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A probabilistic model for fatalities estimation of ship fire accidents

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Abstract: Fatalities estimation is beneficial for both improvement of safety fireproofing of ship design and quick response to such accidents. This paper proposes a probabilistic method for fatalities estimation of fire accidents caused by critical temperature and critical smoke from the perspective of comparing the available safety egress time and required safety egress time. The kernel of this proposed method is first to derive the available safety egress time estimation equation by using fire simulator dynamics to simulate the fire development process, to determine the required safety egress time equation given by the guideline of International Maritime Organization, where the crowd behaviours, including waiting time at corridors, stairs and doors, are considered. The proposed method is applied to a real fire accident and the fatality rate is close to real scenarios. Consequently, this paper proposes a practical and holistic method to estimate the fatalities of fire accidents.

Key words: fatalities estimation; probabilistic model; fire simulator dynamics; ASET and RSET

1 Introduction

Fire accident is a significant type of maritime accidents, which has a relatively high likelihood of occurrence among all types of maritime accidents apart from collision and grounding. For example, Wróbel et al. (2017) found that 24% of maritime accidents are fire from 2011 to 2014 using historical data given by the EMSA report (EMSA 2015); in Hong Kong, the fire accidents accounts for 7% among all types of maritime accidents (Yip 2008); in the gulf of Finland, the fatality rate is around 10% (Kujala et al., 2009). Moreover, as a type of non-navigational accidents, fire also causes more serious consequences than other types of maritime accidents. Specifically, Roberts et al. (2013) discovered that 19% of the fatalities are caused by fire from 501 accident records of bulk carriers. Weng and Yang (2015) concluded that the fire accident caused 132% higher fatalities than other types of maritime accidents.

From the perspective of risk analysis, the human fatality is a contributing factor to analyse the consequence of maritime accidents and it should be beneficial to estimate the fatality rate due to fire accidents. The Ministry of Transportation (MoT) of China issued criteria for defining the minor, major and catastrophic consequence in China, and the fatalities is the key criteria to distinguish the severity of the consequences (Zhang et al, 2016). Moreover, in the SAFEDOR project (which is a maritime research project on risk-based ship design), this criterion is also used for risk analysis of maritime accidents (Guarin et al., 2009). Hence, in order to reduce the fatalities and improve the fire safety, many previous studies have focused on the evacuation of passengers and crewmembers (Cho et al., 2016; Chu et al., 2013; Ha et al., 2012). However, the ship fire accidents cause more fatalities than other types of maritime accidents because ship fire accidents often occur unexpectedly and provides little evacuation time for passengers and crewmembers (Baalisampang et al., 2018). Thus, to estimate the fatality rate of ship fire accidents have the following benefits. First, if the fatality rate can be estimated in a short time, the quick response actions can be taken to minimize the consequence of ship fire accidents. Second, the safety design can be carried out by introducing the fatality estimation model to further analyse the weakness of fire safety (Kang et al., 2017). Third, after introducing the fatality estimation model, the decision-maker can have better understanding of the fire accident development and countermeasures can be taken for fire safety management.

The Available Safety Egress Time (ASET) and the Required Safety Egress Time (RSET) are usually used to estimate the fatality rate in building fires (Hanea and Ale, 2009; Hanea et al., 2012). However, different from building fires, which can use experiment to collect the ASET and RSET data, the estimation of ASET and RSET is a challenge as the uncertainty exists in this process for ship fire accidents, and some studies have carried out to address this challenge. For example, Salem (2016) utilized Monte Carlo simulation to address the uncertainties for estimation of ASET, and Wang et al. (2013) also focused on the uncertainty of ASET for ship fire accident. It can be seen from the above that two academic problems for fatality estimation due to ship fire accidents remain unaddressed in the literature. First, there is lack of a probabilistic method considering both ASET and RSET to estimate the fatality rate. Second, ASET and RSET estimation methods are too complicated because of the uncertainty, a simplified and quantified method to derive ASET and RSET is lack from the literature.

In order to address these two problems, the motivation of this paper is to propose a probabilistic method for estimating the fatality rate from the perspective of both ASET and RSET. Specifically, when estimating ASET, the critical smoke and critical temperature, which is the contributing factor of fatalities in fire accidents, are considered, and the fire simulator dynamics (FDS) simulation method is introduced to estimate the ASET considering several parameters in order to address the uncertainties in this estimation process (Wang et al., 2013; Salem 2016). Moreover, when estimating the RSET, the crowd behaviours including at the corridor, stairs and door are considered for evacuation time estimation.

The remainder of this paper is organized as follows. Section 2 proposes the estimation framework for human fatalities by considering both ASET and RSET. Section 3 applies the proposed method for fatalities estimation by using a fire accident occurred at a bulk carrier as example. Discussion is carried out in Section 4, where the limitations of the probabilistic model and the derivation of ASET and RSET are discussed. Conclusions are drawn in Section 5.

2 Development of fatalities estimation model for ship fire accidents

2.1 Establish a generic estimation framework for ship fire accidents

In order to estimate the fatalities of ship fire accidents, the fatality estimation framework is also developed in the similar way with life safety in the building fire by using ASET and RSET (Hanea et al., 2012; Hanea and Ale, 2009; Kong et al., 2014). However, different from the building fire in nature, the derivation of ASET and RSET in ship fire accidents are different from those of the building fire. This framework is developed in three steps.

First, the ASET is derived by using FDS simulator, which is a widely used tool for fire development simulation for building fire. In this step, the ship cabin is first constructed, and the parameters of ship fire should then be defined. Last, the critical temperature and smoke are derived, which can be used to obtain the critical time for human fatalities using regression analysis.

Second, RSET is obtained by using the guidelines issued by IMO. In this step, three types of human behaviours, which are crowd at doors, stairs and corridors, are considered. Moreover, the response time, detect and alarm time are also modelled in this process.

Third, the fatality rate is determined by comparing the time of ASET and RSET. If $ASET < RSET$, the crewmembers or passengers will not have enough time to escape from the ship fire accident and the probability to cause fatalities is high. If $ASET > RSET$, the probability to cause fatalities is low.

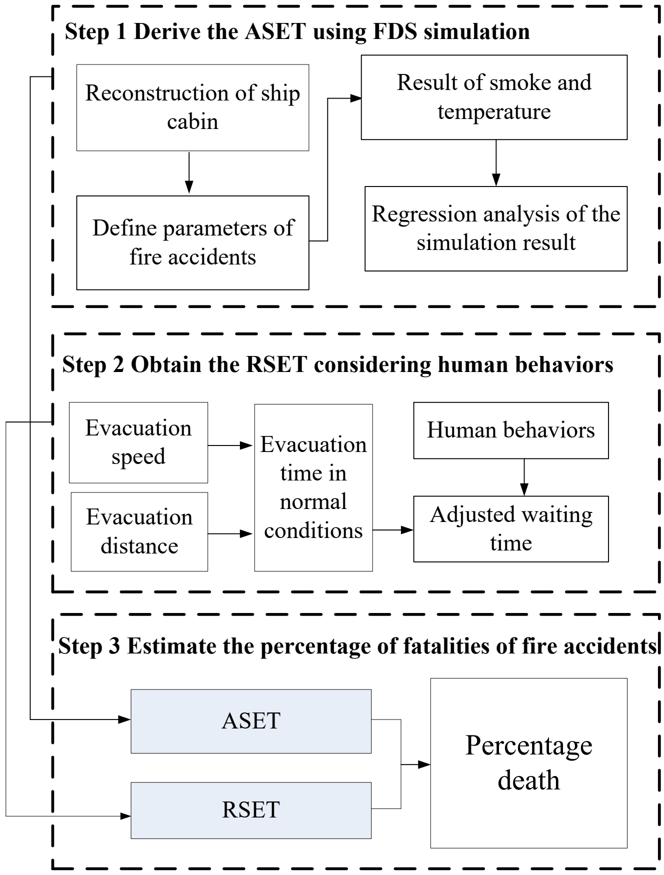


Fig. 1 Fatalities estimation framework for ship fire accidents

2.2 Acquisition of ASET using FDS

Time is a critical factor for emergency response to maritime accidents (Shi et al., 2014; Wu et al., 2017a), and an initial accident will develop into secondary accidents and cause serious consequences if missing the opportunity of best response time (Mazaheri et al., 2014; Wu et al., 2017b). Moreover, from the statistical data (Jasionowski, 2011), such as the accident of MV Estonia ferry (1994) and MV Rocknes (2004), there are only 10 minutes or even shorter time for evacuation. Similarly, time is also the most significant factor and is limited for ship fire accidents, in practice, there are two indexes to define the $ASET$: (1) the time when the critical height of the smoker layer is reached (t_{smo}), (2) the time when the critical temperature is reached (t_{temp}). In practice, ASET is equal to the minimum of them (Hanea et al., 2012; Kong et al., 2014), and this is written as $ASET=min(t_{smo},t_{temp})$.

