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A practical application of the Hierarchical Task Analysis (HTA) and Human Error Assessment and Reduction Technique (HEART) to identify the major errors with mitigating actions taken after fire detection onboard passenger vessels

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ABSTRACT

Fire onboard passenger ships is a major hazard not only for the personnel, passengers, and the environment, but also for the vessel itself. Therefore, the response actions carried out by crewmembers after a fire has been detected onboard a passenger vessel are of outermost importance. SAFEMODE project aims to promote contemporary safety thinking through a collection of carefully selected Human Factors (HFs) Fact Sheets that includes the most-known HFs techniques for accident investigations, to help accident investigators and safety managers within maritime organisations. Therefore, this paper proposes to apply two of the above-mentioned Fact Sheets, namely Hierarchical Task Analysis (HTA) and Human Error Assessment and Reduction Technique (HEART). Hence, this paper initially demonstrates how HTA can be applied to model the human response actions to a fire onboard a passenger vessel, and secondly, it utilises a systematic human error reduction and prediction approach, namely HEART, to predict and quantify which errors are likely to occur. Results from this paper reveal that six human response errors are most likely to occur, with a Human Error Probability of 0.16 according to the HEART analysis. Finally, this paper also suggests remedial measures to mitigate each error identified.

1. Introduction

For the past decades, various authors have researched the contribution of Human Factors (HFs) into past accidents in diverse strategic domains such as aviation or nuclear (Azadeh and Zarrin 2016) and the maritime sector. As a result of the previous studies, numerous authors have estimated that around 80% of maritime accidents can be attributed to some sort of human and organisational errors (Graziano et al., 2016; Turan et al., 2016, Navas de Maya et al., 2018). Some other studies reported the human influence in accidents as much as 96% (Rothblum, 2000). Moreover, the European Maritime Safety Agency (EMSA) has also established that 54% of the accident events analysed were attributed to human actions for the period 2014–2019. In addition, within this category, 61.2% of the contributing factors were related to shipboard operations (EMSA, 2020). Nevertheless, despite all research conducted in the past decade to address HFs, it is still very difficult to precisely specify and quantify the importance of human errors in maritime accidents (Jeong et al., 2016).

There is no doubt that all maritime accidents, irrespective of type, can have catastrophic consequences. Nevertheless, onboard fire and explosion accidents deserve a special mention since a fire on board is a major hazard for the personnel, passengers, and the environment and the asset. Multiple analyses have been already conducted in the available literature regarding fire and explosion accidents onboard ships, which revealed a steady trend accounting for 10% of the total losses per year (Allianz, 2019; Papanikolaou et al., 2015). In addition, fire and explosion events are of utmost importance for passenger ships due to the sheer number of passengers and crew onboard (Baalisampang et al., 2018). Hence, it is critical to ensure that the necessary mitigating actions are carried out after a fire onboard a passenger vessel has been detected.

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Therefore, the objectives of this study are first to demonstrate how Hierarchical Task Analysis (HTA) can be applied to model the response actions after a fire have been detected onboard a passenger vessel, and second, to apply the Human Error Assessment and Reduction Technique (HEART) to predict and quantify which errors are likely to occur on the human response actions to a fire onboard a passenger vessel.

While the context and objective of this study were introduced above, the rest of this paper is structured as follows: Section 2 provides an initial review of the Hierarchical Task Analysis (HTA) technique and the Human Error Assessment and Reduction Technique (HEART), and their applications in previous studies in various critical domains. Section 3 describes the methodology adopted in this paper. In addition, results and discussions are included in Section 4 and Section 5, respectively. Finally, Section 6 provides the conclusions derived from this study.

2. Literature review

2.1. The Hierarchical Task Analysis (HTA) technique

Task analysis denotes all the techniques of collecting, classifying, and interpreting data on the performance of systems that includes at least one person as a system component. In addition, HTA is one of the most well-known task analysis techniques, which is recommended and applied in the Human Factors literature (Lane et al., 2006). HTA was first developed in the 1960s for training process control tasks in the steel and petrochemical industries (Annett and Duncan, 1967; Annett, 2003). The changing nature of industrial work processes around that time meant that tasks were becoming more cognitive in nature, and new approaches that could be used to describe and understand these novel work processes were required and subsequently created (Salmon et al., 2010). Hence, there was a social need for new techniques to be derived into the development of the HTA.

