at the very least, not enhance walking speed [S7, S10-S12]. It was thus assumed that if participants were equally motivated, their speed on a heeled surface would be equivalent to or slower than their speed on a flat surface. However, some participants when walking at 0° heel, after having first traversed the corridor at a greater angle of heel, travelled at a considerably slower speed. Slower walking speed during the second pass through the corridor, while at 0° heel, suggests that the participant might not have had the same level of motivation as they did during the first pass through the corridor. Thus, participants that had a walking speed at 0° heel that was less than 90% of their walking speed at heel were considered not to be engaging appropriately in the trial and so were disqualified and their data excluded from analysis.

Data collected from participants during the registration process, video analysis, and questionnaires resulted in a total of 18480 data points. After the various participants were excluded this reduced to 16192 data points. The breakdown of data points, pre- and post-exclusion, according to the angle of heel, gender, and suit type is presented in Table S4.

Table S4: Number of collected data points as a function of angle of heel, gender, and suit type pre- and post- exclusion

Suit type	Gender	0° Heel		10° Heel		15° Heel		20° Heel	
Disqualified participants		Pre exclusion	Post exclusion	Pre exclusion	Post exclusion	Pre exclusion	Post exclusion	Pre exclusion	Post exclusion
Suit-0	Male	3168	2508	880	528	748	572	1540	1408
	Female	1188	1100	176	176	352	308	660	616
Suit-1	Male	1232	1144	528	484	0	0	704	660
	Female	836	836	308	308	0	0	528	528
Suit-2	Male	1628	1364	528	484	0	0	1100	880
	Female	1188	1144	396	396	0	0	792	748
Total number of datapoints per category		9240	8096	2816	2376	1100	880	5324	4840

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Annex V – Paper III

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

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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:

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

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

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

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

And,

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

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 ($HRF_{Age,Gender,Angle,Suit}$) 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 ($HWS_{Age,Gender,Angle,Suit}$). The HWS is determined using Eq. (8) and Eq. (9).

$$HWS_{Age,Gender,Angle,Suit} = WS_{Age,Gender,Angle=0,Suit=0} \times HRF_{Age,Gender,Angle,Suit} \tag{8}$$

where the reduction factor is given by,

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

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 $HWS_{Age,\ Gender,\ Angle,\ Suit}$ 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 $HRF_{Age,\ Gender,\ Angle,\ Suit}$ 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 ($TNOHRF_{Age,Gender,Angle,Suit=0}$) and one for trim ($TNOTRF_{Age,Gender,Angle,Suit=0}$). These are currently specified within mEX to provide walking speeds for heel and trim given by,

$$TNOHWS_{Age,Gender,Angle,Suit=0} = WS_{Age,Gender,Angle=0,Suit=0} \times TNOHRF_{Age,Gender,Angle,Suit=0} \tag{10}$$

$$TNOTWS_{Age,Gender,Angle,Suit=0} = WS_{Age,Gender,Angle=0,Suit=0} \times TNOTRF_{Age,Gender,Angle,Suit=0} \tag{11}$$

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,

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

where,

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

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).