FDS is suitable for simulation of fire accident development owing to three advantages (McGrattan et al., 2010). First, the ship fire owns the characteristics of low Mach number and the buoyancy driven flow, which makes this tool is especially suitable for ship fire simulation (Khan et al., 2017; Zhao et al., 2017; Kang et al., 2017). Second, the FDS tool is intuitive and easy to be used as it provides the graphical interface for both fire development modelling and simulation results (Su et al., 2012; Salem 2010).Third, the FDS can simulate smoke spread and temperature change in the fire accident development (Su and Wang, 2013), which is required for the estimation of ASET. The procedure of using this tool for fire development modelling can be divided into three stages, which are three-dimensional construction of ship cabin, parameters definition of fire accidents and regression analysis of the critical temperature and smoke. The detailed description of fire development simulation is illustrated in Figure 2.

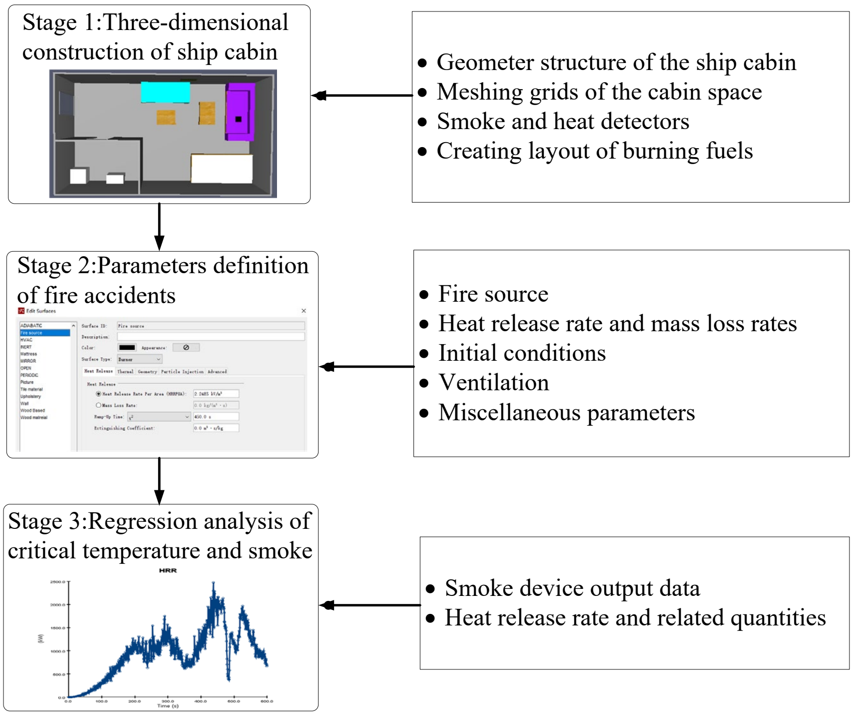


Fig. 2 Modelling process of fire accident development using FDS

In the first stage, the 3D structure of the ship cabin is constructed. This process includes the geometrical structure of the cabin, the development of meshing grid of the cabin, installation of the heat and smoke detectors to obtain the simulation result and defining the layout of different types of fuels.

In the second stage, after constructing the ship cabin, two significant parameters are specified in the modelling process, which are heat release rate (HRR) and density of hazardous smoke. The first significant parameter to be specified is HRR. As time is critical for evacuation, the significant period to determine the ASET is the early stage of fire accident development. In this period, the HRR can be treated as a function of squared time (t^2) and it can be written as $Q = \varepsilon t^2$ (Wang et al., 2013), where Q is the HRR of the ship fire (kW); t is the ignition time of fire (s); ε is the fire growth rate (kW/s^2). It can be seen from this equation that the contributing factor for HRR is fire growth rate, and from Kong et al. (2014), this growth rate is defined as four categories using linguistic terms, as listed in Table 1. Moreover, the second significant parameter is the density of hazardous smoke. There are two types of hazardous smoke to human beings, which are CO_2 and CO, respectively. In the early stage of fire development, CO_2 is the main product as the oxygen is sufficient for burning. Afterwards, CO is the main product when the oxygen becomes insufficient in the closed cabin. Moreover, the rates of hazardous smoke (CO_2 and CO) are different when fuels of the ship cabin are different, and this can be estimated by making reference to SEPE Handbook for fire protection engineering (Hurley 2015).

Table 1 Categories of fire growth rate (Kong et al., 2014)

Category	Fire growth rate (kW/s^2)	Time when Q reaches 1055 kW(s)
Slow	0.0029	600
Medium	0.0117	300
Fast	0.0469	150
Ultra fast	0.1846	75

In the third stage, the simulation result of smoke and temperature spread can be obtained by introducing FDS. As there are two types of hazardous smoke in fire accidents, the ASET can be rewritten as $ASET=min(t_{CO},t_{CO_2},t_{temp})$, where t_{CO} is the time when the concentration of CO reaches the threshold limit value for human beings, and similarly, t_{CO_2} is the time when the concentration of CO_2 reaches the threshold limit for human beings (become toxic to humans). Moreover, based on the data of smoke and temperature spread, the regression method can be introduced to obtain the function of t_{CO} , t_{CO_2} and t_{temp} , and this is introduced for the human fatality estimation in the ship fire accidents in this paper. Hence, the influencing factors of the ASET can be summarised and shown in Figure 3.

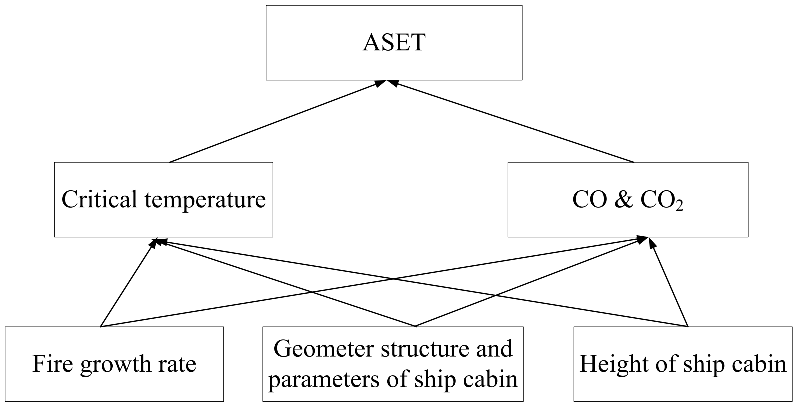


Fig. 3 Influencing factors of ASET for ship cabin fire

2.3 Derivation of evacuation time in normal conditions

RSET is another factor should be discussed and defined. As this paper focuses on the time caused by critical temperature and hazardous smoke, which are discussed in Subsection 2.2, only the time required for evacuation of ship fire accidents is considered. In other words, the time required for response to the secondary accidents (e.g. abandon ship owing to flooding after fire accidents) is not considered. The key factor to define RSET is the evacuation time for passengers and crew members, and some previous studies focused on this factor from the literature (Lee et al., 2004; Kim et al., 2004; Sarvari et al., 2017).

In order to determine the RSET, the evacuation time in normal conditions (ETNC) should be first determined. It can be easily obtained that the ETNC is equal to the evacuation distance (ED) dividing the evacuation speed (ES), and this problem can be transformed to determine the ED and ES. The first node is evacuation distance, and it is related to the horizon, vertical and evacuation locations. The relationship can be simplified as follows. Suppose the height of each deck is the same and the upper deck is positive while the lower deck is negative, the main deck is assumed to be 0, and the other decks can be defined and shown in Figure 4. Therefore, the evacuation distance is the horizon distance plus the weighted vertical distance, where the weights are the number of the deck (n). The horizon and vertical locations are assumed to be random in the corridor and stairs, respectively. The other node, evacuation speed, is determined from the guidelines of International Maritime Organization (IMO), and the initial speed in corridor, stairs (down) and stairs (up) are 1.2, 1.0, and 0.8 m/s respectively (IMO, 2016).

Note that the evacuation location is not determined here because this is one of the input parameters, and this type of input parameters vary in different scenarios and should be specified according to the ship conditions.