The peculiarity of the HTA is that it presents tasks in a strict hierarchical structure, with the primary goal(s) represented at the top whilst tasks/subtasks represented below. Thus, the HTA process is simplistic, involving collecting data about the task or system under analysis via multiple techniques such as observation, experience, questionnaires, interviews, or documentation review, amongst others, and then using the data to decompose and describe the goals and sub-goals involved (Salmon et al., 2010).

HTA is a flexible technique that can be adapted and applied to a huge range of situations and operations, irrespective of the industry. Therefore, it has been widely used in a variety of domains and contexts (Kirwan and Ainsworth, 1992). Namely, in the healthcare domain, it has been extensively applied to identify medication administration errors (Lane et al., 2006) or in surgery, to construct a surgical HTA (Sarker et al., 2006; Sarker et al., 2008). Additional applications of the HTA techniques include design and evaluation of training programme(Piso, 1981; Annett, 2003), team task analysis (Walker et al., 2006), analysis of workload (Kirwan and Ainsworth, 1992), allocation of functions analysis (Stanton et al., 2004) and interface design and evaluation (Hodgkinson and Crawshaw, 1985; Shepherd, 2003). To conduct an HTA, data may be gathered from multiple sources (Salmon et al., 2010), the analysis can be conducted to any desired level of detail, and there is no prescriptions on how the results may be utilised (Annett, 2003). Nevertheless, the analyst is encouraged to follow multiple steps, where the most critical steps are summarised in Table 1.

Table 1
Principal steps in carrying out HTA (adapted from (Annett, 2003)).

No.	Step	Description
1	Establish the purpose of the analysis	To establish and define the main reasons for conducting an HTA. This is the first step in the HTA, and it has decisive implications in terms of the data collection procedures, the depth of the analysis, and the solutions (i.e., remedial measures) that can be suggested.
2	Definition of task goals	To decide which are the outcomes of the HTA. Task performance implies a goal-directed behaviour; hence, it is crucial to determine what is the performance goal(s) and how to realise when it is achieved (Annett, 2003). In addition, a common problem in HTA is to define the task goal(s), since it may vary depending on the stakeholders selected for the HTA.
3	Data acquisition	To identify all relevant data sources that can be used for conducting an HTA. Data concerning performance on pre-existing systems or similar tasks may provide useful information to start the HTA. In addition, when various independent data sources are collected and consulted, it is easier to validate the results of the HTA (Annett, 2003).
4	Decomposition diagram	To break goals down into their constituent tasks. The critical feature of an HTA analysis is to relate what operators already do, why they do it, and the negative consequences of their actions if not performed correctly. Once the previous relationship is fully understood, it is possible to derive a decomposition diagram.
5	Recheck validity	To recheck the validity of decomposition with stakeholders. It has been observed that stakeholders involved in the HTA process may often change their minds, especially if they are not familiar with the HTA technique (Annett, 2003). For this reason, it is highly recommended to cross-check between sources wherever possible

2.2. The Human Error Assessment and Reduction Technique (HEART)

HEART is a human reliability assessment technique established by Williams in 1986 to analyse nuclear power plant accidents (Williams, 1986). The HEART method aims to obtain the generic tasks and to assign them a Human Error Probability (HEP) value from a list of generic tasks following discussions (Furusho, 2019). In addition, where there is no direct fit for a generic task, the task that most resembles the base event under study should be selected. Thus, the decision as to why a generic task is selected should be documented.

HEART is a rapid and straightforward technique to use (Kirwan, 1996), with a small demand for resource usage (Humphreys, 1995), which has a good track record in several industries. For example, railway action reliability assessment (Wang et al., 2018; Zhou et al., 2019) or controller action reliability assessment (Kirwan and Gibson, 2009). In the maritime industry, HEART has also been applied to identify the occupational accidents in maritime accidents (Bowo and Furusho, 2018), to analyse collision at sea (Bowo and Furusho, 2019), to analyse maritime accidents (Bowo et al., 2019; Prilana et al., 2021), and to categorise error-producing conditions on ship grounding accidents (Furusho, 2019). Finally, the list with the most relevant HEART generic tasks and their HEP is displayed in Table 2.