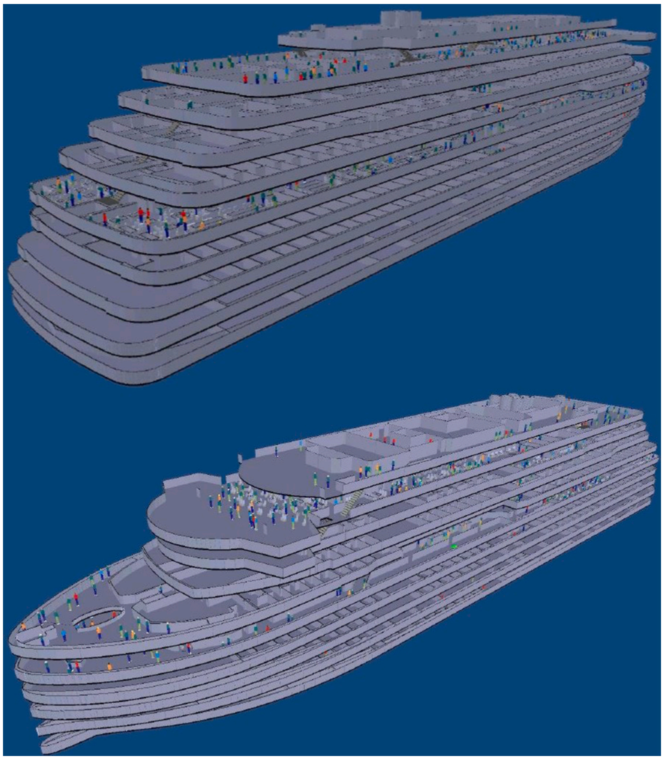

Fig. 2. The hypothetical vessel used within maritimeEXODUS for the evacuation analysis.

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.

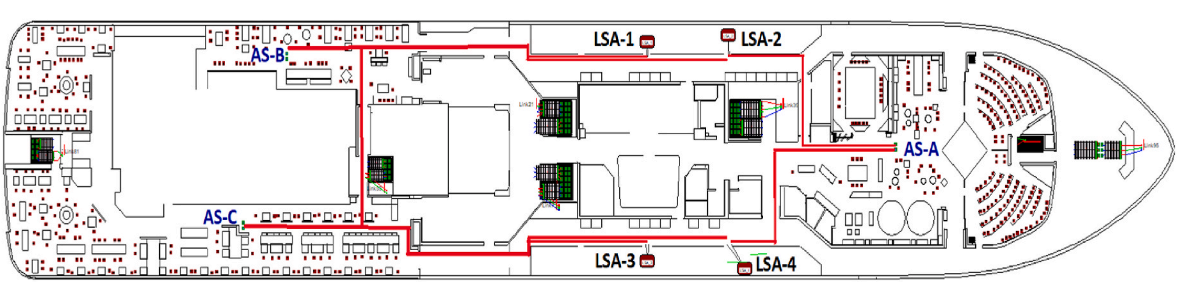

Fig. 3. Deck 6 showing ASs, LSAs and paths from ASs to LSAs.

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

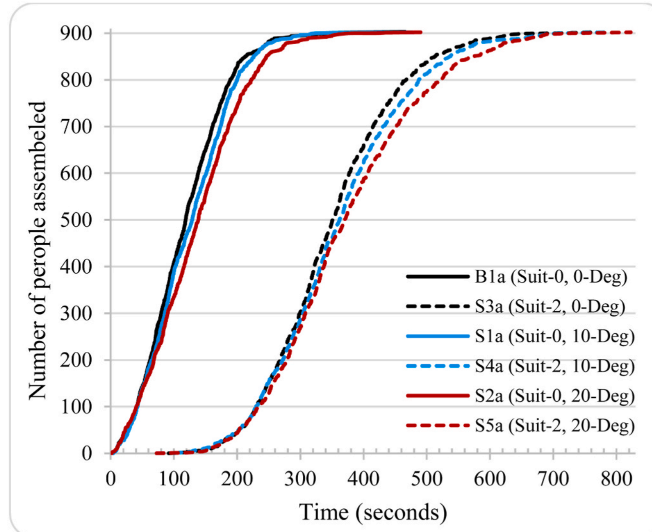

Fig. 4. Assembly times (95th percentile case) for the Day Case Scenarios.

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%

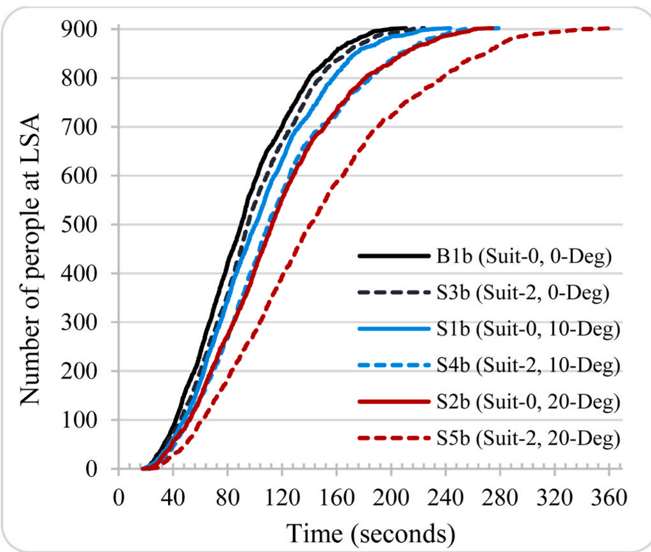

Fig. 5. Abandonment times (WT, 95th percentile case) for the Day Case Scenarios.