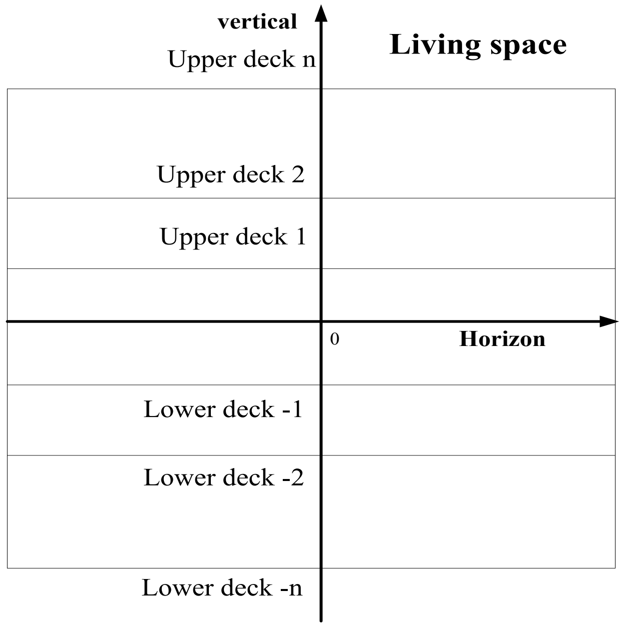


Fig. 4 Evacuation location definition of living space

Table 2 Quantitative relationships of the nodes for evacuation time in normal conditions

Parent node	Child node	Equation	Description
Evacuation time in normal conditions (ETNC)	Evacuation distance (ED) Evacuation speed (ES)	$ETNC=ED / ES$	The evacuation is equal to the evacuation distance dividing the evacuation speed.
Evacuation distance (ED)	Horizon (HZ) Vertical (VC) Evacuation location (EL)	$ED = if(and(-n \leq EL \leq n), HZ, HZ + n \times VD)$	Evacuation distance is the horizon distance plus the weighted vertical distance.
Horizon (HZ)	Corridor length (CL)	$HZ = uniform(0, CL)$	The crews are assumed to distributed in the corridor randomly.
Vertical (VC)	Stairs length (SL)	$VC = uniform(0, SL)$	The crews are assumed to distributed in the corridor randomly.
Evacuation speed (ES)	-	$ES = Triangular(0.8, 1, 1.2)$	From the IMO guideline, the initial speed in corridor, stairs (down) and stairs (up) are 1.2, 1.0, and 0.8m/s respectively.

2.4 Estimation of waiting time considering human behaviour

Human error is contributing factors for human fatalities in fire accidents (Akyuz et al., 2016; Soner et al., 2015; Wang et al., 2011), this is because different human behaviours in fires may cause chaos during the evacuation process. Hence, some studies have focused on this behaviour problem. Sarvari et al. (2017) systematically reviewed the emergency evacuation management for maritime transportation and stressed the importance of human behaviours in evacuation. Similar opinions are also given in other studies (Lee et al., 2003; Roh et al., 2013). Ha et al. (2012) proposed cell-based evacuation simulation model by considering the human behaviour for passenger ships, in that study, three types of human behaviours are considered, which are individual, crowd, and counter flow-avoiding behaviours. Similarly, Cho et al. (2016) developed a velocity-based egress model by considering the individual, crowd, and emergency behaviour for ship evacuation. Moreover, the moving characteristics such as the ship trim and heeling (Sun et al., 2018; Kim et al., 2004) and the layout of the ship (Chu et al., 2013; Park et al., 2004) are also important in evacuation.

From the above analysis, the passenger's characteristics (e.g., age, gender), layout of the ship, individual, crowd, and emergency behaviour are the significant factors for ship evacuation. As this paper intends to estimate the RSET from a probabilistic rather than deterministic perspective, the human behaviours are simplified as follows. The IMO (2016) guideline provides two methods, which are a simplified and an advanced evacuation analysis methods. The main difference between the simplified and advanced methods is whether the passenger's characteristics (e.g., age, gender) are considered. Because the modelling process will be very complicated and it is difficult to get the detailed information of the passengers in the emergent situation when considering the passenger's characteristics, the simplified method of IMO (2016) is applied in this paper. Moreover, as the passengers are requested to participate the training of evacuation after boarding the ships (Liou and Chu 2016; Hanea et al., 2012), the moving characteristics are also ignored because they are trained for evacuation and the moving characteristics will not be too much different. By introducing the simplified method, the crowd behaviour can be categorised as crowd at stairs, corridor and doors.

The first human behaviour is crowd behaviour at the corridor. This is very simple because each deck is separate and only the density of corridor should be considered. From the IMO guidelines (IMO, 2016), the speed of person (m/s) is 0.67 when the density flow (p/m/s) is above 1.3, and the speed in corridor (m/s) is 1.2 when the specific flow (p/m/s) is below 0.65. Therefore, the equation of evacuation speed in the corridor can be listed in Table 3.

Table 3 Quantitative relationships of the nodes for waiting time in corridor

Parent node	Child node	Equation	Description
Waiting time at corridor (WTC)	Corridor speed (CS) Corridor length (CL) Evacuation speed (ES)	$WTC = CL / CS - CL / ES$	The waiting time exist when the CS is lower than the ES in normal conditions.
Corridor speed (CS)	Density in corridor (DC)	$CS = \begin{cases} 0.65 \;\; if \;\; DC \leqslant 1.2 \\ 0.67\text{-}(DC\text{-}1.3) \times 0.53/0.65)) \\ \;\; if \;\; 0.67 < DC < 1.2 \\ 1.3 \;\;\; if \;\; DC \geqslant 0.67 \end{cases}$	The CS depends on the density of person in the corridor.
Density in corridor (DC)	Number of people (NP) Corridor area (CA)	$DC = NP / (2n \times CA)$	The people is assumed to be randomly distributed in the corridor of each deck.
Corridor area (CA)	Corridor length (CL) Corridor width (CW)	$CA = CL \times CW$	The corridors are treated as a regular rectangle.

The second human behaviour is crowd at the stairs, which can be divided into stairs (up) and stairs (down). The evacuation speed at the stairs is assumed to be the minimum of the evacuation speed (up) and speed down so that the waiting time will be maximum time between the time (up) and time (down). Similarly, the evacuation speed (up and down) depend on the density of the people at the stairs. The relationships among these nodes are summarized and shown in Table 4.

Table 4 Quantitative relationships of the nodes for waiting time in stairs

Parent node	Child node	Equation	Description
Waiting time at stairs (WTS)	Stairs up speed (SUS) Stairs down speed (SDS) Stairs length (SL) Evacuation speed (ES)	$WTS = SL / \min(SUS, SDS) - SL / ES$	The waiting time exist when the stairs speed (minimum between up and down) is lower than the ES.
Stairs up speed (SUS)	Stairs density up (SDU)	$SUS = \begin{cases} 0.8 \ \ if \ SDU \leqslant 0.43 \\ 0.44\text{-}(SDU\text{-}0.88) \times 0.8 \\ \ if \ 0.43 < SDU < 0.88 \\ 0.44 \ \ if \ SDU \geqslant 0.88 \end{cases}$	The SUS depends on the density of person in the stairs.
Stairs down speed (SDS)	Stairs density down (SDD)	$SDS = \begin{cases} 1.0 \ \ if \ SDD \leqslant 0.54 \\ 0.55\text{-}(SDD\text{-}1.1) \times 15/19 \\ \ if \ 0.54 < SDD < 1.1 \\ 0.55 \ \ if \ SDU \geqslant 1.1 \end{cases}$	The SDS depends on the density of person in the stairs.
SDU(SDD)	Stair area (SA) Evacuation location (EL) Number of people (NP)	$if(1 < EL \leqslant n, 1 \times NP, 0) / SA$ (SDU) $if(-n < EL \leqslant 1, 1 \times NP, 0) / SA$ (SDD)	The density in the stairs depends on the people up or down dividing the stairs area.
Stair area (SA)	Stair length (SL) Stair width (SW)	$SA = SL \times SW$	The stairs are treated as a regular rectangle.

The third human behaviour is crowd behaviour at the door. As all crewmembers or passengers have to pass the door of the main deck, the waiting time at door (WTD) should consider the evacuation of this deck and also from the other decks. In order to estimate WTD, two steps are carried out in this process. First, the probability of crowd (PR) at door from the main deck is estimated. Take the main deck for example, assume the distribution of each stair is normal, this can be achieved by using equation $PR = \sum_{i=1}^{n} Normal(NPS_i, \rho_i)$,where ρ_i vary from the number of deck because the evacuation people need more time from the farer deck than closer deck. Moreover, NPS_i stands for the number of people in stairs, this is achieved by counting the people from the adjacent decks using equation $NPS_1 = if(-1 < EL < 1, 1, 0)$ for the first deck. Second, the WTD is equal to the probability of crowd multiply the number of people, which is written as equation $WTD = PR \times NP$.

2.5 Prediction of probability of fatalities for fire accidents using Bayesian Network

In order to estimate the probability of fatalities due to fire accidents, the Bayesian Network is introduced in this paper. Bayesian Network is a widely used method for risk analysis and decision-making for maritime transportation. The merits of using Bayesian Network are as follows. First, this method can intuitively represent the relationship among multiple influencing factors owing to the graphical structure (Eleye-Datubo et al., 2006; Wu et al., 2017c). Second, this method provides a probabilistic tool to quantify the relationship among these influencing factors (Fu et al., 2016), and it can deal with both discrete and continuous variables (Cinicioglu and Shenoy 2009). Last, some software, such as GeNIe (Montewka et al., 2014) and Hugin (Goerlandt and Montewka 2015; Matellini et al., 2013), provides a practical tool for Bayesian Network modelling.

From the above analysis, the ASET and RSET can be determined by using the above established equations. The developed Bayesian Network is simplified as follows. The sub-model is introduced to reduce the nodes. In this paper, four sub-models are introduced (i.e. evacuation time in normal conditions, waiting time at corridor, waiting time at stairs and waiting time at door). The associated intermediate nodes are included in these four sub-models. Specifically, the sub-model of waiting time at corridor includes corridor area, density in corridor, corridor speed, waiting time at corridor. The sub-model of waiting time at stairs includes stairs up speed, stairs down speed, stairs density up, stairs density down, stair area, waiting time at stairs. The sub-model of waiting at door includes probability of crowd and waiting time at door. However, the input variables, which require further information from the specific fire accidents, are excluded in the sub-model and they are shown in purple colour.