3. Proposed methodology

As per the aforementioned, many studies in the literature have discussed the importance and the consequences of fire onboard passenger vessels. Hence, it is critical to ensure that the necessary response actions are carried out after a fire onboard a passenger vessel has been detected. Therefore, the proposed approach followed in this paper has three stages. The first stage includes developing an understanding of the problem being addressed, which is the human response actions that are needed when a fire onboard a passenger vessel has been detected. A starting point is to explore past fire accidents to gather an insight into the right and wrong actions that were taken. In addition, the current procedures and checklist might be able to provide further insights into the actions that need to be taken after a fire has been initiated onboard. Once preliminary information has been collected and collated, the

Table 2
HEART generic tasks and their HEP (Adapted from (Williams, 1988)).

Reference	Generic Task	HEP
A	Totally unfamiliar, performed at speed with no real idea of the likely consequences	0.55
B	Shift or restore a system to a new or original state on a single attempt without supervision or procedures	0.26
C	Complex task requiring a high level of comprehension and skill	0.16
D	Fairly simple task performed rapidly or given scant attention	0.09
E	Routine, highly practised rapid task involving relatively low level of skill	0.02
F	Shift or restore a system to a new or original state following procedures with some checking	0.003
G	Completely familiar, well designed, highly practised, routine task occurring several times per hour, performed to the highest possible standard by highly trained and experienced personnel, totally aware of the implications of failure, with time to perform the task …	0.00004
H	Respond correctly to a system command even when there is an augmented or automated supervisory system providing an accurate interpretation of the system state	0.00002
M	Miscellaneous task for which no other task description can be found	0.03

second stage involves the application of the HTA technique. HTA is a way of breaking the task down into its component parts (Lane et al., 2006). It is also a useful way of investigating how people interact with equipment and with various aspects of their working environment. Therefore, there is still merit in analysing the process at the task level to assess, via design solutions, how these fire detection errors can be reduced. Thus, carrying out some form of human error analysis enables us to gain an understanding of how human interaction with fire detection tasks might lead to serious incidents. Finally, the last stage applies the HEART method to the response actions identified in the HTA. The goal is to predict and quantify which errors are likely to occur on the human response actions to a fire onboard a passenger vessel. Fig. 1 provides a clear insight into the approach adopted within this study.

4. Results

4.1. Stage 1: understanding the problem being addressed

At this stage, three relevant sources of information were collected and collated, namely, accident reports on previous fire/explosion accidents onboard passenger vessels, regulations, and procedures and checklists. Therefore, regarding the first source of information, ten fire/explosion accidents on passenger vessels were reviewed. In addition, current regulation on fire response was also investigated (i.e., SOLAS) together with protocols to be followed in case of fire and a checklist from two different ship operators, which remain confidential.

4.2. Stage 2: application of the Hierarchical Task Analysis (HTA) technique

The application of the HTA technique is a progressive activity that can be conducted individually or as a group exercise between various stakeholders. For this study, a group exercise was conducted, in which four members from different fields and areas of expertise participated. The HTA analysis was conducted by the first two authors, that can be considered experts with a marine background as naval architects and marine engineers, trained on accident investigation, and familiar with the techniques being used. Furthermore, the remaining authors reviewed the full analysis. In addition, further insights into the field and area of expertise of each analyst are displayed in Table 3.

In the context of this study, the purpose of the analysis is to understand the human response to fire detection onboard passenger vessels. In

Table 3
Group composition and expertise area.

No.	Field	Expertise area
1	Industry/ Academia	Human Factors, Accident Investigation, Resilience Engineering
2	Industry/ Academia	Accident Investigation, Fire investigation, Independent Ship Surveyor
3	Industry	Human Factors, Maritime Safety, Safety Culture
4	Industry	Maritime Safety, Ship inspections

