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Fire Risk Assessment in Engine Rooms Considering the Fire-Induced Domino Effects

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Abstract: This paper proposes a dynamic evolutionary model to quantify the domino effect of ship engine room fires. Based on the spatial and temporal characteristics of fire accidents, the dynamic probability of the domino effect of multiple accident units is calculated using matrix calculation and Monte Carlo simulation. The uncertainties of shipboard personnel, automatic detection systems, sprinkler systems, and the synergistic effects of multiple escalation vectors from different units are addressed. The dynamic probability of the domino effect of multiple accident units is calculated, and a risk assessment of complex fire scenarios in ship engine rooms is implemented. This study also presents the model feasibility in terms of fire risk assessment in cabins with numerous pieces of equipment. The results indicate that 2 min and 4 min are vital time nodes for the development and spread of fires. The extinguishing work on key equipment in the path of the fire's spread can effectively restrain its further expansion. The results can provide critical references for ship fire prevention, fire suppression, and fire protection design.

Keywords: engine room fire; domino effect; risk assessment; Monte Carlo simulation

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1. Introduction

Fire accidents seriously threaten the navigation safety of ships, leading to loss of life and property and marine environment pollution [1,2]. Ship fires are the biggest safety issue in the shipping industry. The Allianz safety report for 2021 showed that fire was the second leading cause of ships capsizing in 54 ship accidents. In the last five years, there have been more than 43,000 insurance claims regarding ship fires, which is the most expensive cause of losses [3]. According to data from the IMO (2019), 270 of the 1400 accidents reported between 2000 and 2017 were related to fires and explosions, accounting for 19.2 percent of reported incidents. The engine room fires accounted for more than 75 percent of all ship fires [4]. In 2017 alone, there were dozens of accidents caused by ship engine room fires. The fire is characterized by strong concealment, rapid fire spread, and great difficulty in fighting the fires [5]. The degree of damage and difficulty in fighting fires far exceed the hazards of fires caused in areas such as living quarters and cargo holds [6,7]. These fires are prone to domino effect accidents that may lead to loss of the propulsion and steering capabilities of the ship. Consequently, it may lead to the ship grounding or even capsizing. Although the IMO has introduced many regulations and preventive measures to improve ship safety, it still cannot prevent the occurrence of fire. Therefore, it is of great significance to study the fire evolution characteristics and assess the fire risk of the ship engine room.

The occurrence and development of fires are characterized by determinism and randomness. The certainty of fire refers to the development and spread of fire in a specific situation according to the basic law. The development of a fire is divided into five stages:

fire initiation, development, intense combustion, decay, and extinguishment. The nature of combustibles determines the rate of combustion and the rate of the heat release of the fire. Ventilation conditions and oxygen concentration are related to fire development. Many scholars have carried out relevant studies based on the physical characteristics of fire occurrence and development. Zhang et al. [8] studied the influence of subdivision height on pool fires in a closed engine room by measuring parameters such as mass loss rate, combustion rate, and heat release rate. He et al. [9] studied the effects of fire size and ceiling vent size on fires in engine rooms. Chen et al. [10] studied the influence of pressure on heat transfer by pool fire in a closed chamber and observed the power function between average mass combustion flux and pressure. Wang et al. [11] studied the vertical distribution of temperature rise in the process of sealed ship engine room fires and established an empirical model of vertical temperature rise along the height distribution of sealed engine room fires at the highest temperature. Liu et al. [12] used diesel fuel as an ignition source to study its combustion characteristics and flame flow around equipment in the engine room under cross-wind conditions at 0.8–2.4 m/s velocity.

To sum up, the researchers studied the single physical characteristics of fire sources, such as the spatial location of the fire, the ventilation state of the engine room, the pressure of the engine room, the temperature distribution field, and other combustion characteristics of the fire source. However, ship engine room fires are complex dynamic processes with coupling effects of multiple physical characteristics. They are affected by uncertain factors such as active fire-fighting equipment and fire damage control personnel. Therefore, fire experiments under the coupling of multiple physical characteristics are difficult to carry out because of their high experimental cost.

With the development of the global ocean engineering field, the fire risk of ships has been paid increasing attention [13]. Many experts and scholars try to use the risk assessment method to solve the fire uncertainty problem. Guan et al. [14] studied the risk of fire and explosions in ship engine rooms using the Fault Tree Analysis method. Sarıalioğlu et al. [15] employed the Human Factors Analysis and Classification System (HFACS) method to classify the factors of engine room fire formation in a hierarchical structure. The Fuzzy Fault Tree Analysis method was adopted to calculate accident scenarios and probabilities. It is proposed that hot surfaces in the engine room due to main engine operation are prone to fire accidents when combined with fuel leaks. Jia et al. [16] calculated the fire damage of a ship using Bayesian networks based on specialist marking methods and statistical data, demonstrating that fuel load plays a decisive role in fire intensity. The fire damage can be effectively reduced by shortening the fire detection response time. Ahn and Kurt [17] applied the Cognitive Reliability and Error Analysis Method framework to assess personnel reliability in ship engine room fire emergency response, where the highest probability of personnel error was found for detecting engine room fires and inspecting firefighters' equipment and other personal rescue equipment.

The above researchers studied the fire risk of ship engine rooms from the perspective of risk, proving the high risk of ship engine room fires and the great uncertainty in the reliability of spray facilities and personnel [18,19]. However, the development and evolution of fires are time-varying. The actions of fire detection by personnel, automatic detection systems, and sprinkler systems all impact the development and spread of a fire when a ship engine room fire occurs. In the process of fire development, the fire of certain equipment will cause multiple equipment fires. The synergistic effect of the joint combustion of multiple fire units will cause fire consequences of different severities. Therefore, the complex and changeable fire scene poses a great challenge to the safe navigation of ships.

The development and evolution of fire accidents is a dynamic process with a significant domino effect. The domino effect or domino accident is defined as a major accident that propagates continuously or simultaneously within or near a facility, triggering one or more secondary accidents. Subsequently, an incident may trigger additional higher-level contingencies, resulting in more severe aggregate consequences [20]. The domino effect is an important aspect of fire risk assessment in the petrochemical process industry, and numerous quantitative risk studies have been conducted for complex domino effect fire scenarios. Zarei et al. [21] analyzed the domino effect in the process of gasoline transportation based on the dynamic Bayesian network analysis model and proved the effectiveness of the model in simulating the domino effect accident with examples. They also stated that when dealing with the stochastic uncertainty caused by the random parameter, advanced methods such as Monte Carlo simulations or Markov chains are preferable. Huang et al. [22] proposed a model based on Monte Carlo simulation to analyze the dynamic evolution process of the domino effect considering the synergistic effect of multiple escalation vectors from different units. The model is applicable to analyze complex fire scenarios with multiple incident units. It is demonstrated that the fire consequences of multiple major fire incident units are much more severe than those of a single fire incident unit. The development and evolution processes of ship engine room fires share a strong commonality in nature with fires in the petrochemical process industry. Therefore, it is feasible to apply the domino effect accident principle to conduct dynamic probability analysis of engine room fires in multiple equipment units and carry out research on ship engine room fire risk assessment.