Note that when considering the RSET, the detection time, and alarm time, and the response time should be considered, which depends on the time of day and fire drills. Moreover, they are the parent node of the response and the quantitative relationship can be defined as follows. From Hanea et al. (2012), the response time at day can be treated as a uniform distribution and defined as equation $RT_1 = uniform(30,60)$, while at night-time, the response time increased and it is defined as equation $RT_0 = uniform(60,120)$. Considering the passengers are required to participate fire drills after boarding on the ship, and they are not as family as the crewmembers with the procedures, the response time of the passengers are treated as 80% of the normal conditions and defined as $RT_1 = 0.8 \times uniform(30,60)$ and $RT_0 = 0.8 \times uniform(60,120)$, respectively. The graphical structure of this developed Bayesian Network is shown in Fig. 5.

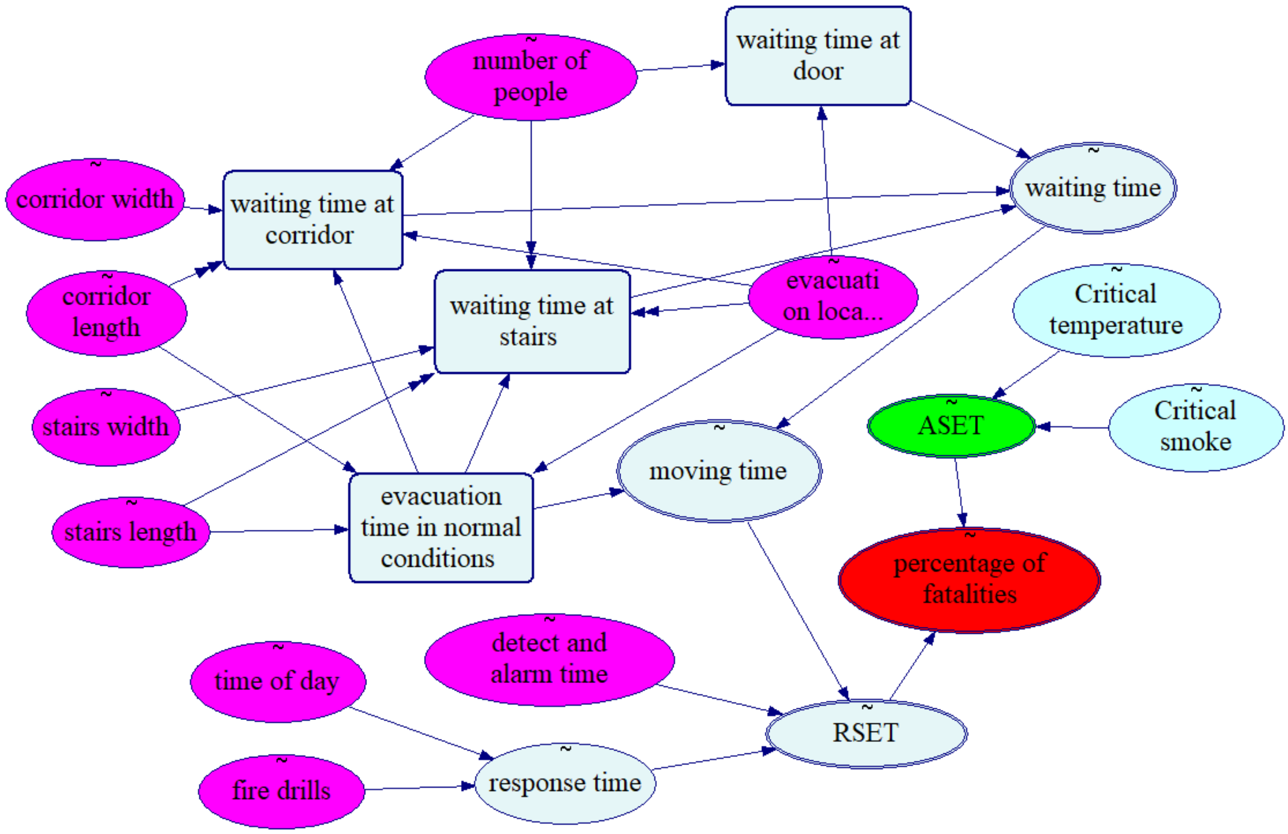


Fig. 5 Graphical structure of fatalities estimation for fire accidents

3Application of the proposed model for fatalities estimation

3.1 Scenario description of fire accidents

In August 2010, a fire accident occurred in the Yangtze River. At 10:00, the fire accident was detected in the cabin of the ship at the main deck, at that time, the fire was small and little smoke can be found. The ship was a bulk carrier with total length of 150m and breadth 26m. As there were many flammable materials in the cabin, the fire was quickly spread to other cabins and crew rooms in the living space. After evacuation the crewmembers, the fire was extinguished with the help of department of fire fighting at 15:00. However, one crewmember died in this process. Finally, the fire caused one fatality and serious damage to the ship.

Moreover, from the investigation report, the fire was deduced to be occurred around one minute ago before the fire was detected. There were only three decks in the living spaces. There were 17 crewmembers on this ship. The ship's particulars are as follows, the corridor and stairs width is around 0.9m; the corridor length is around 60m; the stairs length is around 3m. The detailed information of the fire accidents is shown in Table 5.

Table 5 Detailed information of the fire accidents

factor/variable	value	factor/variable	value
Time of day	Day	Corridor width	0.9 m
Detect and alarm time	Approximately 75s	Corridor length	60m
Number of decks	3	Stairs width	0.9m
Crew members	17	Stairs length	3m
Fatalities	1	Evacuation location	Main deck

3.2 Use of FDS for critical conditions estimation to estimate ASET

3.2.1 Three-dimension construction of ship cabin

In order to obtain the ASET using FDS simulation, the three-dimension of ship cabin should be constructed. The following four steps achieve this in the FDS simulation software.

First, the number of meshing grid is defined. Assume the living space is approximately 30m length, 7.5m width and 2.1m height, as each grid is defined as 0.1m, the total number of the meshing grid is defined by using equation $2^{300} \times 3^{75} \times 5^{21} = 47250$.

Second, the parameters of the ship cabin should be defined. In this paper, as the fire occurred in the living room, the length is defined 5m. The fuel is another significant parameter and is specified. In this paper, a bed, sofa, tea table, desk, chair and shower room are defined, and their sizes are also defined. it can be seen that majority of these furniture are wooden. In order to simply the modelling process, three assumptions are carried out. (1) The first assumption is that all the furniture are rectangle. (2) The small components of the cabin are ignored as the heat released by these components is small. Third, the fuels in the corridor is rare and the corridor is assumed to be a place with empty fuels. Based on these assumptions, the cabin is developed and shown in Figure 6.

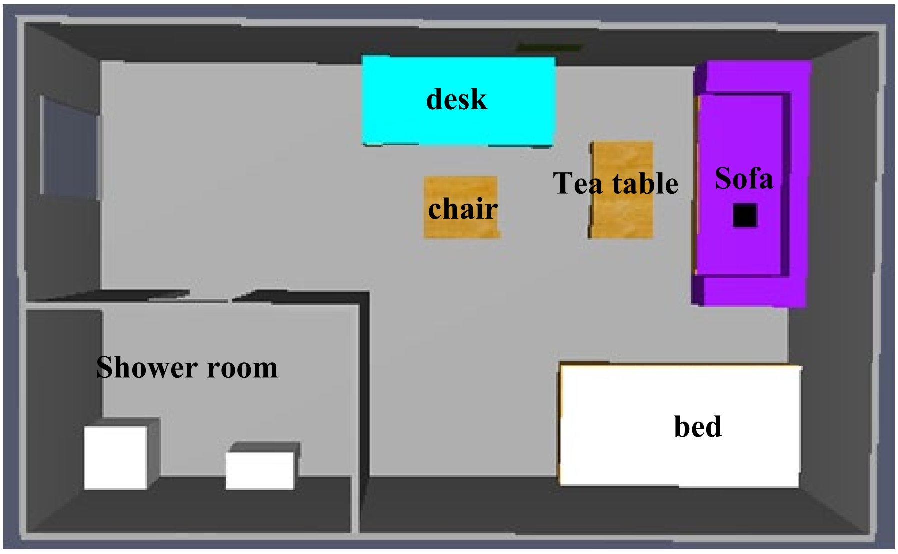


Fig. 6 Development of 3D structure of the ship cabin

Third, the parameters of the fire accidents should be defined, note that two significant parameters should be carefully handled. (1) The HRR ($\dot{Q}$). $\dot{Q} = \varepsilon \times \dot{m} \times \Delta H$, where ε is the coefficient factors of fire burning, which stands for the degrees of the fuels has been burned; $\dot{m}$ is the burning rate of mass for the fuels, and the unit is kg/s, ΔH stands for the heat of the fuels, and the unit is kJ/kg . Traditionally, the coefficient factor (ε) is a predefined value between 0.3 and 0.9, in this paper, it is defined as 0.6. Moreover, the $\dot{m}$ and ΔH are 0.016 and 17.3 for the wooden materials, respectively, and the $\dot{m}$ and ΔH are 0.026 and 22.5 for the polyester foam, respectively. Based on these parameters, the HRR($\dot{Q}$) in this paper can be calculated and the value is 1.952MW.