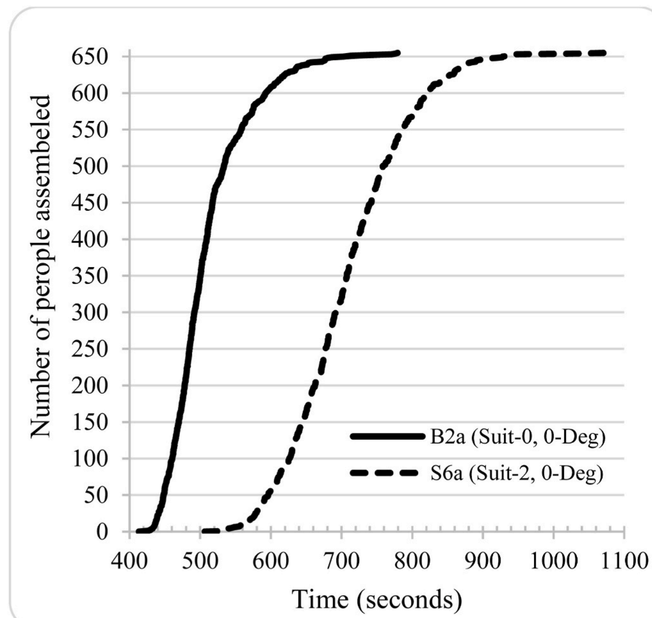

Fig. 6. Assembly times (95th percentile case) for the Night Case Scenarios.

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)

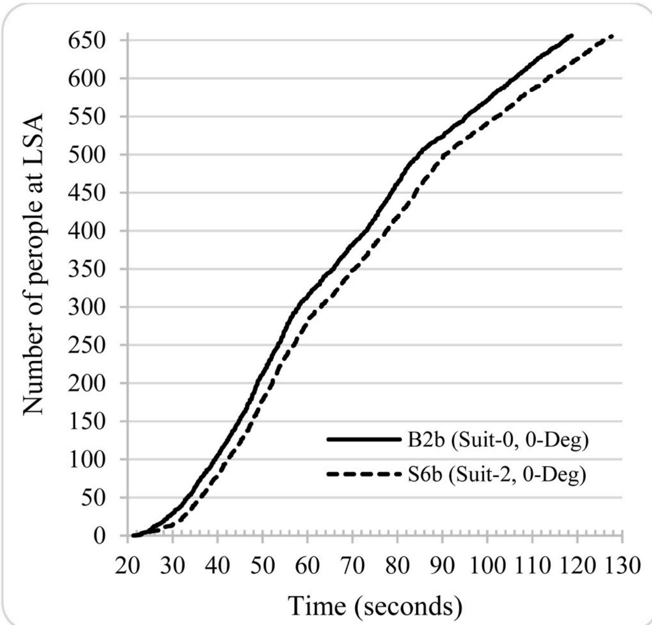

Fig. 7. Abandonment times (WT, 95th percentile case) for the Night Case Scenarios.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2023.114725.

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Annex VI – Supplementary material for Paper III

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

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

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This document presents supplementary material for [S1] relating to the details of the layout of a hypothetical passenger ship (based on the general layout of MS Roald Amundsen) which was used in the modelling (Section S1), the approach adopted within the software to representing passenger stair speeds while wearing TPIS in angles of heel (Section S2) and trim (Section S3) and the verification of the approach adopted to represent walking speed while in trim (Section S4).