Considering the inadequacy of the aforementioned studies, this paper establishes a model that considers the personnel on board, the firefighting facilities, and the synergistic effects of multi-equipment combustion. The model is designed for a more realistic ship engine room fire environment than existing studies and aims to quantify the effect of uncertainty on the evolutionary characteristics of fire. Fire suppression strategies are provided based on the probability of fire consequences. Firstly, an event tree model of ship engine room firefighting facilities was developed. The model is used to analyze the uncertainty of the fire-fighting facilities. The uncertainties were characterized using a probabilistic approach. The Monte Carlo method [23] was used to generate stochastic scenarios of fires. Upon this basis, the equipment status is updated using matrix calculations. Then, the equipment in the engine room that can cause serious consequences during a fire is studied based on the results on the fire probability of occurrence scale. Finally, the key equipment status is given by analyzing the fire spread path. The further research aims to analyze the other major cabins based on this method. Eventually, the fire risk assessment of the whole ship will be realized. In summary, the contributions of this paper are as follows:

(1) Ship engine room fire evolution characteristics are studied based on the domino effect of fire;
(2) The uncertainties of shipboard personnel, automatic detection systems, sprinkler systems after the fire are addressed;
(3) Employing matrix calculations and Monte Carlo simulation methods, the synergistic effects of multiple escalation vectors from different units are considered;
(4) The fire size probability of occurrence is calculated, and vital time nodes and key equipment in the fire spread process are identified;
(5) According to the proposed engine room fire risk assessment model, the foundation is laid for developing multi-compartment and ship-wide fire risk assessments.

This paper is organized as follows: Section 2 analyzes the dynamic characteristics of the domino effect. Section 3 elaborates and explains the dynamic domino probability model and the corresponding algorithm. Section 4 presents the case study using the developed model. The conclusions of this study are presented in Section 5.

2. Problem Description

According to a report published by ClassNK, the proportion of ships damaged by engine room fires is 75 percent, and 52 percent of them were unseaworthy [24]. The engine room is the heart of a ship. A fire in the engine room can easily result in serious damage to the power system of a ship, which will lead to loss of maneuverability of the ship and may even lead to collisions and grounding accidents. Ship engine room fires are usually caused by pool fires due to oil leaks or related reasons [25]. Therefore, it is difficult to put out a fire in a ship engine room. A 10 min delay in putting out a fire in the engine room may cost USD 200,000, while a 20 min delay may cost up to USD 2,000,000 [26]. The speed of spreading fire is so fast that the difficulty and cost of putting out a fire are also rapidly increased. The essence of fire spreading is the thermal radiation effect of fire [27]. The adjacent equipment reaches a critical failure threshold under the action of thermal radiation, resulting in a fire. However, the characteristics of fire spread are full of uncertainties. These uncertainties have an impact on the consequences of fire incidents. The risk of engine room fires varies with the degree of uncertainty. This is a subject that needs to be carried out urgently. The study of the heat radiation transfer characteristics of ship engine room fires aims to grasp the fire propagation pattern. The method for rapidly controlling a fire is sought according to the key equipment in the path of the fire's spread. The consequences of fire accidents can be minimized. The evolution process of fire accidents is time-varying, involving both time and space. Changes in the time dimension are reflected in how long it takes to detect the fire after the fire occurs, whether firefighting facilities can intervene, and whether the fire will spread further. The longer the fire lasts, the higher the complexity and diversity of the fire. The change in the spatial dimension is reflected in the initial location of the fire, the effect of the fire-fighting facilities on the fire, and the influence of on-fire units on surrounding units. These factors determine whether and to what extent fire accidents will be expanded. The spatial dimension represents the size of fire accidents and quantifies the consequences of the fire.

In terms of ship engine room fires, the domino effect of fire can cause the whole engine room to be engulfed by fire in a few minutes due to the narrow space and large combustion load. Therefore, the main objective of this study is to analyze the dynamics of the domino effect of ship engine room fires. In the domino effects of fire accidents, the more units there are, the more complex the fire's spread path will be and the faster the rate of the spread. Meanwhile, there are fire-fighting facilities in the engine room, including fire detection and alarm systems, sprinkler systems, CO_2 extinguishing systems, and foam extinguishers. These play a certain role in restraining the spread of the fire. This leads to a high degree of diversity and uncertainty in engine room fire scenarios.

As shown in Figure 1, unit 1 is the initial fire accident unit. Unit 2 and unit 3 are affected by thermal radiation from unit 1, which causes the fire to spread, leading to a first-level domino effect. Thereafter, with the synergistic effect of the simultaneous combustion of unit 2 and unit 3, unit 4 will be ignited in a shorter period of time, resulting in a second-level domino effect. However, what is shown in Figure 1 is only the domino effect of fire accidents in ideal units and ideal distribution. If there are differences in unit properties and physicochemical properties in the region, the failure threshold in the thermal radiation condition is different. The transmission path of the domino effect is therefore diverse. It is worth noting that, in the case of the accident in Figure 1, when unit 1 is the main accident unit, there are as many as 25 possible combinations of domino propagation chains [28]. It can be imagined that whenever the number of units in the region increases by one, the combination of domino propagation chains may increase exponentially and dramatically.

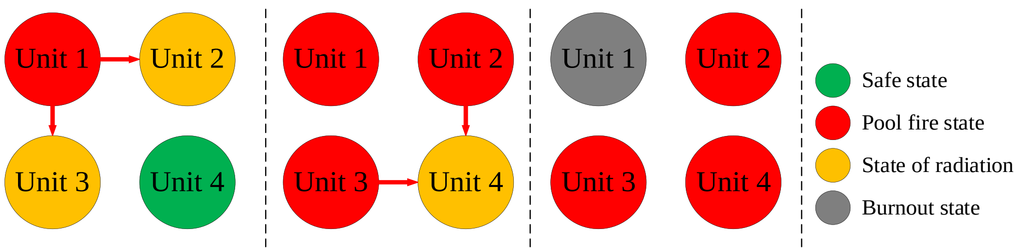

Figure 1. Spatio-temporal evolution of fire domino effect.

The dynamic evolution process of the domino effect of a fire accident is shown in Figure 2. The process includes four states: safe state, under radiation state, pool fire state, and burnout state. The safety state and the under radiation state are non-fire states. When the thermal radiation intensity received by the unit AR is greater than the thermal radiation threshold, RT, the safety state is changed from the safe state to the radiation state. When the thermal radiation intensity is insufficient, the two states can change to each other. When the irradiated unit's effective emergency rescue time (TTE) is greater than the failure time (TTF), the irradiated state will turn to the pool fire state. If the time during the pool fire (DPF) of the unit is greater than the time of the unit burning (TTB), the pool fire state will be converted to the burnout state.

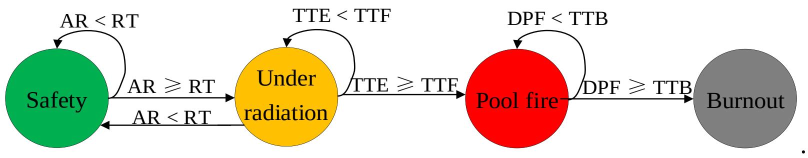

Figure 2. Dynamic evolution process of fire domino effect.

3. Methodology

In this paper, the domino effect model of the ship engine room fire is established. The dynamic evolution process of a ship engine room fire accident is analyzed. The dynamic probability of fire accident consequences is obtained based on matrix calculation and Monte Carlo simulation. The flow chart is shown in Figure 3. The main modelling steps include (Step 1) determining the main fire accident scenario; (Step 2) collecting basic information; (Step 3) setting the model parameters; (Step 4) state analysis of each unit; and (Step 5) calculation of dynamic domino probability.