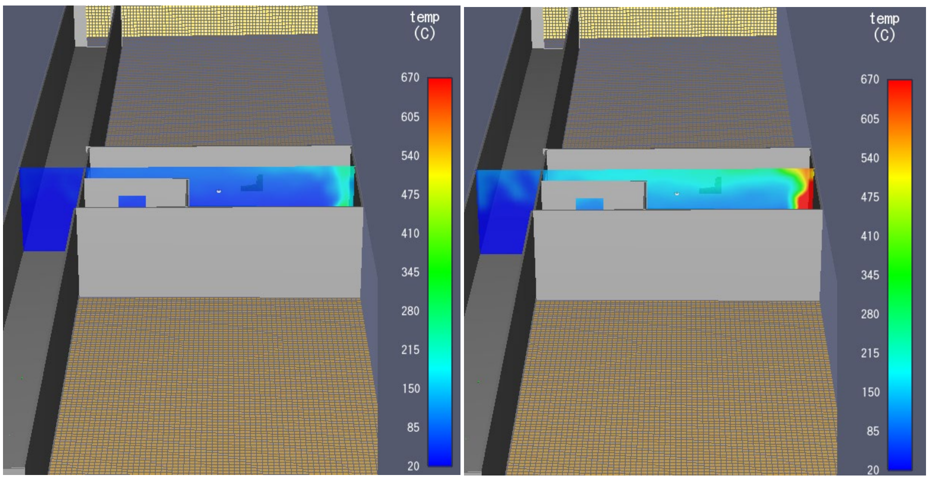
(2) The fire growth rate (α). As the fuels are wooden materials and polyester foam, the fire growth rate can be defined as 0.04689 kW/m^2 from Table1. All the above parameters are summarized and shown in Table 6.

Table 6 Parameters used for FDS simulation

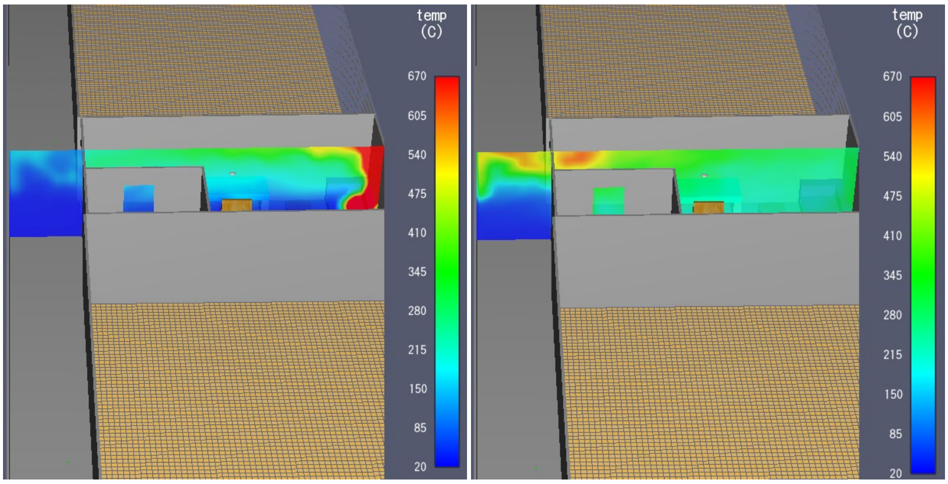
factor/variable	value	Description
Number of meshing grids	47,250	The number of meshing grid is $2^{300}\times3^{75}\times5^{21}$, where 300, 75 and 21 are the meshing grid in the direction of x, y and z.
Cabin height	2.1m	The height of ship cabin is approximately 2.1m.
Cabin length	5m	The cabin length is approximately 5m.
HRR	1.952MW	The HRR can be calculated as described.
Fire growth rate	0.04689 kW/m^2	Majority of the cabin is furnished with wood fuels.

3.2.2 Simulation result of critical time for temperature

As the ASET is determined by the critical temperature and critical smoke, the detectors are used in this model to obtain the data of temperature and smoke. In this paper, four heat detectors are used with one in the ship cabin and three in the corridor. Moreover, eight smoke detectors for CO and CO_2 detection are also used. The detectors are installed at the height of 1.5m, which is the same with the height of human beings (defined as 1.8m in this paper). It can be seen from the investigation report that the fire spread fast, therefore, the simulation time is set as 600s in this paper. After defining these parameters, the simulation result of temperature change over time is shown in Figure 7.



(a) T=60s (b) T=90s



(c) T=140s (d) T=300s

Fig. 7 Simulation result of temperature change over time

From Figure 7, four phenomena can be observed. First, the obvious stratification of temperature field exit in this fire accident development process, and the upper and lower layers of temperature differ a lot. Second, the temperatures with the same height are approximately the same in the different locations. Third, the temperature increases suddenly in the initial accident development process, and the highest temperature is 250°C at the time of 300s. As the temperature above 100°C may cause serious injury to the human beings, the time when the temperature reached 100°C is assumed to be the critical time. Therefore, regression analysis of the critical time for temperature is carried out, and it is shown in Figure 8. Based on this regression analysis, the critical time for temperature can be defined as $t_{temp}=uniform(149,172)$ s .

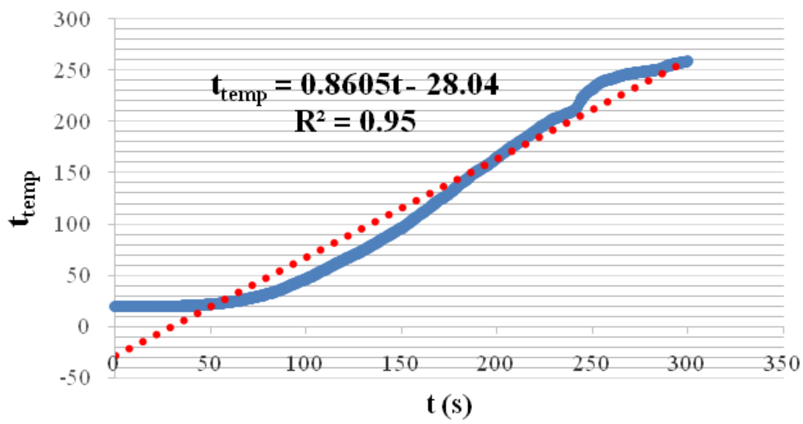


Fig. 8 Regression analysis of the temperature change over time

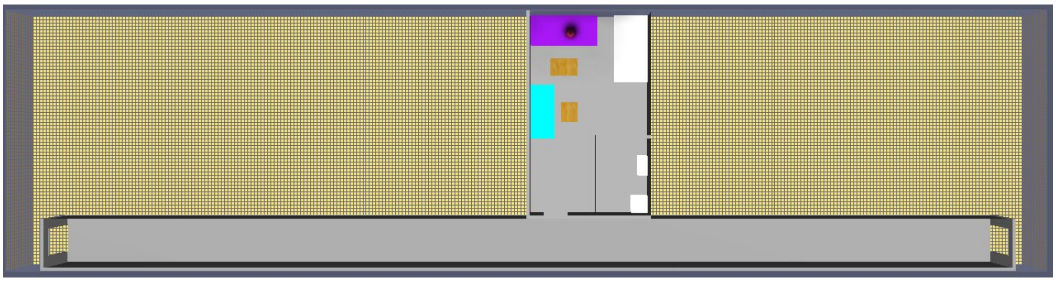
3.2.3 Simulation result of critical time for hazardous smoke

Traditionally, the combustion products are water vapour and carbon dioxide (CO_2). However, the incomplete combustion will produce hazardous products, carbon monoxide (CO). According to the fire experiment conducted by the National Institute of Standards and Technology (NIST) in the United Stated (Yeoh and Yuen 2009), the production rate in cabin is as follows.

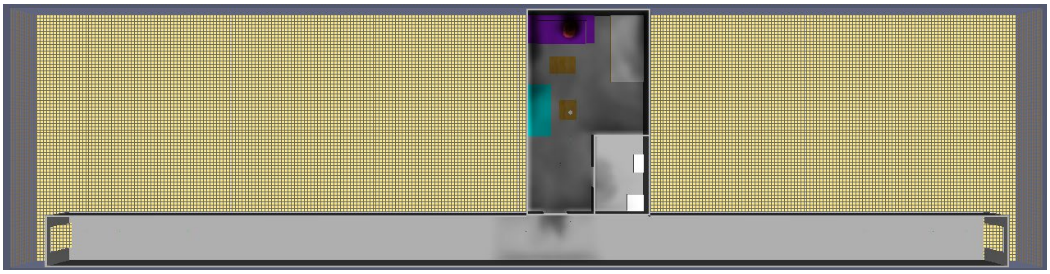
1) When the fuel is wooden material, the production rate of CO is 0.3gram for per gram of fuel (0.3g/g), the production rate of CO_2 is 1.1g/g, and the consumption rate of oxygen is 0.9 g/g.