S1. Layout of the MS Roald Amundsen

The vessel layout used in the evacuation simulations presented in [S1] is based on a hypothetical passenger ship with general layout similar to that of the MS-Roald Amundsen (MSRA). This vessel was selected as the basis of the ship model used in the numerical simulations as it is a passenger ship that operates in polar waters. The general arrangement of the hypothetical vessel differs from that of the MSRA by deleting some of the interior walls or modifying their length and location. Furthermore, the width of the doors and pathways were modified and many of the interior objects within the general arrangement were either moved or deleted. The vessel has an approximate length and beam of 140 m and 23.6 m, respectively. The vessel in the hypothetical model has 265 passenger cabins with a total cabin capacity of 530 passengers. In addition, there are 90 crew cabins and a total of 151 crew members. The ship has four main vertical zones spread across 11 decks. Passenger 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. The ship has one staircase in the forward (Staircase 1) that connects decks 3, 4, and 5 to deck 6 (assembly deck), and one staircase in the mid forward (Staircase 2) that connects deck 2 to deck 10. Staircase 3 is a twin staircase that runs from deck 3 to deck 11. The fourth staircase is located in the ship's mid-aft area and runs from deck 3 all the way up to deck 10. Staircase 5 is located in the aft of the ship and runs from deck 4 to deck 9.

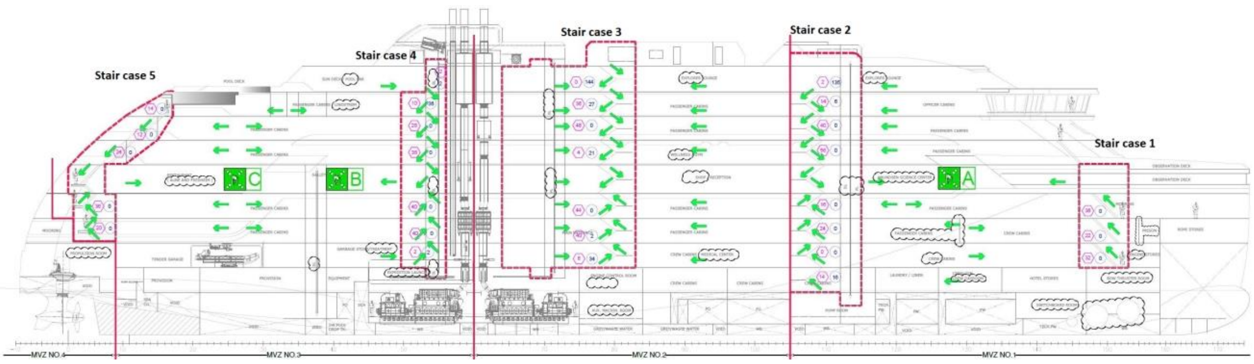


Figure S1: Arrangement of stairs in the MS Roald Amundsen

S1.1. Deck 2

Deck 2 is located above deck 1 (engine room) and has 32 crew cabins. This deck also houses the crew service space.

Figure S2: Layout of deck 2 in MS Roald Amundsen

S1.2. Deck 3

Deck 3 includes a hospital, and 38 crew cabins in forward.

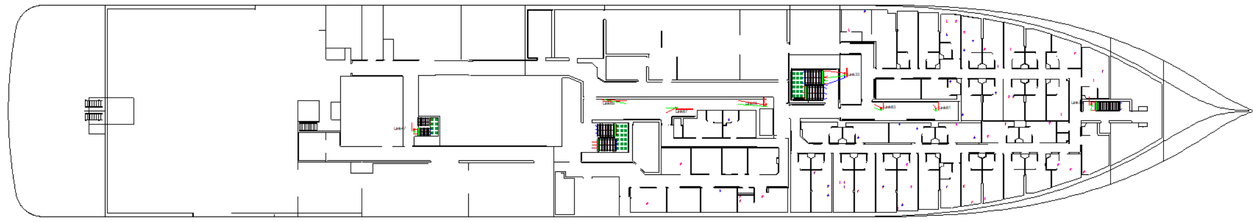


Figure S3: Layout of deck 3 in MS Roald Amundsen

S1.3. Deck 4

Deck 4 is the lower passenger deck, with 20 crew cabins on the forward side and the rest of the deck is occupied by the passenger cabins. Deck 4 has 56 passenger cabins.