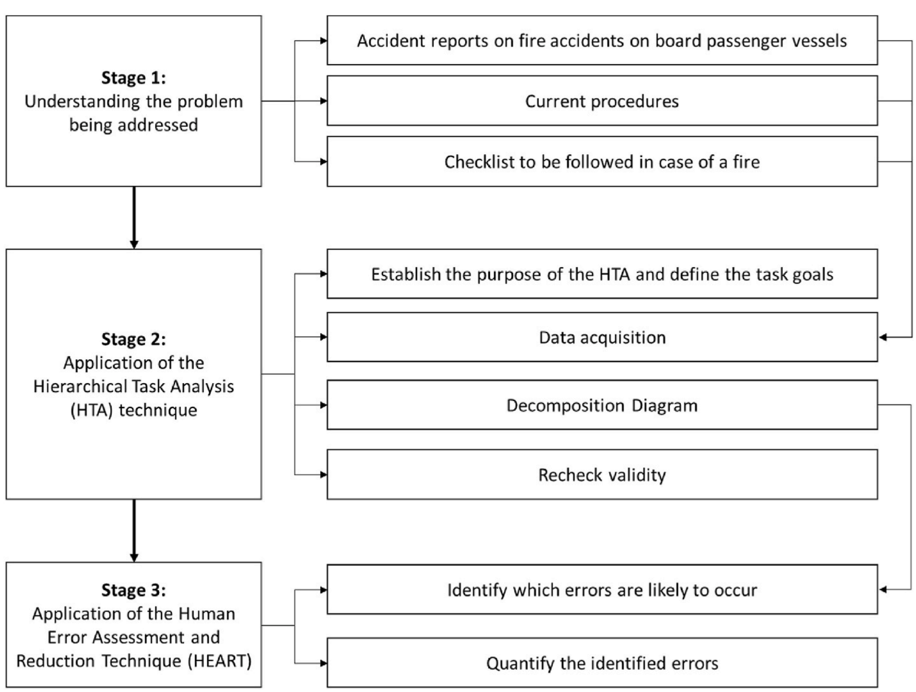

Fig. 1. Proposed human factors approach to unravel the major errors on actions taken after fire detection onboard passenger vessels.

addition, the major goal is to model the human response actions to a fire onboard a passenger vessel.

After the purpose and the goal of the HTA have been identified, the next step includes the creation of a Decomposition Diagram by utilising the available sources, which is displayed in Fig. 2. The top-level goal of the system is to identify the actions taken after a fire has been detected, which is indicated in the Diagram as Action 0. The necessary actors to complete Action 0 are actors 1–6, which are presented on the next level of the hierarchy. In addition, the actions taken by each actor are further broken down at the lower levels. Thus, it is important to mention that these actions follow the order in which these actions should be carried out in an ideal situation. In addition, Table 4 describe in detail for each task and subtask how the human factor will affect the system and errors. Finally, several assumptions have been considered while developing the Decomposition Diagram as follows:

- The severity of the fire detected on board is high.
- The scenario being modelled is an ideal scenario, which implies that the fire does not obstruct and/or inhibit communication and appropriate fire-fighting systems and response.
- All vessel systems with respect to fire-fighting are in good operating conditions.

Finally, the last step on the HTA includes rechecking the validity of the analysis carried out. The HTA presented in Fig. 2 was drawn up by two experts on human factors and fire investigation. In addition, it was also reviewed by two managers from a shipping company, whose expertise mainly lies in the areas of human factors, maritime safety, and ship inspections, as described in Table 3. Therefore, the actions described in the Decomposition Diagram were validated.

4.3. Stage 3: application of the Human Error Assessment and Reduction Technique (HEART)

The last stage of the approach proposed in this paper is to apply the HEART method to the response actions identified by the HTA to predict and quantify which errors are likely to occur with the human response actions to fire onboard a passenger vessel. In addition, for this task, a group exercise was also conducted, were experts involved were carefully selected, and had a combination of a Naval Architecture degree, expertise with ship operations, knowledge on regulatory elements, and expertise in Human Factors (HFs)(Table 3). To that effect, a discussion was held, where an agreement was reach for the values of each error mode and HEP. Thus, justifications for selecting these values were included, and remedial measures were also proposed for each task.

Results and insights of the HEART exercise are recorded in tabular form in Table 5. The first columns provide the number of the task step (e.g.,1.1 or 1.2) together with an outline (description) of the error within each task. In this case, the description would be rewritten as “crew-member fails to” followed by the actions drawn in the Decomposition Diagram. At this stage of the analysis, it is possible to predict what the consequence of each error might be. For instance, for task 1.1, if the crew member who detects the fire fails to inform the Marine Engineer Of the Watch (MEOW) - Engine Control Room (ECR), then the MEOW-ECR cannot proceed with either informing the bridge or taking further actions to avoid propagation or even extinguish the fire (if possible). Then, appropriate error modes were selected from Table 2 and inputted for each task respectively in the third column. The fourth column includes a