2) When the fuel is furniture, the production rate of CO is 0.2g/g, the production rate of CO_2 is 1.5g/g, and the consumption rate of oxygen is 1.8 g/g.

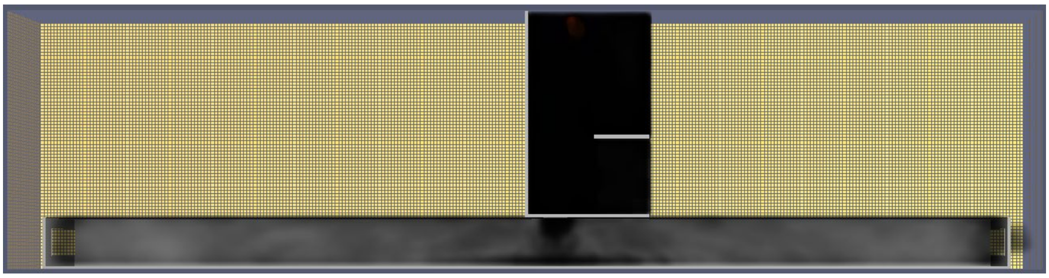
As majority of fuels are wooden and furniture in the ship cabin, the production rate of CO is assumed to be 0.25g/g, and the production rate of CO_2 be 1.5g/g. After installation of the eight smoke detectors, the development of hazardous smoke can be derived and shown in Figure 9.



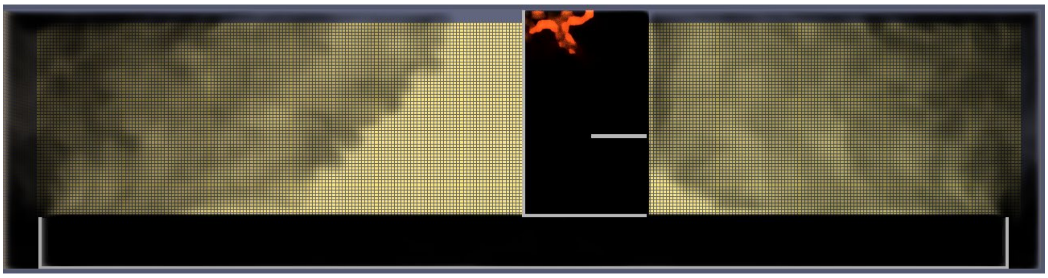
(a) T=10s



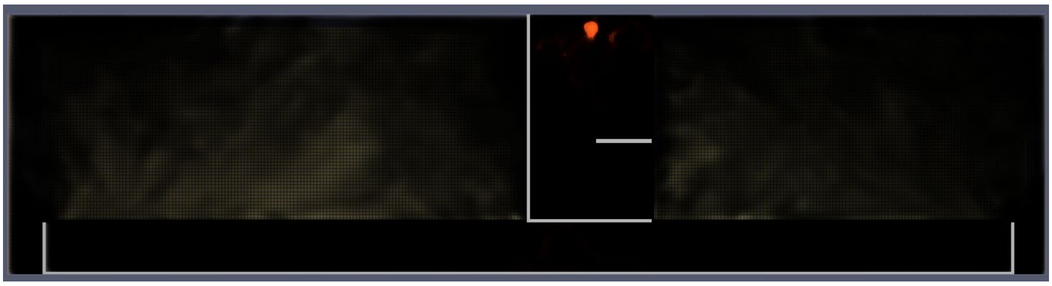
(b) T=40s



(c) T=85s



(d) T=145s



(e) T=200s

Fig. 9 Development of hazardous smoke for ship fire

As shown in Figure 9 (b), the ship cabin is filled with smoke at the time of 40s. Afterwards, smoke spreads through the door to the corridor and then the corridor is filled with smoke at the time of 85s, as shown in Figure 9 (c). Finally, all the computational domain is filled with smoke at the time of 200s, as shown in Figure 9 (e). Moreover, the data of the production of CO and CO_2 are obtained from this simulation. The regression analysis of these two hazardous smoke of CO_2 and CO are shown in Figure 10 and Figure 11, respectively.

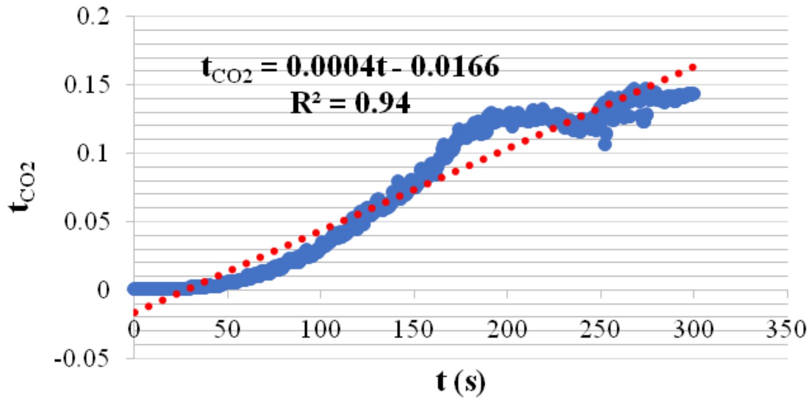


Fig. 10 Regression analysis of production of CO_2

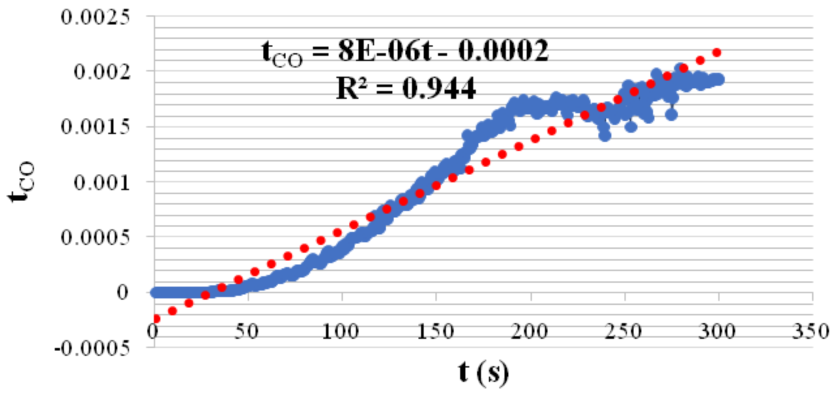


Fig. 11 Regression analysis of production of CO

Based on previous studies on the critical time of hazardous smoke (Zukoski and Kubota 1980; Gupta et al., 2001), human beings are in danger when the rate of CO_2 is 0.05kg/kg (i.e. 5,000ppm). Moreover, from Figure 10 and Figure 11, as the production rate of CO_2 is higher than that of CO, the critical time of CO is longer than that of CO_2. Therefore, in this paper, only the critical time of CO_2 is considered because this critical time is shorter, and the critical CO_2 rate is defined as 0.05-0.06kg/kg. From these assumptions, the critical time for CO_2 is $t_{smo}=t_{co_2}=Uniform\,(166,192)\,\mathrm{s}$.

3.3 Result of fatalities predication for fire accidents

3.3.1 Quantify the input variables of Bayesian Network

In order to obtain the estimated fatalities of fire accidents, the input variables should be quantified by using distribution functions. From the investigation report, the width and length of the corridor are around 0.9 and 60m, respectively, so they are defined as follow the normal distribution with expected width and length. Similarly, the width and length of stairs also follow the normal distribution. As there are only three decks in this fire accident, the evacuation location is defined as discrete distribution with the probability of 0.2 in the main deck, and with the probability of 0.4 in both wheelhouse and engine room. Time of day follows the Bernoulli distribution such that if this accident occurred at daytime, the variable Time of Day is 1 and the probability of night is 0. The detection and alarm time varies in different scenarios and is assumed to follow the normal distribution by defining 75s as the average. This is consistent with the investigation report, which found the alarm time was 75s. Moreover, the number of people is 17, because there are 17 crewmembers. All these crewmembers are assumed to be well trained as they are certificated by authorized authorises and are required to carry out fire drills each month. Differently, the critical temperature and critical smoke are derived from the simulation result by using FDS, which is decried in the earlier subsection. All these variables and corresponding description are summarised in Table 7.

Table 7 Quantified distribution of the input variables

Factor/variable	Description	Distribution
Corridor width [m]	The corridor is around 0.9m width	Normal (0.9,0.01)
Corridor length [m]	The corridor is around 60m length	Normal (60,0.01)
Stairs width [m]	The stairs is around 0.9m width	Normal (0.9,0.01)
Stairs length [m]	The stairs is around 3m length	Normal (3,0.01)
Evacuation location	The majority of crewmembers are in the wheelhouse and engine room	Custom PDF (0,-1,1, 0.2, 0.4,0.4)
Time of day	It is daytime or nighttime, 1= daytime, 2=nighttime	Custom PDF (1,2, 1, 0)
Detect and alarm time [s]	The interval of time from ignition until the fire is detected, and finally the population is alarmed.	Normal (75,1)
Number of people	The number of people on board when the fire was occurred.	Normal (17,0.2)
Fire drills	It is well trained or not, 1= well trained, 2=not well trained	Custom PDF (1,2, 1, 0)
Critical temperature [s]	The time when the temperature reaches 100°C, and it is derived from FDS simulation.	Uniform (149,172)
Critical smoke [s]	The time when the hazardous smoke reaches 1.5m height, and it is derived from FDS simulation.	Uniform (166,192)

3.3.2 Result analysis of the estimated fatalities

By introducing the distribution of the input variables and the functional nodes in Section 2, the final result of the fatality rate of this ship fire accident is shown in Figure 12.