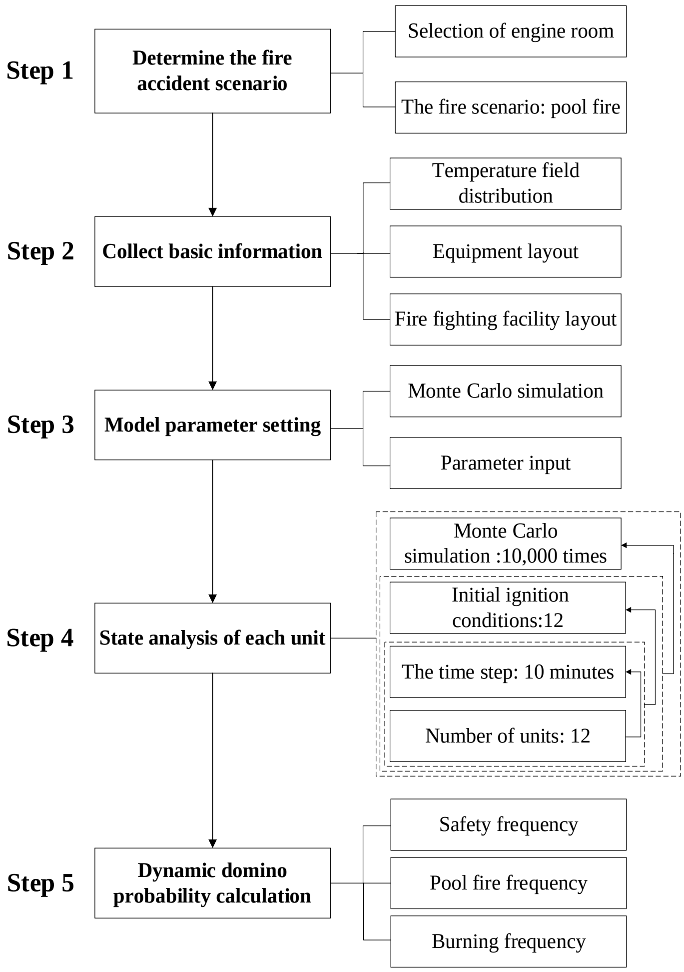

Figure 3. Flowchart for calculating the dynamic probability of domino effect in an engine room fire.

3.1. Determination of the Fire Accident Scene

For establishing the domino effect accident scenario of a ship engine room fire, time is an important factor. Because time is related to the emergency response performance of fire-fighting facilities and to fire escalation. It is necessary to simultaneously consider the fire location, detection by personnel, automatic detection, and automatic fire extinguishing devices, which are related to the occurrence and development of fires. If personnel detected the fire quickly, it is considered that the fire has been effectively controlled in the early stages. Otherwise, it must rely on the engine room fire detection system to detect the fire. When the fire is successfully detected, it triggers the engine room sprinkler system. The logical sequence of the scenarios is shown in Figure 4, using the event tree method in chronological order. The ship engine room equipment containing a large number of pipe systems and oil storage cabinets can be considered as atmospheric pressure storage tanks. The fire scenario is a pool fire. It was found that the burning state of a pool fire can be divided into three modes, including laminar combustion, turbulent combustion, and the transition mode between laminar and turbulent modes. However, it is not necessary for the model to consider the combustion mode of the pool fire.

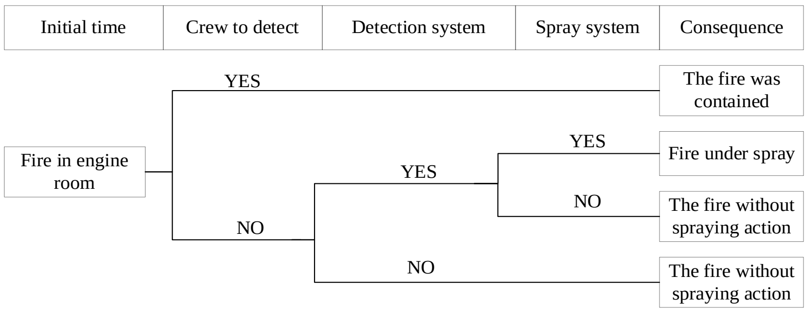

Figure 4. Engine room fire firefighting facilities event tree.

3.2. Collecting Basic Information

The layout information of equipment and fire-fighting facilities in the engine room is collected as the input of the model.

The equipment information includes: (1) n: the number of equipment in the engine room; (2) ***NSR***: n × n dimensional matrix, where NSRij represents the thermal radiation from element *i* to element *j* without spray; (3) ***SR***: n × n dimensional matrix, where SRij represents the thermal radiation from element *i* to element *j* under the action of spray; (4) ***RT***: 1 × n dimensional matrix, where RTi represents the thermal radiation threshold of element *i*; and (5) ***TTB***: 1 × n dimensional matrix, where TTBi represents the continuous burning time after the fire in unit *i*.

The fire-fighting facility information includes: (1) the ventilation system layout of the engine room; (2) the fire detection system layout and reliability, PD; (3) the spraying system layout and reliability, PS; (4) personnel detection reliability, PC; and (5) ***TTE***: 1 × n dimensional matrix, where TTEi represents the time of effective emergency rescue for unit *i*.

The intensity of heat radiation from the equipment is an important indicator for assessing the escalation of the domino effect. The central part of the method is the matrix calculation of the intensity of heat radiation [29]. ***NSR*** and ***SR*** can be obtained through the fire dynamics simulation software *Pyrosim*. According to the engine room layout information, the fire scene is modelled. The temperature measurement point is arranged in the center of the unit surface to obtain the temperature distribution of unit *i* in the engine room. The thermal radiation can be converted from the blackbody radiation formula as follows:

$$R = \sigma T^4, \quad (1)$$

where σ is the blackbody radiation constant with a value of $5.67 \times 10^{-8} W/m^2 \cdot K^4$; T is the blackbody thermodynamic temperature.

3.3. Parameter Settings

After determining the main fire scenario and collecting the relevant basic information, the parameters need to be input into the model for the Monte Carlo simulation. In the calculation process, the state of each unit at each time step needs to be updated. Some temporary parameters need to be set to record the state of the unit, mainly including: ***US***: T × n dimensional matrix, where USti represents the state of unit *i* at time step T. When T = 0, ***US*** is a 1 × n dimensional matrix representing the initial state of each unit. ***DPF***: 1 × n dimensional matrix, where DPFi represents the duration of unit *i* in the pool fire state. The initial state value is zero matrices. ***AR***: T × n dimensional matrix, where ARti represents the thermal radiation received by unit *i* at time step T. The initial state value is zero matrices. ***EERT***: 1 × n dimensional matrix, where EERTi represents the duration of unit *i* exposure beyond the thermal radiation threshold. ***Fs***, ***Fp***, ***Fb***: T × n dimensional matrix, representing the frequency of unit *i* in safe, pool fire, and burnout states at time step T, which is used as the parameter for the calculation of fire risk probability. The calculation flow chart of the dynamic domino effect probability is shown in Figure 5.