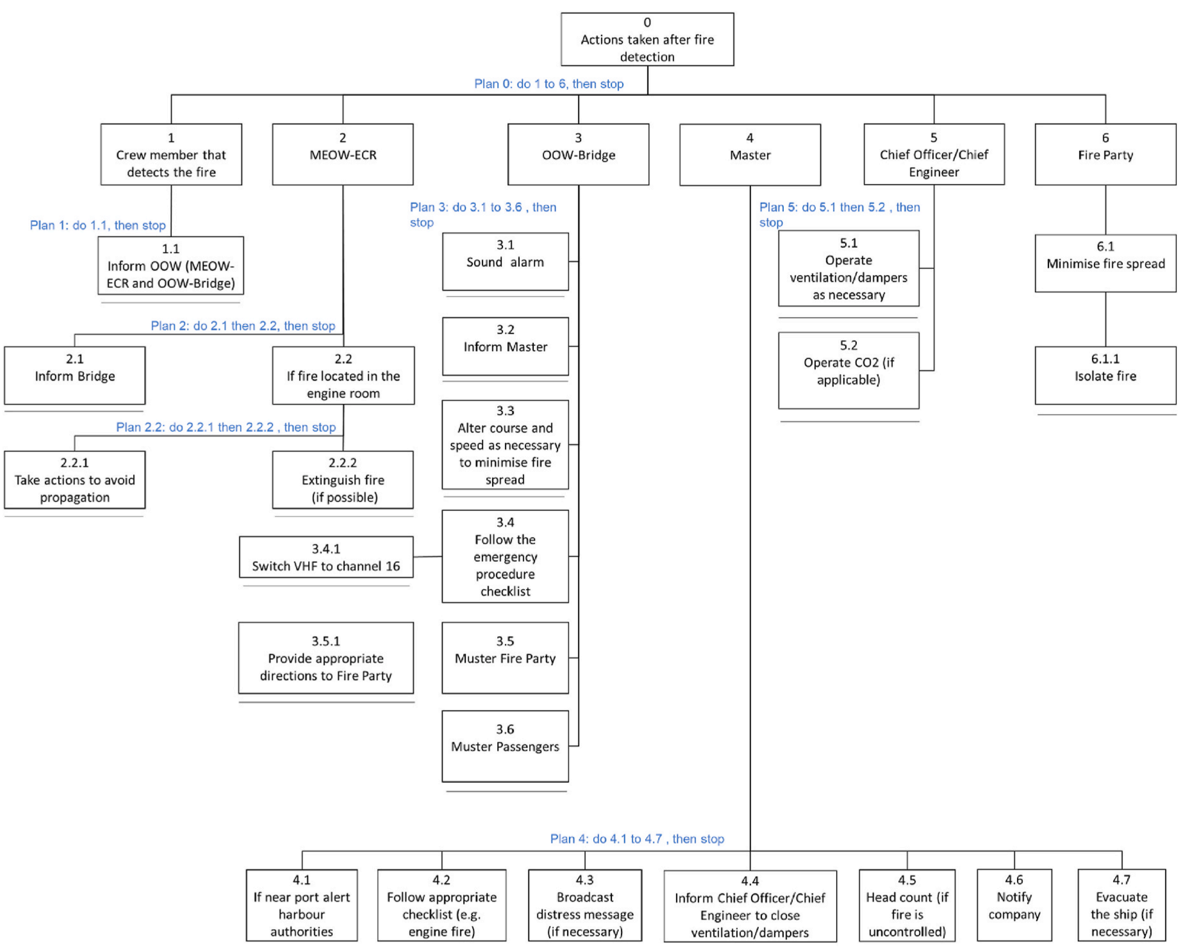

Fig. 2. Decomposition diagram.

Table 4
Description for each task and subtask on how the human factor will affect the system and errors.