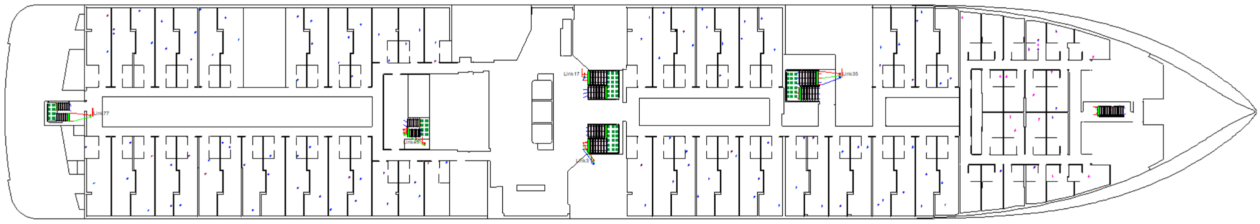


Figure S4: Layout of deck 4 in MS Roald Amundsen

S1.4. Deck 5

Deck 5 has 74 passenger cabins and is located below the assembly deck (6). Passengers from this deck can use all five staircases to reach the assembly deck.

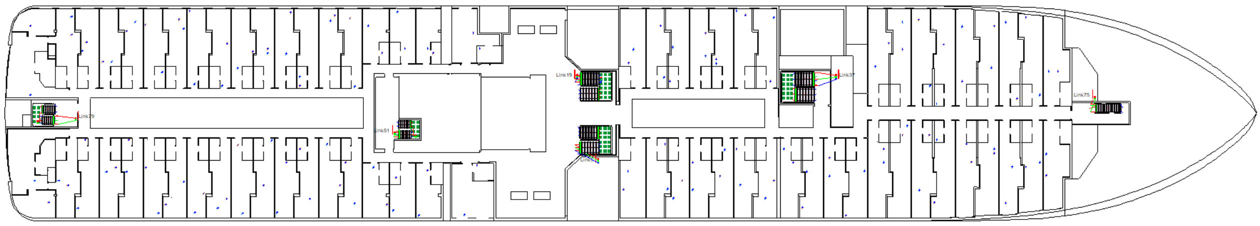
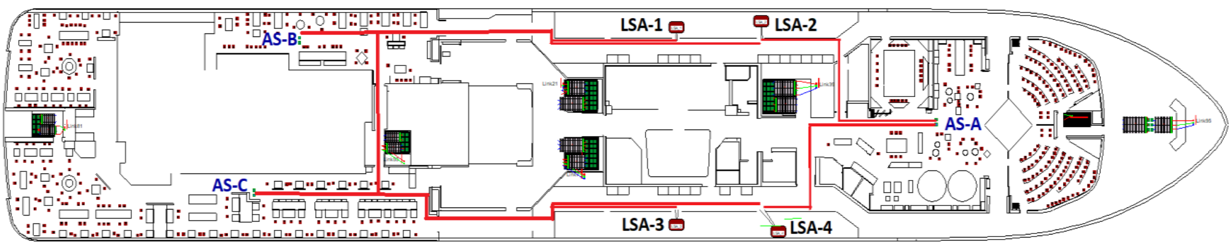


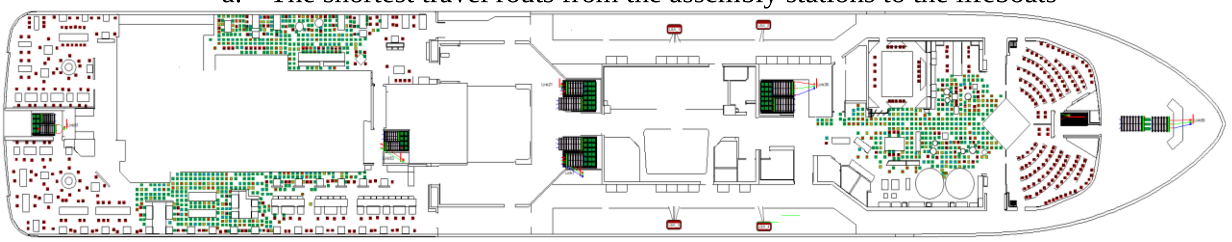
Figure S5: Layout of deck 5 in MS Roald Amundsen

S1.5. Deck 6:

Deck 6 is the assembly deck. This deck contains three Assembly Stations (ASs): AS-A, AS-B, and AS-C. AS-A is located in the forward part of deck 6. The other two ASs are located in the aft of deck 6, one on the port side and one on the starboard side. ASs B and C are both restaurants. Passengers from all assembly stations have access to the lifeboats on both sides of the ship. The red lines in Figure S10 (a) depict the route from the ASs to the lifeboats. The distribution of passengers (for the day case scenarios) between the three ASs on deck 6 is presented in Figure S10 (b).



a. The shortest travel routs from the assembly stations to the lifeboats



b. Distribution of the passengers in the assembly stations

Figure S6: Layout of deck 6 in MS Roald Amundsen

S1.6. Deck 7:

Deck 7 contains 54 passenger cabins and is located above the assembly station (deck 6). On deck 7, there is a public space (gym and sauna) in the midship area. The outdoor area on the forward part of deck 7 is a public space that can be occupied by passenger.