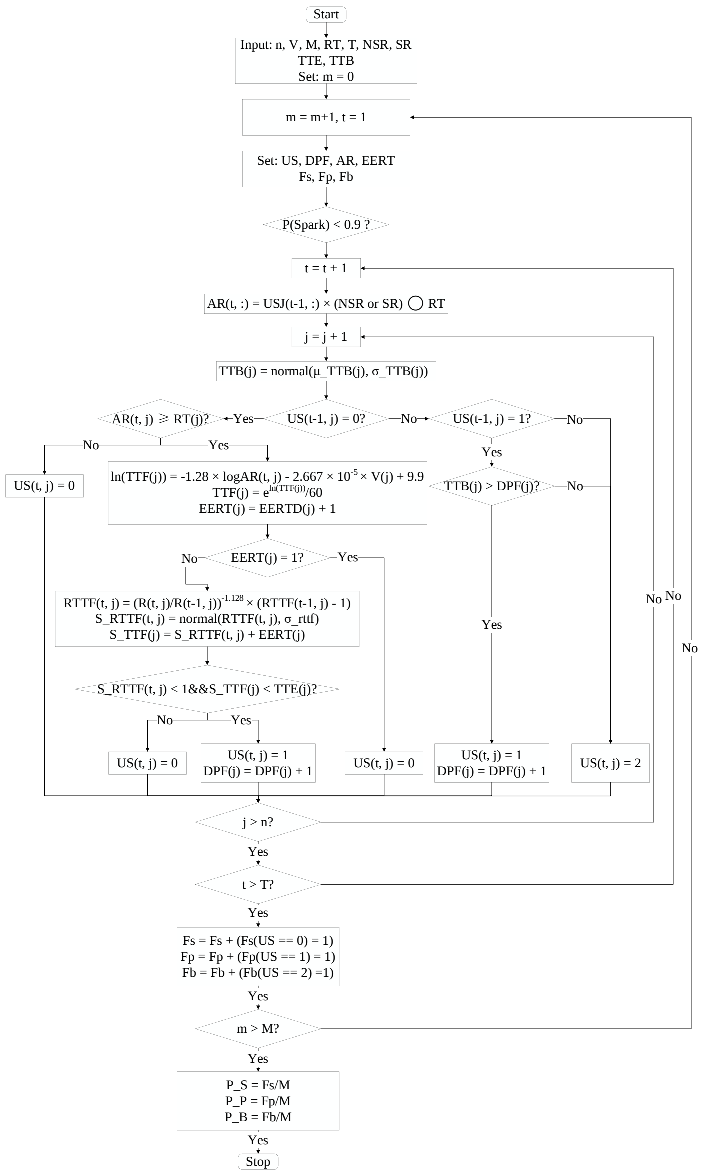

Figure 5. Flowchart of dynamic domino effect probability calculation.

3.4. Status Analysis of Each Unit

The essence of the dynamic analysis model of the domino effect is to calculate the model M times using a Monte Carlo simulation. In each calculation, the state of each unit at each time step is updated, and the state of the unit is recorded.

First, according to the trigger logic of the fire-fighting facilities event tree in the fire scene in Section 3.1, it is determined whether the engine room fire occurs under the action of the sprinkler system. Then, the initial fire unit i is determined. The initial state matrix ***US****(0, :)* represents the state of each unit when the time step is 0. Finally, the other basic information is input into the model.

When T ≥ 1, that is, when entering the next time step, ***US****(t, :)* is updated at time T according to ***US****(T − 1, :)* at time T − 1. A 1 × n dimensional matrix ***USJ*** should be created to determine the units in the pool fire state at time T − 1, where the units in the pool fire state USJ_i =1. The units in the safe state and burnout state USJ_i = 0. Then, the thermal radiation intensity received by each unit at the time step is judged. The synergistic effect of the thermal radiation of multiple fire units is considered. The formula can be expressed as follows:

$$AR(t,:) = USJ(\text{t}-1,:) \times (NSRorSR) \odot RT, \tag{2}$$

where the $\odot$ operation symbol [30] is defined as:

$\odot : X \odot Y = Z$, where, X, Y, and Z are 1×n dimensional matrices, and x_i, y_i, and z_i are their elements, respectively. z_i is expressed as: $z_i = \begin{cases} x_i, & x_i > y_i \\ 0, & otherwise \end{cases}$

Next, update the state of each unit at the time step T:

(I) If the state of unit j at the last time step T − 1 is safe, then ***US****(t − 1, j)* = 0:

Firstly, it is judged whether the thermal radiation intensity ***AR****(t, j)* received by element j at the time step T exceeds the thermal radiation threshold ***RT****(j)* of element j. If ***AR****(t, j)* < ***RT****(j)*, then ***US****(t, j)* = 0. Otherwise, the state of unit j is further analyzed as follows:

At the time step T, the failure time ***TTF****(j)* of the element under the action of thermal radiation intensity ***AR****(t, j)* is shown in Equations (3) and (4) [31,32]:

$$\ln(TTF(j)) = -1.13 \times \ln AR(t,j) - 2.67 \times 10^{-5} \times V(j) + 9.9, \tag{3}$$

$$TTF(j) = e^{\ln(TTF(j))}/60, \tag{4}$$

Calculate the duration for which the unit's thermal radiation exceeds the threshold: If the thermal radiation of the unit just exceeds the threshold, ***EERT****(j)* = 1; then, ***US****(t, j)* = 0.

If it is not the first time that the unit is exposed to thermal radiation that exceeds the threshold, in other words, ***EERT****(j)* $\neq 1$, calculate the remaining time of each unit failing ***RTTF*** (T × n dimensional matrix), as shown in Equation (5) [29]. The parameter c is related to the emergency rescue time and is set as −1.128 here. The sampling of the remaining time of unit failure is obtained as shown in Equation (6). It should be noted that in the process of accident propagation here, it is considered that the fire occurs when the unit fails [33]:

$$RTTF(t,j) = (AR(t,j)/AR(t-1,j))^c \times (RTTF(t-1,j) - 1), \tag{5}$$

$$S\_RTTF(j) = \text{normrnd}(RTTF(j), \sigma\_rttf), \tag{6}$$

If $S\_RTTF(j) < 1$, that is, in the current time step, the unit j turns to the failure state and the time for effective emergency rescue is longer than the total time after the accident, the unit j state will be updated to the pool fire state. Otherwise, it will remain in a safe state.

(II) If the state of the unit at the previous time T − 1 step is a pool fire, then $US(t-1,j)$= 1:

The burnout time $TTB(j)$ of the unit j is analyzed. If $TTB(j)$ is longer than the burning time $DPF(j)$ of the pool fire, the state of the unit j at the time step T is still pool fire. Otherwise, it is updated to burn out. In dynamic probability analysis, $TTB(j)$ requires randomization, as shown in Equation (7). The mean value $\mu\_TTB(j)$ can be obtained by calculating the combustion rate. The standard deviation $\sigma\_TTB(j)$ can be determined according to the relevant meteorological conditions, experimental data, and combustible material characteristics.

$$TTB(j) = normrnd\Big(\mu TTB(j), \sigma TTB(j)\Big), \tag{7}$$

(III) If the state of the unit j at the time step T − 1 is burnout, that is, $US(t-1, j) = 2$, the state of the unit j at the current time step T is still burnout, that is $ST(t, j) = B$.

The above calculation is carried out iteratively until the specified end time T.

3.5. Dynamic Domino Probability Calculation

After the completion of the first simulation, return to the parameter setting in Section 3.4. The simulation is run again until the total number of simulations is completed. In this process, after the end of each simulation, the state of each unit at each time step is calculated, as shown in Equations (8)–(10);

$$Fs = Fs + (Fs(US == 0) = 1), \tag{8}$$

$$Fp = Fp + (Fp(US == 1) = 1), \tag{9}$$

$$Fb = Fb + (Fb(US == 2) = 1), \tag{10}$$

where, Fs, Fp, and Fb are T × n dimensional matrices. Each element records the state number of the corresponding time step. $Fs(US == 0) = 1$ represents the frequency of the unit in the safe state +1; $Fp(US == 1) = 1$ represents the frequency of the unit in the pool fire state +1; $Fb(US == 2) = 1$ represents the frequency of the unit in the burnout state +1.

After all the sub-simulations M are completed, the dynamic domino probability of each unit is calculated, as shown in Equations (11)–(13):

$$PS = Fs/M; \tag{11}$$

$$PP = Fp/M; \tag{12}$$

$$PB = Fb/M; \tag{13}$$

where PS, PP, and PB are T × n dimensional matrices, indicating that each element represents the probability of each unit state, SA, PF, and B at each time step.

M_0 is the value of fire development and spread after M simulations. Under the condition of fire development and spread, the dynamic domino probability of fire in each unit at each time step is shown in Equations (14)–(16):

$$CPS = Fs/M_0, \tag{14}$$

$$CPP = Fp/M_0, \tag{15}$$

$$CPB = Fb/M_0, \tag{16}$$

where CPS, CPP, and CPB are all T × n dimensional matrices.