Task step	Description	Possible error that might occur
1.1	Crew member that detects the fire fails to inform MEOW-ECR and OOW-Bridge	Depending on the severity and location of the fire, delay can render the fire powerful enough which can lead to abrupt propagation and severity which the on-board extinguishing systems cannot handle.
2.1	MEOW-ECR fails to inform the bridge	Ditto
2.2.1	MEOW-ECR fails to take actions to avoid propagation	Fire may propagate outside the engine room geometry jeopardising safety of both crew and occupants with respect to heat and smoke propagation.
2.2.2	MEOW-ECR fails to extinguish fire (if possible)	Fire may escape engine room geometry, increasing risk exposure of all occupants.
3.1	OOW-Bridge fails to sound the alarm	In case of smoke propagation outside of engine room, panic will ensue from the passenger and the crew.
3.2	OOW-Bridge fails to inform the Master	Master will not be able to muster the fire party.
3.3	OOW-Bridge fails to alter course and speed as necessary to minimise fire spread	Wind may feed more oxygen into the fire which would result in greater intensity and hence risk.
3.4.1	OOW-Bridge fails to switch VHF to channel 16	Authorities may not be able to communicate with the ship which could lead in increased risk of exposure in case firefighting or seach and rescue is needed.
3.5.1	OOW-Bridge fails to provide appropriate directions to Fire Party	If the party is sent to the wrong geometry or if the plan of (fire) attack is flawed, the fire severity might increase, so will the risk.
3.6	OOW-Bridge fails to muster the passengers	Depending on the severity of the fire and the necessity of evacuation, this step might lead to fatalities/PLL (or increased PLL)
4.1	Master fails to alert harbour authorities	If the ship is close to the shore, the port & land based firefighters will aid, averting possible fatalities of damage to the ship and environment.
4.2	Master fails to follow the appropriate checklist	Wrong procedure might be followed, which leads to increased risk for both crew and passengers.
4.3	Master fails to broadcast distress message (if necessary)	In the case that the fire is uncontrolled this failure will lead to increased risk and quite possibly more fatalities (depending on where the accident takes place)
4.4	Master fails to inform Chief Officer/Chief Engineer to close ventilation/dampers	Smoke will propagate out of the engine room which will create panic to the passengers, irrespective of the severity of the fire.
4.5	Master fails to conduct a headcount	CO2 might be released in the engine room with crew trapped inside, which would lead to certain death.
4.6	Master fails to notify the company	Depending on the scenario and location, the company might provide aid in handling and/or averting a fire crisis.
4.7	Master fails to evacuate the ship	Depending on the scenario and location, this failure will lead to fatalities or injuries.
5.1	Chief Officer/Chief Engineer fails to operate ventilation/dampers as necessary	Smoke will propagate out of the engine room which will create panic to the passengers, irrespective of the severity of the fire.
5.2	Chief Officer/Chief Engineer fails to operate CO_2 (if applicable)	Fire will grow in size until it starves itself in the geometry of origin or will propagate to other spaces increasing the risk.
6.1.1	Fire Party fails to isolate the fire	Fire may escape the space of origin, propagating to other geometries whilst increasing in severity. This will increase risk of exposure to fire effluents and/or will lead to increased injuries/fatalities.

justification for selecting each specific error mode, which is based on the experience and expertise of the analysts. The fifth column includes the HEP, which was also selected from Table 2. Finally, the last column shows the remedial measures that could be implemented to reduce errors. These measures are mainly concerned with appropriate drills that are often conducted, crewmembers are familiar with the vessel, and they have the appropriate qualifications, communication systems are available, and procedures and checklists are up to date. It is important to note that to implement any proposed solution effectively; it needs to be implemented at an organisation level.

5. Discussion on the results

As stated previously, fire and explosion events are of utmost importance for passenger ships due to the sheer number of passengers and crew onboard (Baalisampang et al., 2018). Therefore, the response actions carried out by crewmembers after a fire onboard a passenger vessel has been detected are of outermost importance. Hence, the objectives of this papers were first, to demonstrate how HTA can be applied to model the human response actions to a fire onboard a passenger vessel, and second, to utilise a systematic human error reduction and prediction approach, namely HEART to predict and quantify which errors are most likely to occur in this scenario. In addition, the analyses carried out in this paper provided remedial measures that can be considered by ship operators to achieve better results.

With these objectives in mind, information in terms of fire/explosion accidents onboard passenger vessels, regulations, and procedures and checklist was first collected and collated to gain an initial understanding of the human response actions that need to be followed after a fire has been detected onboard. Secondly, a thorough analysis was carried out by a group of experts in the areas of human factor, accident investigation, fire investigation, and maritime safety, amongst others, that consisted of the application of the HTA technique, which allowed for the identification and modelling of the main human response actions to a fire onboard a passenger vessel. Thirdly, HEART was applied to predict and quantify which errors are most likely to occur.

In addition, the analysis conducted revealed that six response errors are most likely to occur, with a Human Error Probability of 0.16 according to the HEART analysis. The above-mentioned most frequent response errors are namely “MEOW-ECR fails to take actions to avoid propagation”, “MEOW-ECR fails to extinguish the fire (if possible)”, “OOW-Bridge fails to muster the passengers”, “Master fails to conduct a headcount”, “Master fails to evacuate the ship”, and “Fire Party fails to isolate the fire”.