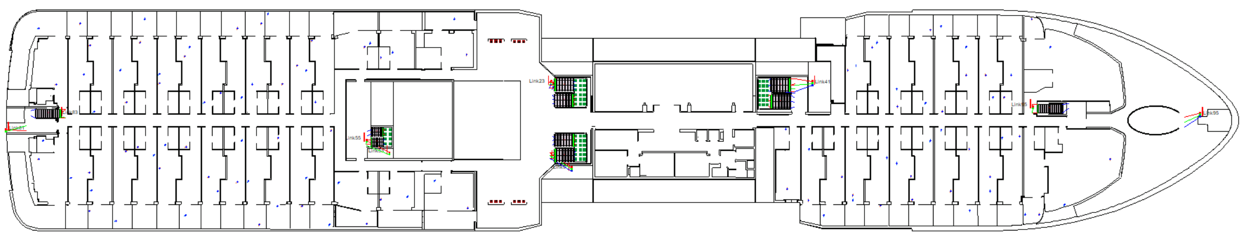


Figure S7: Layout of deck 7 in MS Roald Amundsen

S1.7. Deck 8:

Deck 8 has 54 passenger cabins and passengers from this deck have access to the assembly deck via all five staircases.

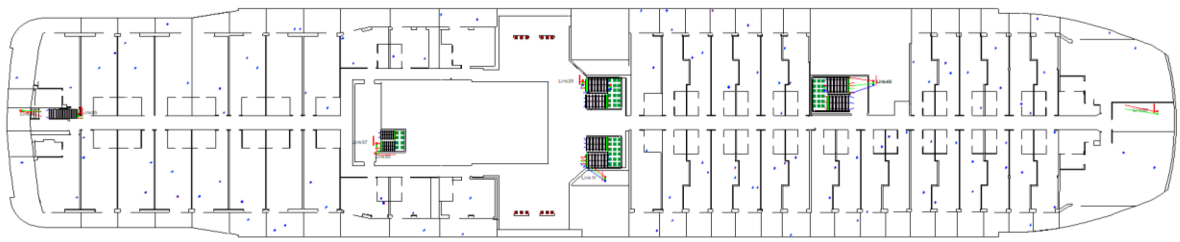


Figure S8: Layout of deck 8 in MS Roald Amundsen

S1.8. Deck 9:

Deck 9 is the highest deck with passenger cabins. This deck has 27 passenger cabins and a public space (restaurant) on the port side. Passengers on deck 9 can use stairs 2, 3, 4, and 5 to descend to the assembly deck (6).

Figure S9: Layout of deck 9 in MS Roald Amundsen

S1.9. Deck 10:

Deck 10 is a public area with an indoor bar/café and an outdoor swimming pool. Deck 10 and Deck 11 are connected by two sets of stairs in the outdoor area. Passengers can reach deck 9 from deck 10 via stair cases 2, 3, and 4. Deck 10 has an additional stair on the forward port side that connects it to the balcony of the bridge on deck 9. This stair is rarely used by passengers for daily circulation.