4. Case Analysis

4.1. Domino Effect Model of Ship Engine Room Fire Risk Assessment

The engine room of a container ship is selected as the research object in this paper. The size of the engine room is 22.5 m (L) × 18 m (W) × 3.5 m (H). The size of the door is 1 m (W) × 1.8 m (H), and 5 vents and 12 automatic spray probes are set. The layout of the engine room is shown in Figure 6. The fire-fighting detection facilities mainly include personnel detection, an automatic smoke detection system, and a spray system. The reliability is shown in Table 1. Since the engine room contains several pieces of equipment, the equipment is simplified for the convenience of calculation. The characteristics of the equipment are shown in Table 2. Take each piece of equipment in the engine room as the initial fire source. The fire dynamics simulation was carried out using the method proposed in Section 3.2. The heat radiation intensity of unit i to unit j under the action of no sprinkler system is shown in Table 3. The heat radiation intensity of unit i to unit j under the action of the sprinkler system is summarized in Table 4. The dynamic analysis of the domino effect of ship engine room fire is carried out by taking 12 equipment units in the engine room as initial fire source positions.

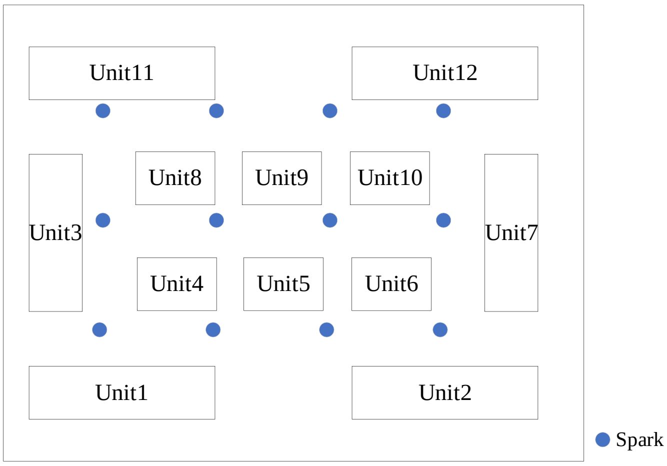

Figure 6. Layout of the engine room.

Table 1. Reliability of fire detection facilities.

	Detection Measures	Probability of Reliability
a	Detection by crew	0.59 [34]
b	Smoke detector	0.778 [34]
c	Automatic water sprinkler system	0.96 [34]

Table 2. Characteristics of engine room equipment.

Code	Length(m) × Width(m) × Height(m)	Substance	Equipment Size (m^3)
E1	7.0 × 2.0 × 2.0	Diesel	28
E2	7.0 × 2.0 × 2.0	Diesel	28
E3	6.0 × 2.0 × 2.0	Diesel	24
E4	3.0 × 2.0 × 2.0	Diesel	12
E5	3.0 × 2.0 × 2.0	Diesel	12
E6	3.0 × 2.0 × 2.0	Diesel	12
E7	6.0 × 2.0 × 2.0	Diesel	24
E8	3.0 × 2.0 × 2.0	Diesel	12
E9	3.0 × 2.0 × 2.0	Diesel	12
E10	3.0 × 2.0 × 2.0	Diesel	12
E11	7.0 × 2.0 × 2.0	Diesel	28
E12	7.0 × 2.0 × 2.0	Diesel	28

Table 3. Thermal radiation intensity (KW/m^2) of element i to element j without spray system.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
E1	88.4	6.7	59.5	63.0	15.9	8.2	4.9	15.5	13.8	8.9	15.4	6.0
E2	7.4	94.7	5.9	8.8	16.2	82.4	65.2	8.7	12.8	18.8	6.0	17.7
E3	22.4	6.9	83.2	25.7	11.6	7.7	6.2	63.8	22.5	9.1	27.0	7.4
E4	7.8	6.4	13.7	103.6	11.2	5.4	4.5	23.4	8.1	5.3	6.5	5.2
E5	7.5	7.9	5.3	10.7	76.9	14.1	7.3	8.1	16.8	6.8	5.5	5.5
E6	6.2	7.5	4.8	5.7	8.6	91.6	18.8	5.4	7.3	31.6	6.1	6.2
E7	6.5	21.7	6.0	7.2	10.6	30.1	93.1	10.1	19.2	64.1	7.9	24.4
E8	7.3	4.7	15.3	13.9	7.1	4.7	4.2	148.4	10.2	5.2	7.1	5.5
E9	5.9	5.2	5.5	7.8	11.6	7.3	5.7	10.7	80.8	9.3	7.1	7.6
E10	5.5	8.4	4.7	5.7	7.7	40.7	12.1	5.7	9.7	96.6	5.6	8.8
E11	17.3	6.6	52.5	16.4	13.2	6.9	5.1	68.8	12.6	6.1	87.3	6.6
E12	7.9	20.4	6.0	9.6	13.8	15.5	62.8	10.6	16.3	51.1	6.3	96.8

Table 4. Thermal radiation intensity (KW/m^2) of element i to element j under the action of sprinkler system.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
E1	35.9	4.8	8.7	5.0	24.6	4.8	23.0	8.0	5.8	8.5	7.5	5.8
E2	5.5	36.5	5.2	9.3	4.5	26.8	6.1	6.9	28.8	6.4	6.8	9.2
E3	10.2	5.4	11.2	5.9	38.6	5.5	13.8	7.5	5.2	20.3	9.5	6.5
E4	7.0	5.8	5.5	4.3	13.1	4.2	78.3	10.5	4.6	9.5	5.6	4.3
E5	7.4	7.0	4.4	4.3	4.5	5.7	8.4	56.9	9.3	5.5	8.8	5.4
E6	5.8	7.1	4.7	5.8	4.2	14.4	4.5	6.7	64.2	4.5	5.2	23.9
E7	5.2	9.6	5.9	14.9	5.1	44.9	5.1	6.5	10.8	5.7	8.5	20.2
E8	6.3	4.5	6.0	4.7	11.1	3.9	14.1	6.0	4.1	79.7	9.7	4.6
E9	5.5	4.5	5.8	5.4	4.9	5.2	7.4	9.9	5.8	8.7	56.7	7.4
E10	5.0	7.3	4.9	6.2	4.2	11.4	4.4	5.9	20.9	4.3	7.1	72.8
E11	9.9	5.0	41.4	4.8	29.0	4.2	9.7	6.5	5.5	27.7	8.6	4.8
E12	5.6	11.9	5.2	54.3	5.0	28.2	6.5	8.0	13.1	6.7	11.5	28.1

4.2. Fire Risk Assessment of a Ship Engine Room Based on Dynamic Analysis of the Domino Effect

Through the analysis of the fire domino effect of 12 pieces of equipment in the ship engine room, when the time step is 10 min, the results of the fire probability of occurrence scale caused by the initial fire position of each equipment unit is shown in Table 5. The highest probability of causing an engine room fire is observed in the initial fire location E11, which reaches 0.224. E11, E12, and E2 had the highest probabilities of causing fires of 0.393, 0.366, and 0.347, respectively, in more than 75 percent of the whole engine room. According to the preliminary analysis, the equipment most likely to cause large-scale fires is arranged at the edge of the engine room, where the effect of the sprinkler system is weak. The probability of fire spreading to the whole engine room is the highest, resulting in a higher risk of large-scale fire in the engine room. Therefore, the inspection and maintenance of this equipment should be strengthened. The effective measures should be taken to reduce the probability of equipment fires. The arrangement of the sprinkler system in the engine room should be optimized to improve the suppression of fires at the edges and corners of the engine room by the sprinkler system. When a fire occurs, the ability of detection should be enhanced for efficient control of the fire at its onset.