In addition, within the HTA conducted, many of the actions included in the Decomposition Diagram could have been subdivided into further levels of component tasks and operations, thus revealing a highly detailed description of the scenario being modelled. Therefore, the main disadvantage found by the authors in applying the HTA was the lack of guidance in terms of when to stop the analysis, which has further implications in terms of the data collection procedures, the depth of the analysis, and the solutions (i.e., remedial measures) that can be suggested.

Regarding the HEART analysis, the main advantage identified was that the error mode taxonomy included in HEART prompts the analysts to consider potentially unforeseen errors and the error reduction

Table 5
HEART error modes, justification, and remedial measures.

Task step	Description	Error mode	Justification	HEP	Remedial measures
1.1	Crew member that detects the fire fails to inform MEOW-ECR and OOW-Bridge	D	This is a communication issue that does not require skills	0.09	Ensure that crew is familiar with the vessel. Frequent and appropriate drills.
2.1	MEOW-ECR fails to inform the bridge	D	This is a communication issue that does not require skills	0.09	Ensure that crew is familiar with the vessel. Frequent and appropriate drills
2.2.1	MEOW-ECR fails to take actions to avoid propagation	C	Halting the fire propagation is highly dependent on the nature of the fire and the location.	0.16	Drill scenarios must cover all possible types of fire (e.g., alternative fuel fire on car deck)
2.2.2	MEOW-ECR fails to extinguish fire (if possible)	C	Halting the fire propagation is highly dependent on the nature of fire and the location.	0.16	Drill scenarios must cover all possible types of fire (e.g., alternative fuel fire on car deck)
3.1	OOW-Bridge fails to sound the alarm	E	Raising the alarm does not require any skills.	0.02	Ensure that crew is familiar with the vessel.
3.2	OOW-Bridge fails to inform the Master	D	This is a communication issue that does not require skills	0.09	Ensure that crew is familiar with the vessel. Frequent and appropriate drills
3.3	OOW-Bridge fails to alter course and speed as necessary to minimise fire spread	G	OOW shall be capable of manoeuvring the ship	0.00004	Ensure that crew has appropriate qualifications
3.4.1	OOW-Bridge fails to switch VHF to channel 16	G	OOW shall be capable of operating communication equipment	0.00004	Ensure that crew has appropriate qualifications
3.5.1	OOW-Bridge fails to provide appropriate directions to Fire Party	D	This is a communication issue that does not require skills	0.09	Ensure that crew is familiar with the vessel. Frequent and appropriate drills
3.6	OOW-Bridge fails to muster the passengers	C	Mustering passengers is not a trivial task as the fire, and the panic induced by it might hinder this task as very complex	0.16	Ensure that crew is familiar with the vessel (muster and evacuation procedures) and appropriate drills.
4.1	Master fails to alert harbour authorities	G	Master shall be familiar with all bridge equipment	0.00004	Ensure that crew has appropriate qualifications. Ensure the checklist are up to date and applicable.
4.2	Master fails to follow the appropriate checklist	E	Master shall be familiar with all checklists	0.02	Ensure the checklist are up to date and applicable. Conduct drills
4.3	Master fails to broadcast distress message (if necessary)	E	Master shall be familiar with all emergency procedures	0.02	Ensure the Master has appropriate qualification
4.4	Master fails to inform Chief Officer/ Chief Engineer to close ventilation/ dampers	D	This is a communication issue that does not require skills	0.09	Ensure that crew is familiar with the vessel. Frequent and appropriate drills.
4.5	Master fails to conduct a headcount	C	Fire scenario might inhibit and/or prohibit a headcount	0.16	N/A (Highly dependent on the scenario)
4.6	Master fails to notify the company	E	Informing the company does not require any skills	0.02	Ensure that the Master has available means of communications.
4.7	Master fails to evacuate the ship	C	Fire scenario might inhibit and/or prohibit an evacuation.	0.16	N/A (Highly dependent on the scenario)
5.1	Chief Officer/Chief Engineer fails to operate ventilation/dampers as necessary	E	Engine crew shall be capable of operating ventilators and dampers	0.02	Vessel familiarisation and drills
5.2	Chief Officer/Chief Engineer fails to operate CO_2 (if applicable)	E	The Chief Engineer shall be familiar with all procedures regarding the release of CO_2.	0.02	Ensure that crew has appropriate qualifications
6.1.1	Fire Party fails to isolate the fire	C	Halting the fire propagation is highly dependent on the nature of fire and the location.	0.16	Drill scenarios must cover all possible types of fire (e.g., alternative fuel fire on car deck)