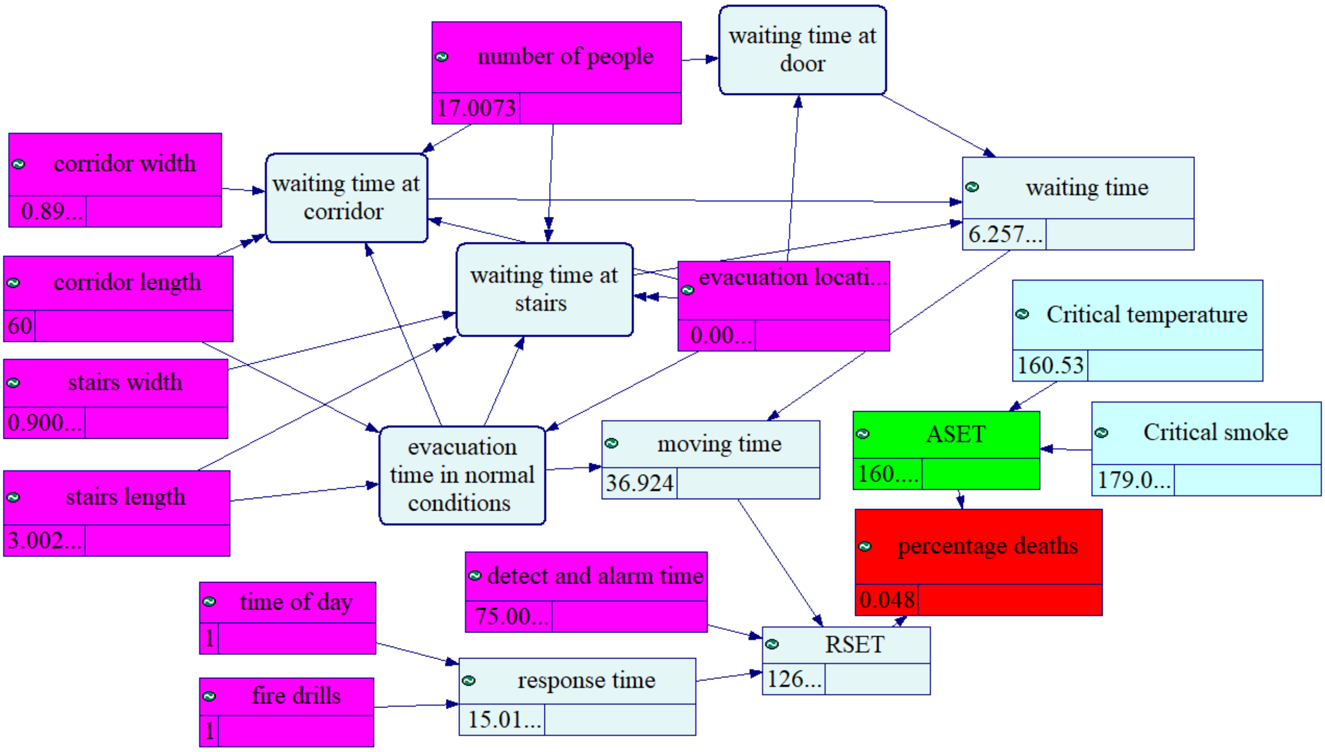


Figure 12 Estimated fatality rate of fire accident

From Figure 12, it can be seen that the predicted fatality rate is 0.048, which is close to the real death in this fire accident (i.e. $1/17=0.058$). Moreover, the RSET is around two minutes (i.e. 126s), this is also close to the real scenario because the majority of the crewmembers have escaped from fire accidents. One thing should be noted that there are only 17 crewmembers in this fire accident, the waiting time is very short and the longest waiting time in this fire accident is waiting at the door, which is 15s. This is also reasonable as this ship is a bulk carrier and there are no passengers on this ship, however, for the fire accident occurred in the passenger ships, this waiting time will be long and will cause the RSET a bit longer.

4 Discussion

According to Kwiecińska (2015), it is found that 9% fire accidents are caused by unknown factors, which shows special attention are required for the investigation of such accidents (Baalisampang et al., 2018). Moreover, the fire accident development is complex and some uncertainties exist when predicting the fatality rate, which may influence the accuracy of the result. In this paper, only the death caused by critical temperature and critical smoke is considered, while the death caused in the process of abandoning ships, which is also a significant factor to cause fatalities in maritime accidents (Jasionowski, 2011; Hu et al., 2013), is not considered. However, as the fatalities in this paper are caused by critical smoke, this factor can be ignored in this specific scenario. In the future, the time of escaping from the fire and the time of abandoning ships should be incorporated to gain the RSET from a holistic perspective.

Another significant thing should be discussed is the derivation of ASET. In this paper, the ASET is derived by using FDS considering the critical temperature and critical smoke. In practice, when determining the critical time of temperature and smoke using FDS, three significant steps should be carried out. First, the ship cabin should be reconstructed and the fuels should be defined. Second, the parameters of the fire accident should be set. Specifically, the fire source, and HRR and mass loss rates should be specified. Third, the relationship between critical temperature (smoke) and time can be derived. From this analysis, it can be deducted that these three steps will cost some time because this process is a little bit complicated. However, in practice, if the estimation of fatality rate costs a lot of time, the result will be meaningfulness because the response to the fire accident is restricted in time. Therefore, in order to have quick response to fire accidents and reduce the time for estimate the ASET, two ways can be introduced to derive the ASET. First, the historical data can be collected and the distribution of the ASET can be used for such estimation. Second, the uncertainty analysis can be introduced to obtain the relationship between critical temperature (smoke) and the time by using several simulations in different scenarios.

The last thing should be noted is the RSET. In this paper, the accidental ship is a bulk carrier. From the simulation result, the waiting time is very short because there are only 17 crewmembers, which means they did not need to wait as this scenario is not crowded. However, if a passenger ship is considered, the situation will be quite different. When the number of people increases from 17 to 40, the waiting time increases from 6s to 27s. Moreover, when the number of people reaches 60, this waiting time is 47s. This is reasonable because when the number of people increases, there will be crowded in the corridor and especially at the door. Therefore, when estimating the fatality rate, this phenomenon should be noted and carefully handled. However, the stair width, evacuation location and other parameters are also different for the passenger ships, when predicting the fatality rate of passenger ship in fire, the ASET, which is derived by using FDS, should also be updated simultaneously by using a new simulation.

5 Concluding remarks

The main contribution of this paper is to propose a probabilistic method for estimation of fatality rate of ship fire accidents. Specifically, the fatality rate is estimated by comparing the ASET and RSET. As the fire accident is complex, this paper focuses on the fatality estimation caused by critical temperature and critical smoke, while the fatalities caused by subsequent incidents is not considered. The FDS software, which is widely used for fire development simulation, is introduced for estimating the ASET in ship fires. Moreover, the RSET is estimated by using equations derived from the historical data in the guideline issued by the IMO. The merit of this proposed method is that it provides a practical framework for estimating the fatality rate, and it is useful for improving the ship design and enhancing the fire safety.

The proposed method can be extended further to fatality estimation due to subsequent incidents e.g. abandoning the ship, flooding and human errors. When applying this proposed method to practice, the waiting time of the passenger ships should be carefully handed by changing the equations of ASET, which is derived by using FDS simulation. Future works can be done to analyse the uncertainty of estimating ASET when considering the different types of parameters and the structure of the ship cabin, and a generic relationship can be obtained to describe this relationship so that the ASET can be quickly derived after this further analyse.

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References

Akyuz, E. (2016). Quantitative human error assessment during abandon ship procedures in maritime transportation. Ocean Engineering, 120, 21-29.

Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M. (2018). Review and analysis of fire and explosion accidents in maritime transportation. Ocean Engineering, 158, 350-366.

Cho, Y. O., Ha, S., & Park, K. P. (2016). Velocity-based egress model for the analysis of evacuation process on passenger ships. Journal of Marine Science and Technology, 24(3), 466-483.

Chu, C. W., Lu, H. A., & Pan, C. Z. (2013). Emergency evacuation route for the passenger ship. Journal of Marine Science and Technology, 21(5), 515-521.

Cinicioglu, E. N., & Shenoy, P. P. (2009). Arc reversals in hybrid Bayesian networks with deterministic variables. International Journal of Approximate Reasoning, 50(5), 763-777.