Table 5. The results of fire scale probability of occurrence caused by the initial fire position of each equipment unit.

Fire Size	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
1	0.002	0.000	0.002	0.115	0.103	0.002	0.001	0.103	0.108	0.001	0.000	0.000
2	0.005	0.000	0.005	0.005	0.017	0.009	0.005	0.004	0.003	0.009	0.000	0.000
3	0.009	0.002	0.008	0.007	0.029	0.019	0.007	0.008	0.003	0.015	0.000	0.001
4	0.011	0.005	0.012	0.017	0.012	0.015	0.014	0.013	0.007	0.011	0.001	0.002
5	0.009	0.005	0.010	0.011	0.020	0.017	0.012	0.011	0.007	0.015	0.000	0.002
6	0.009	0.004	0.013	0.010	0.028	0.019	0.016	0.010	0.009	0.016	0.000	0.004
7	0.012	0.009	0.013	0.016	0.024	0.016	0.017	0.014	0.009	0.020	0.001	0.004
8	0.019	0.014	0.019	0.026	0.021	0.024	0.026	0.025	0.015	0.022	0.003	0.010
9	0.033	0.028	0.032	0.035	0.033	0.041	0.037	0.038	0.029	0.040	0.009	0.022
10	0.062	0.064	0.065	0.060	0.047	0.068	0.066	0.059	0.057	0.070	0.039	0.058
11	0.117	0.131	0.111	0.073	0.048	0.093	0.100	0.072	0.088	0.103	0.130	0.139
12	0.123	0.152	0.127	0.050	0.027	0.080	0.108	0.054	0.080	0.089	0.224	0.169

Furthermore, relatively high probabilities can be found in E5, E4, E8, and E9. The fire was controlled at the initial stage before further spread. The aforementioned equipment is distributed in the middle of the engine room area. In the middle area of the engine room, the array of distributed sprinkler systems was the densest, and the sprinkler system worked the best. This area played a great role in inhibiting the development of fire.

Generally, in Figure 7, when the time step is 10 min, the fire scale and corresponding probability show a stepwise upward trend, indicating a significant domino effect of a ship engine room fire.

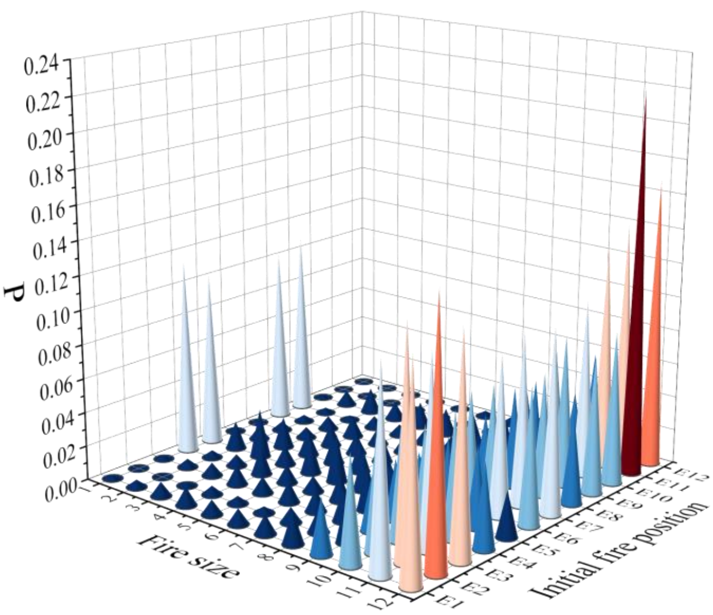

Figure 7. The result of fire size probability of occurrence caused by the initial fire position for each equipment unit.

4.3. Analysis of Key Equipment in the Engine Room Fire

According to the analysis in Section 4.2, E2, E11, and E12 are the initial fire source positions with the highest risk of causing large-scale engine room fires. Therefore, these three pieces of equipment are taken as key research objects to analyze the dynamic probability of the domino effects of engine room fires.

The probabilities of fire for the other equipment in the engine room at each time step when E11, E12, and E2 are the initial fire locations are shown in Tables 6–8. As shown in Figure 8, when E11 was the initial fire location, it triggered the fire of four surrounding equipment at a time step of 2 min, including E3, E5, E8, and E10. Just two minutes later, a fire covering 40 percent of area was caused in the engine room. Then, the other equipment in the engine room enters the fire state at a time step of 4 min under the influence of the synergistic effect of thermal radiation from E11, E3, E5, E8, and E10. The fire probability rises sharply in the subsequent time step. When the time step is 10 min, the fire probabilities of all equipment in the engine room are greater than 0.9. The fires caused by E11 will spread rapidly within a short time, resulting in an engine-room-wide fire, which is extremely dangerous.

Table 6. Fire probability of equipment in an engine room at each time step when the initial fire source is E11.

Step Length	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
1 min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000
2 min	0.000	0.000	0.477	0.000	0.341	0.000	0.000	0.118	0.000	0.346	1.000	0.000
3 min	0.000	0.000	0.710	0.000	0.522	0.000	0.000	0.182	0.000	0.529	1.000	0.000
4 min	0.198	0.038	0.854	0.087	0.680	0.037	0.118	0.373	0.217	0.628	1.000	0.163
5 min	0.433	0.138	0.922	0.161	0.790	0.147	0.285	0.561	0.447	0.676	1.000	0.331
6 min	0.658	0.376	0.957	0.377	0.865	0.399	0.500	0.717	0.646	0.774	1.000	0.552
7 min	0.806	0.611	0.975	0.602	0.916	0.631	0.679	0.826	0.775	0.859	1.000	0.707
8 min	0.885	0.768	0.985	0.762	0.944	0.766	0.812	0.893	0.850	0.906	1.000	0.825
9 min	0.933	0.863	0.989	0.854	0.963	0.857	0.884	0.933	0.899	0.941	1.000	0.899
10 min	0.957	0.916	0.993	0.902	0.973	0.903	0.928	0.955	0.928	0.957	1.000	0.937

Table 7. Fire probability of equipment in an engine room at each time step when the initial fire source is E12.

Step Length	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
1 min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
2 min	0.000	0.000	0.000	0.332	0.000	0.345	0.121	0.000	0.000	0.115	0.000	1.000
3 min	0.000	0.000	0.000	0.514	0.000	0.533	0.178	0.000	0.000	0.181	0.000	1.000
4 min	0.000	0.154	0.000	0.621	0.057	0.715	0.368	0.100	0.242	0.216	0.000	1.000
5 min	0.000	0.363	0.000	0.677	0.112	0.833	0.562	0.280	0.483	0.231	0.000	1.000
6 min	0.127	0.562	0.092	0.784	0.287	0.898	0.714	0.504	0.677	0.363	0.221	1.000
7 min	0.317	0.713	0.283	0.864	0.495	0.940	0.808	0.684	0.797	0.545	0.471	1.000
8 min	0.531	0.825	0.506	0.921	0.671	0.962	0.875	0.798	0.871	0.695	0.672	1.000
9 min	0.703	0.891	0.686	0.949	0.779	0.972	0.927	0.872	0.918	0.802	0.805	1.000
10 min	0.814	0.937	0.812	0.966	0.849	0.980	0.953	0.913	0.943	0.866	0.882	1.000

Table 8. Fire probability of equipment in an engine room at each time step when the initial fire source is E2.