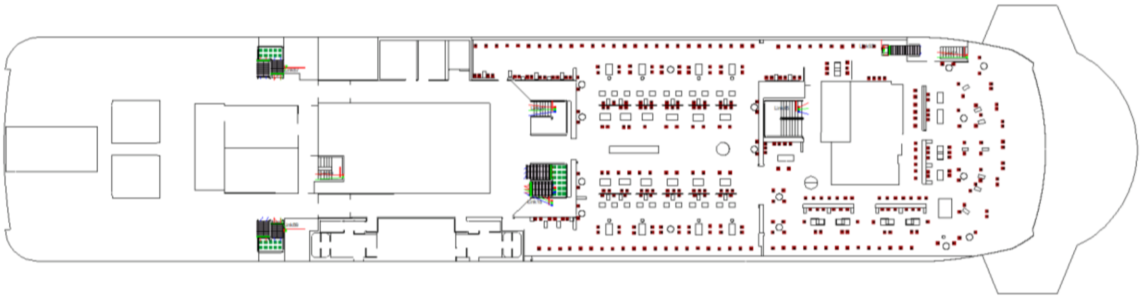


Figure S10: Layout of deck 10 in MS Roald Amundsen

S1.10. Deck 11:

Deck 11 is the highest level. This deck is simply an outdoor area where passengers can walk and exercise. Passengers can access deck 10 from this deck via staircase 3 and the two stairs in the aft section (outdoor part of deck 10 to 11). There is also a small stair on the forward port side of deck 11 that connects deck 11 to the balconies on decks 10 and 9 (emergency escape route).

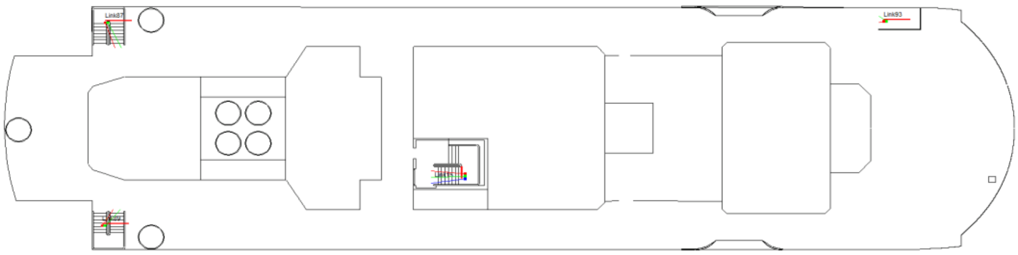


Figure S11: Layout of deck 11 in MS Roald Amundsen

S2. Walking speed on stairs at angles of heel while wearing TPIS

As described in [S1], the evacuation simulation software used in the analysis is maritimeEXODUS V6.0 [S2]. Modifications were made to the software to implement both the donning time for Suit-2, based on data collected in [S3] and walking speed data at different angles of heel while wearing Suit-2, based on data collected in [S4]. However, within a general evacuation simulation, it may also be necessary to represent the impact of wearing TPIS on passenger Stair Walking Speeds (SWS). Unfortunately, SWS data at different angles of heel while wearing TPIS are not currently available, and the trials conducted in [S4] did not take into account the impact of heel or trim on stair walking speeds while wearing TPIS. However, for the analysis presented in [S1] it was not necessary to represent passengers walking up or down stairs while wearing TPIS and so this data was not required. Nevertheless, described here are modifications that could be implemented within maritimeEXODUS as a first approximation to represent walking speeds on stairs in heel and trim (see Section S3 for trim) while wearing TPIS. The suggested modifications could be implemented as an approximation until appropriate stair walking speed data is available.

It is assumed that the stair walking speed while wearing TPIS can be approximated in the same way as the corridor walking speed while wearing TPIS and is related to the TNO measured stair walking speed data [5] without TPIS.

Within maritimeEXODUS the stair walking speed at angle of heel (HSWS) is given by Eq. (S2):

$$HSWS_{Age,Gender,Angle,Suit=0} = SWS_{Age,Gender,Angle=0,Suit=0} \times TNOSHRF_{Age,Gender,Angle,Suit=0} \quad \text{(S1)}$$

Where SWS is the stair walking speed as specified in the IMO requirements [S6] and TNOSHRF is the TNO reduction factors that take into account the angle of heel and are defined in [S2 and S6].

While Eq. (S1) provides the reduction in stair walking speed as a result of heel, it does not take into account the impact of the TPIS. As a reduction factor for TPIS on stairs is not currently available, here we assume that the reduction factor due to TPIS for stairs is the same as the reduction factor for deck walking speeds, i.e., TPISRF, see Eq. (13) in [S1]. Clearly, this is a crude approximation and is not substantiated by data, but it will generate a reduced walking speed on stairs due to the TPIS, and it incorporates the TNO reduction factor for heel on stair walking speeds.