strategies are readily identified. However, numerous disadvantages were also identified in the application of this technique. First, one disadvantage of using HEART as an error prediction tool is that a task analysis has to be drawn up before error predictions can be made. In order to gain a full description of every action taken by each crew member after a fire has been detected, several long HTAs would be required. Thus, to obtain a high level of details could be time-consuming, particularly in cases where no formal guidance exists. Another limitation of applying HEART is the limited error modes that are available (Table 2) and the small difference between some error modes, for example, "Routine, highly practised rapid task" and "Completely familiar routine task", which increase the complexity of the analysis carried out by the analysts. Finally, the HEART method was developed for the nuclear industry; hence, the authors' view is that the available error modes need to be modified and expanded to increase their applicability for the maritime context and to reflect the reality of the maritime domain.

In addition, after applying the HTA and HEART techniques, remedial measures were formulated upon the results. The formulation of recommendations for corrective action was a final critical element in this study since the quality and practicality of the formulated recommendations will determine their acceptability by ship operators.

The authors acknowledge the high uncertainty related with some of the steps and assumptions taken during the application of the above HRAs. Therefore, aiming to reduce the uncertainty in this case study to a minimum, experts involved in this case study were carefully selected. Thus, the aforementioned experts had a combination of a Naval Architecture degree, expertise with ship operations, knowledge on regulatory elements, and expertise in Human Factors (HFs). In addition, the initial results from this case study were later discussed in a meeting involving personnel from the HSQE department from a known shipping company, which decided to remain anonymous. As a result of the above meeting, not only the decomposition diagram (Fig. 2) was updated to reflect a most accurate situation onboard, but also the HEART error modes and the remedial measures were discussed and agreed on.

Finally, the results of this study reinforce the idea of the authors that the response actions carried out by crewmembers after a fire onboard a passenger vessel has been detected are of extreme importance. Effective communication between crewmembers and officers when a fire has been detected is essential to encounter this critical situation. Thus, conducting regular drills to get crewmembers familiar with the procedures to be followed in a fire event is also of utmost importance, as identified in this study.

6. Conclusions

This paper has first demonstrated how HTA can be applied to model the human response actions to a fire onboard a passenger vessel, and second, it has utilised a systematic human error reduction and prediction approach, namely HEART to predict and quantify which errors are most likely to occur in this scenario. This information can be extraordinarily valuable for academics and maritime stakeholders, especially ship operators and shipping companies since they can allocate more efforts to addressing the major errors identified. Furthermore, although the proposed application of the HTA and the HEART techniques to identify the human response actions to a fire onboard a passenger vessel and to quantify their errors is novel, it is worth highlighting some limitations of this study. First, several assumptions were made to represent an ideal scenario (i.e., the fire does not obstruct and/or inhibit communication and appropriate fight-fighting systems, and all vessel systems with respect to fire-fighting are in operating conditions). However, in a real fire/explosion accident, an ideal scenario is most unlikely to occur. Second, as the application of the HTA and HEART techniques in the engineering domain, and most specifically in the maritime domain, is relatively low, a limited amount of guidance, previous studies, and applications were available to conduct this study.

Finally, the authors recognise that there a multiple additional HRAs that could have been potentially applied in this study as an alternative to HTA and HEART. However, the purpose of this study was to demonstrate how two examples of the most-known HFs techniques for accident investigations can be applied to help accident investigators and safety managers within maritime organisations. Therefore, as future work, it would be worthy to compare the results obtain in this study with additional HRAs. In addition, the HTA and HEART techniques can be further applied to fire/explosion accidents to model the response to a specific fire, for example, an electrical fire or a fire initiated in the engine room and to predict and quantify which errors are most likely to occur in these scenarios. Moreover, the above techniques can also be extended into additional accident categories (e.g., collision or grounding accidents).

CRediT authorship contribution statement

Beatriz Navas de Maya: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Alexandros Komianos:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ben Wood:** Validation, Supervision. **Louis de Wolff:** Validation, Supervision. **Rafet Emek Kurt:** Validation, Supervision. **Osman Turan:** Validation, 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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