Step Length	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
0	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1 min	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2 min	0.000	1.000	0.000	0.000	0.000	0.466	0.118	0.000	0.349	0.000	0.000	0.000
3 min	0.000	1.000	0.000	0.000	0.000	0.712	0.175	0.000	0.533	0.000	0.000	0.000
4 min	0.000	1.000	0.000	0.000	0.079	0.839	0.207	0.030	0.692	0.080	0.164	0.219
5 min	0.000	1.000	0.000	0.000	0.146	0.908	0.221	0.070	0.796	0.144	0.330	0.453
6 min	0.131	1.000	0.115	0.192	0.267	0.948	0.339	0.240	0.877	0.323	0.539	0.638
7 min	0.307	1.000	0.296	0.429	0.404	0.971	0.514	0.442	0.922	0.515	0.692	0.768
8 min	0.503	1.000	0.505	0.629	0.557	0.982	0.678	0.627	0.951	0.670	0.807	0.862
9 min	0.668	1.000	0.666	0.760	0.692	0.988	0.796	0.754	0.966	0.787	0.884	0.921
10 min	0.786	1.000	0.788	0.852	0.793	0.993	0.875	0.836	0.976	0.856	0.928	0.949

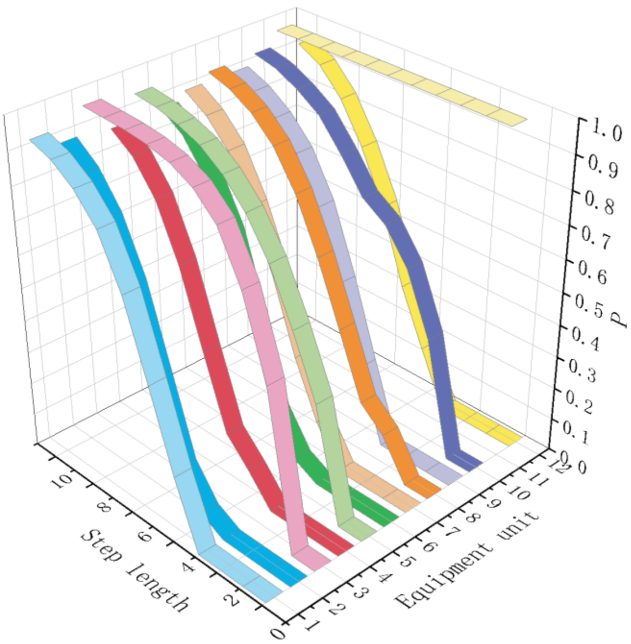

Figure 8. The fire probability of the equipment in the engine room changes at each time step when E11 is the initial fire source.

In Figure 9, when E12 is the initial fire location, the fires in E4, E6, E7, and E10 are triggered when the time step is 2 min. The fire area in the engine room is 40 percent. At the time step of 4 min, the fire area in the engine room is 66 percent. By the time step of 6 min, all equipment in the engine room is on fire. Finally, the probability of fire in the engine room equipment is about 0.9 for a time step of 10 min, which also holds a high risk. Comparing E11 to the initial fire location of fire equipment, the cases where the initial fire source position is E12 caused by the fire spreading process can be divided into three stages, which causes the third-level domino accidents. Comparatively, the process of the fire's spread is moderate, which means that the ship's firefighters have the opportunity to control its further spread under the condition of effective fire-fighting measures within 6 min.

When E2 was the initial fire source location, as shown in Figure 10, the domino accident effect was more moderate compared to the other two groups of conditions. At the time step of 2 min, three equipment fires were triggered in E2, E7, and E9. The engine room fire area was 33 percent. Five equipment fires in E5, E8, E10, E11, and E12 were started in the 4 min time step and covered 66 percent of the engine room fire area. Eventually, the probability of fires in E6, E9, E11, and E12 was above 0.9 for the time step of 10 min. The probability of fires in other equipment was around 0.8. Obviously, the first-level domino accident fire caused by E2 is relatively small, whose second-level domino accident also reaches the scale of the fire of the above two conditions. Thus, the time from the initial fire to the fist 4 min is the most effective time point to control the fire. Otherwise, the fire may develop into a difficult-to-control situation.

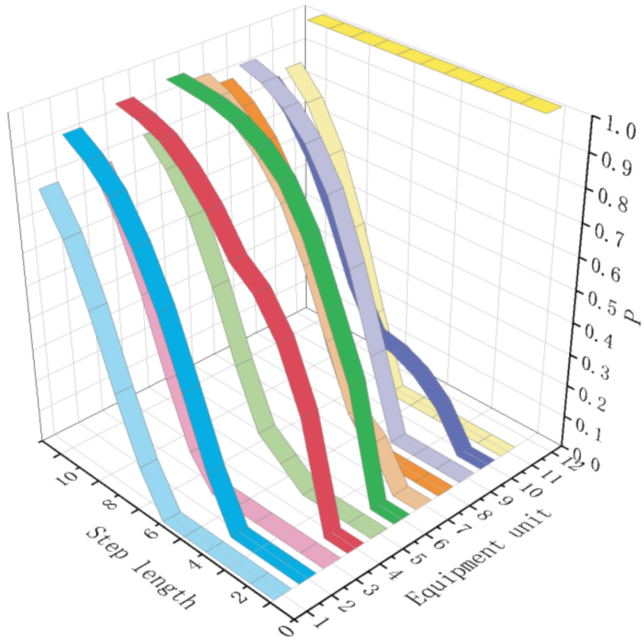

Figure 9. The fire probability of the equipment in the engine room changes at each time step when E12 is the initial fire source.

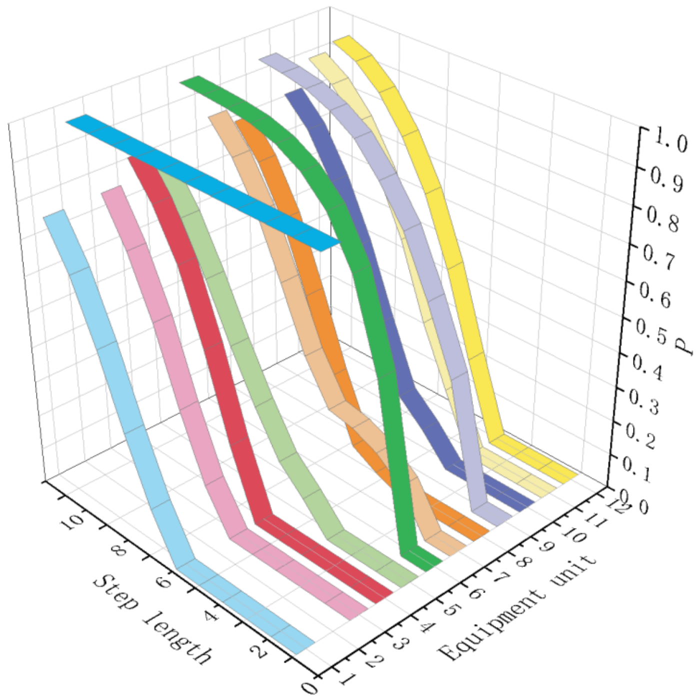

Figure 10. The fire probability of the equipment in the engine room changes at each time step when E2 is the initial fire source.

From the above analyses, in the processes of three conditions of the fire domino effect accident, three vital accident nodes (2 min, 4 min, 6 min) exist in most cases. Three time nodes were recorded when the fire spread to a multi-scale emergency, which provides a critical rescue reference for ship rescue personnel.

4.4. Analysis of Key Equipment in the Fire Spread Path

When E11, E12, and E2 are the initial fire source locations, the fire's domino effect evolution paths in the engine room at time steps of 2 min, 4 min, and 6 min are shown in Table 9. From the statistical analysis shown in Figure 11, the fire spread paths of the three groups of fire conditions are basically spread from their respective locations to the surrounding locations. In the three vital time points of the three conditions, although there was no equipment common to all three conditions, similarities were found between two of the three conditions.

Table 9. Vital time nodes of the engine room fire's domino effect evolution.