Using this assumption, the HSWS is approximated by,

$$HSWS_{Age,Gender,Angle,Suit} = SWS_{Age,Gender,Angle=0,Suit=0} \times TNOSHRF_{Age,Gender,Angle,Suit=0} \times TPISRF_{Age,Gender,Angle,Suit} \tag{S2}$$

Where, as defined by Eq. (12) in [S1], TPISRF is given by,

$$TPISRF_{Age,Gender,Angle,Suit} = \frac{HRF_{Age,Gender,Angle,Suit}}{TNOHRF_{Age,Gender,Angle,Suit=0}} \tag{S3}$$

As noted in [S1], 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 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.

S3. Walking speed on stairs at angle of trim while wearing TPIS

The approximation for the SWS while wearing TPIS at a given angle of trim is approximated in a similar manner to that of heel in Section S2. Within maritimeEXODUS the stair walking speed at angle of trim (TSWS) is given by Eq. (S5):

$$TSWS_{Age,Gender,Angle,Suit=0} = SWS_{Age,Gender,Angle=0,Suit=0} \times TNOSTRF_{Age,Gender,Angle,Suit=0} \tag{S4}$$

Where SWS is the stair walking speed as specified in the IMO requirements [S6] and TNOSTRF is the TNO reduction factors that take into account the angle of trim and are defined in [S2].

In addition to assuming that WS reduction factors due to heel and TPIS for decks also apply to stairs (see Section S2), it is further assumed that the impact of the TPIS on stair walking speeds while in trim (TSWS) will be the same as the impact of the TPIS on SWS in heel (HSWS). Thus, reduction factors associated with the impact of the TPIS while walking on stairs at a given trim angle (TSRF) will be the same as the reduction factors of the same angle of heel while walking on a flat deck (HRF) and so the $TPISRF_{Age, Gender, Angle, Suit}$ previously determined for decks (see Eq. (S3)) applies to stairs. Furthermore, as the ARCEVAC data does not currently contain any stair walking speed data, the existing TNO trim dataset [S5] is used.

It is acknowledged that this assumption is made purely for convenience, but in the absence of stair walking speed data while wearing a TPIS it is a necessary assumption. Essentially, this assumption implies that the impact of the TPIS alone on walking speeds is the same on stairs and a level deck in heel and trim. Given this assumption, we approximate the TSWS as follows,

$$TSWS_{Age,Gender,Angle,Suit} = SWS_{Age,Gender,Angle=0,Suit=0} \times TNOSTRF_{Age,Gender,Angle,Suit=0} \times TPISRF_{Age,Gender,Angle,Suit} \tag{S5}$$

Where, $TPISRF_{Age, Gender, Angle, Suit}$ is given by Eq. (S3).

Thus, to determine the $TSWS_{Age, Gender, Angle, Suit}$ 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. (S3).

S4. Verification of deck walking speed implementation at angles of Trim with Suit-2

To verify that the walking speed under conditions of trim while wearing Suit-2 was correctly implemented in the software, a single agent was required to walk along a 30 m corridor while wearing Suit-0 and Suit-2 at two angles of trim, 0° and 20°. The time required to walk this distance generated by the modified maritimeEXODUS software was compared with the time calculated using Eqs. (12) and (13) in Section 3.2 of [S1]. The unconstrained initial walking speed of each agent was set to 1.5 m/s. Results are generated for both male and females for ages 25 years and 65 years (see Table S1). As seen in Table S1, the travel times predicted by the modified software agree with the hand calculations to within 1.6%, suggesting that the trim reduction factor equations have been correctly implemented.

Table S1: The time required for an agent with unconstrained walking speed of 1.5 m/s to walk a 30m long corridor at different angles of trim wearing Suit-0 and Suit-2 as determined by maritimeEXODUS and hand calculations.

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	20	21.4	21.4
		65	20	20	21.4	21.4
	20°	25	26.5	26.8	34.5	34.9
		65	31.6	31.1	41.2	40.5
Female	0°	25	20	20	21.4	21.4
		65	20	20	21.4	21.4
	20°	25	28.1	28.5	36.6	37.1
		65	33.6	33.0	43.7	43.0

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