Eleye-Datubo, A. G., Wall, A., Saajedi, A., & Wang, J. (2006). Enabling a powerful marine and offshore decision-support solution through Bayesian network technique. Risk Analysis, 26(3), 695-721.

EMSA. Annual overview of marine casualties and incidents 2014. Lisbon; 2015.

Fu, S., Zhang, D., Montewka, J., Yan, X., & Zio, E. (2016). Towards a probabilistic model for predicting ship besetting in ice in Arctic waters. Reliability Engineering & System Safety, 155, 124-136.

Goerlandt, F., & Montewka, J. (2015). A framework for risk analysis of maritime transportation systems: a case study for oil spill from tankers in a ship–ship collision. Safety Science, 76, 42-66.

Gupta, A. K., Kumar, R., Yadav, P. K., & Naveen, M. (2001). Fire safety through mathematical modelling. Current Science, 80(1), 18-26.

Guarin, L., Konovessis, D., & Vassalos, D. (2009). Safety level of damaged RoPax ships: Risk modelling and cost-effectiveness analysis. Ocean Engineering, 36(12-13), 941-951.

Hanea, D., & Ale, B. (2009). Risk of human fatality in building fires: A decision tool using Bayesian networks. Fire Safety Journal, 44(5), 704-710.

Hanea, D. M., Jagtman, H. M., & Ale, B. J. (2012). Analysis of the Schiphol Cell Complex fire using a Bayesian belief net based model. Reliability Engineering & System Safety, 100, 115-124.

Ha, S., Ku, N. K., Roh, M. I., Lee, K. Y. (2012). Cell-based evacuation simulation considering human behavior in a passenger ship. Ocean Engineering, 53, 138-152.

Hu, L. F., Ma, K., Ji, Z. S. (2013). A M–H method-based decision support system for flooding emergencies onboard warship. Ocean Engineering, 58, 192-200.

Hurley, M. J., Gottuk, D. T., Hall Jr, J. R., Harada, K., Kuligowski, E. D., Puchovsky, M., WIECZOREK, C. J. (Eds.). (2015). SFPE handbook of fire protection engineering. Springer.

IMO, MSC.1/Circ.1533, (2016). Revised guidleines on evacuation analyis for the new and existing passenger ships.

Jasionowski, A. (2011). Decision support for ship flooding crisis management. Ocean Engineering, 38(14-15), 1568-1581.
Kang, H. J., Choi, J., Lee, D., & Park, B. J. (2017). A framework for using computational fire simulations in the early phases of ship design. Ocean Engineering, 129, 335-342.
Kim, H., Park, J. H., Lee, D., Yang, Y. S. (2004). Establishing the methodologies for human evacuation simulation in marine accidents. Computers & Industrial Engineering, 46(4), 725-740.
Kong, D. P., Lu, S. X., Kang, Q. S., Lo, S. M., & Xie, Q. M. (2014). Fuzzy risk assessment for life safety under building fires. Fire Technology, 50(4), 977-991.
Khan, E. A., Ahmed, M. A., Khan, E. H., & Majumder, S. C. (2017). Fire Emergency Evacuation Simulation of a shopping mall using Fire Dynamic Simulator (FDS). Journal of Chemical Engineering, 30(1), 32-36.
Kujala, P., Hänninen, M., Arola, T., & Ylitalo, J. (2009). Analysis of the marine traffic safety in the Gulf of Finland. Reliability Engineering & System Safety, 94(8), 1349-1357.
Kwiecińska, B. (2015). Cause-and-effect analysis of ship fires using relations diagrams. Zeszyty Naukowe Akademii Morskiej w Szczecinie, 116(44), 187-191.
Lee, D., Park, J. H., Kim, H. (2004). A study on experiment of human behavior for evacuation simulation. Ocean Engineering, 31(8-9), 931-941.
Lee, D., Kim, H., Park, J. H., & Park, B. J. (2003). The current status and future issues in human evacuation from ships. Safety Science, 41(10), 861-876.
Liou, C., & Chu, C. W. (2016). A System Simulation Model for a Training Ship Evacuation Plan. Journal of Marine Science and Technology, 24(2), 107-124.
Matellini, D. B., Wall, A. D., Jenkinson, I. D., Wang, J., & Pritchard, R. (2013). Modelling dwelling fire development and occupancy escape using Bayesian network. Reliability Engineering & System Safety, 114, 75-91.
Mazaheri, A., Montewka, J., & Kujala, P. (2014). Modeling the risk of ship grounding-a literature review from a risk management perspective. WMU Journal of Maritime Affairs, 13(2), 269-297.
McGrattan, K., Klein, B., Hostikka, S., & Floyd, J. (2010). Fire dynamics simulator (version 5), user's guide. NIST special publication, 1019(5), 1-186.
Montewka, J., Ehlers, S., Goerlandt, F., Hinz, T., Tabri, K., & Kujala, P. (2014). A framework for risk assessment for maritime transportation systems — A case study for open sea collisions involving RoPax vessels. Reliability Engineering & System Safety, 124, 142-157.
Park, J. H., Lee, D., Kim, H., & Yang, Y. S. (2004). Development of evacuation model for human safety in maritime casualty. Ocean Engineering, 31(11-12), 1537-1547.
Roh, M. I., & Ha, S. (2013). Advanced ship evacuation analysis using a cell-based simulation model. Computers in Industry, 64(1), 80-89.
Roberts, S. E., Pettit, S. J., & Marlow, P. B. (2013). Casualties and loss of life in bulk carriers from 1980 to 2010. Marine Policy, 42, 223-235.
Salem, A. (2010). Fire engineering tools used in consequence analysis. Ships and Offshore Structures, 5(2), 155-187.
Salem, A. M. (2016). Use of Monte Carlo Simulation to assess uncertainties in fire consequence calculation. Ocean Engineering, 117, 411-430.
Sarvari, P. A., Cevikcan, E., Ustundag, A., Celik, M. (2017). Studies on emergency evacuation management for maritime transportation. Maritime Policy & Management, 1-27.
Shi, W., Su, F., & Zhou, C. (2014). A temporal accessibility model for assessing the ability of search and rescue in Nansha Islands, South China Sea. Ocean & Coastal Management, 95, 46-52.

Soner, O., Asan, U., & Celik, M. (2015). Use of HFACS–FCM in fire prevention modelling on board ships. Safety Science, 77, 25-41.

Sun, J., Lu, S., Lo, S., Ma, J., & Xie, Q. (2018). Moving characteristics of single file passengers considering the effect of ship trim and heeling. Physica A: Statistical Mechanics and its Applications, 490, 476-487.

Su, S., Wang, L. (2013). Three dimensional reconstruction of the fire in a ship engine room with multilayer structures. Ocean Engineering, 70, 201-207.

Su, S., Wang, L., Nie, Y., Gu, X. (2012). Numerical computation and characteristic analysis on the center shift of fire whirls in a ship engine room fire. Safety Science, 50(1), 12-18.

Wang, Y. F., Xie, M., Ng, K. M., & Habibullah, M. S. (2011). Probability analysis of offshore fire by incorporating human and organizational factor. Ocean Engineering, 38(17-18), 2042-2055.

Wang, J. H., Chu, G. Q., Li, K. Y. (2013). Study on the uncertainty of the available time under ship fire based on Monte Carlo sampling method. China Ocean Engineering, 27(1), 131-140.

Weng, J., & Yang, D. (2015). Investigation of shipping accident injury severity and mortality. Accident Analysis & Prevention, 76, 92-101.

Wróbel, K., Montewka, J., & Kujala, P. (2017). Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. Reliability Engineering & System Safety, 165, 155-169.

Wu, B., Yan, X., Wang, Y., Zhang, D., & Guedes Soares, C. (2017a). Three-stage decision-making model under RSETricted conditions for emergency response to ships not under control. Risk analysis, 37(12), 2455-2474.

Wu, B., Yan, X., Wang, Y., & Guedes Soares, C. (2017b). An evidential reasoning-based CREAM to human reliability analysis in maritime accident process. Risk analysis, 37(10), 1936-1957.

Wu, B., Yan, X., Yip, T. L., & Wang, Y. (2017c). A flexible decision-support solution for intervention measures of grounded ships in the Yangtze River. Ocean Engineering, 141, 237-248.

Yip, T. L. (2008). Port traffic risks–A study of accidents in Hong Kong waters. Transportation Research Part E: Logistics and Transportation Review, 44(5), 921-931.

Yeoh, G. H., & Yuen, K. K. (2009). Computational Fluid Dynamics in Fire Engineering: Theory, Modelling and Practice. Butterworth-Heinemann.

Zhao, G., Beji, T., & Merci, B. (2017). Study of FDS simulations of buoyant fire-induced smoke movement in a high-rise building stairwell. Fire Safety Journal, 91, 276-283.

Zukoski, E. E., & Kubota, T. (1980). Two-layer modeling of smoke movement in building fires. Fire and Materials, 4(1), 17-27.

Zhang, J., Teixeira, Â. P., Guedes Soares, C., Yan, X., & Liu, K. (2016). Maritime transportation risk assessment of Tianjin Port with Bayesian belief networks. Risk analysis, 36(6), 1171-1187.