Initial Ignition Location	2 min	4 min	6 min
E11	E3, E5, E8, E10	E1, E2, E4, E6, E7, E9, E12	
E12	E4, E6, E7, E10	E2, E5, E8, E9	E1, E3, E11
E2	E6, E7, E9	E5, E8, E10, E11, E12	E1, E3, E4

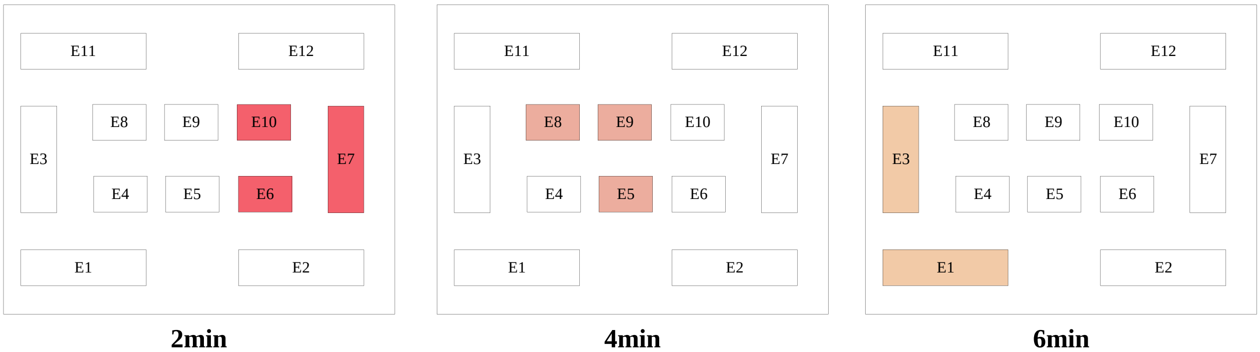

Figure 11. Key equipment in the engine room at an important time.

In the time step of 2 min, when the first-level domino accident is triggered, two two conditions have three key piece of equipment, E6, E7, and E10, in common. In the 2 min time node, the fire is still in the primary stage of the engine room and the fire area is within 40 percent, which is the most effective period in which to control it. When the fire occurs after the initial stage, the ship's damage control personnel can target these three pieces of equipment to start fire-fighting work. It is fast and effective in preventing the spread of the fire. In the daily inspection and maintenance process, effective fire prevention measures can be targeted to these three key pieces of equipment.

When the time step of the second-level domino accidents is 4 min, the common key pieces of equipment are E5, E8, and E9 between the two conditions. is the time node of 4 min represents the middle stage of the fire's spread, where the fire spread to about 60 percent of the engine room. The fire is difficult to control in this stage. If the fire has been developed to this stage, fire extinguishing work can be carried out on these three pieces of equipment in a targeted manner. Alternatively, effective measures such as cooling can be taken for these three units of equipment at the time point before 4 min.

In the third-level domino accident caused by a time step of 6 min, the common key equipment between the two conditions is E1 and E3. When the step is 6 min, the fire has almost spread to the whole cabin. E1 and E3 equipment allow fire-fighting personnel to take control measures that can still effectively restrain the fire's spread. However, the engine room environment will become dramatically worse at this time-step, and it is difficult to start a targeted rescue, and thus the engine room should be sealed or other effective measures should be taken [35].

Through the above analysis, it is found that the three equipment units located at the edge of the engine room caused serious domino effects in case of fire accidents. The multi-level domino effects are all cause by equipment located in the middle of the engine room. Although the results of the analysis in Section 4.1 show that the sprinkler system in the engine room performed an essential role in suppressing the spread of the fire, the multi-level domino effect caused by these three pieces of equipment was significant.

5. Conclusions

This paper proposed a ship engine room fire risk assessment method based on the dynamic analysis of the domino effect, which established a dynamic probability calculation model of ship engine room fire domino effects using matrix calculations and Monte Carlo simulation. The method can quickly obtain the evolution path, evolution time, and probability of fire scenarios for ship engine room fires. The uncertainty of ship personnel, automatic detection systems, sprinkler systems, and the synergistic effect of multiple units burning simultaneously are considered. The state of each equipment unit in the engine room under different time steps is calculated. The dynamic probability of each equipment unit's state under different time steps is evaluated to implement a ship engine room fire risk assessment. Finally, the analysis of the three initial fire source locations that caused the largest fires in the engine room was carried out.

The results Indicate that the probability of E11, E12, and E2 causing a full engine room fire is the highest, and the risk of these fires is the highest. The 2, 4, and 6 min time steps are vital time points for the fire's development and spread. It is necessary to analyze the key equipment in the path of the fire's spread. The extinguishing work for the key equipment can effectively restrain the further expansion of the fire. According to the risk assessment results, corresponding fire control measures are proposed. Furthermore, this methodology can be extended to multi-compartment and ship-wide domino effect fire risk safety assessments.

The threshold formula and equipment failure time are sufficient for the current study. However, the failure thresholds and the reliability of fire-fighting equipment under fire in the ship engine room can be updated in future research to make the assessment model more applicable.

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References

1. Yazir, D. Application of IF-TOPSIS method on fixed fire fighting systems for cargo hold fires on the dry/bulk cargo ships. *Ocean. Eng.* **2022**, *260*, 1–12. [CrossRef]
2. Deng, J.; Liu, S.; Xie, C.; Liu, K. Risk Coupling Characteristics of Maritime Accidents in Chinese Inland and Coastal Waters Based on N-K Model. *J. Mar. Sci. Eng.* **2022**, *10*, 4. [CrossRef]
3. Allianz. *Safety and Shipping Report 2021*; Allianz: Shanghai, China, 2021.
4. International Maritime Organization (IMO). *Global Integrated Shipping Information System (GISIS)*; International Maritime Organization: London, UK, 2019.
5. Ji, J.; Ma, Z.; He, J.; Xu, Y.; Liu, Z. Research on Risk Evaluation and Dynamic Escape Path Planning Algorithm Based on Real-Time Spread of Ship Comprehensive Fire. *J. Mar. Sci. Eng.* **2020**, *8*, 602. [CrossRef]
6. Su, S.C.; Wang, L. Three dimensional reconstruction of the fire in a ship engine room with multilayer structures. *Ocean. Eng.* **2013**, *70*, 201–207. [CrossRef]

7. Ahn, Y.-J.; Yu, Y.-U.; Kim, J.-K. Accident Cause Factor of Fires and Explosions in Tankers Using Fault Tree Analysis. *J. Mar. Sci. Eng.* **2021**, *9*, 844. [CrossRef]
8. Zhang, J.Q.; Lu, S.X.; Li, Q.; Yuen, R.; Yuan, M.; Li, C.H. Impacts of elevation on pool fire behavior in a closed compartment: A study based upon a distinct stratification phenomenon. *J. Fire Sci.* **2013**, *31*, 178–193. [CrossRef]
9. He, Q.; Ezekoye, O.A.; Li, C.; Lu, S. Ventilation limited extinction of fires in ceiling vented compartments. *Int. J. Heat Mass Transf.* **2015**, *91*, 570–583. [CrossRef]
10. Chen, J.; Zhao, Y.L.; Chen, X.; Li, C.; Lu, S. Effect of pressure on the heat transfer and flame characteristics of small-scale ethanol pool fires. *Fire Saf. J.* **2018**, *99*, 27–37. [CrossRef]
11. Wang, J.H.; Jiao, Y.; Shi, L. An experimental and non-dimensional study on the vertical temperature distribution of a sealed ship engine room fire. *Ocean. Eng.* **2018**, *165*, 22–33. [CrossRef]
12. Liu, W.; Wang, L.; Su, S.C.; Wu, Z.Z.; Guo, Y.S.; Du, K.D. Study of the flame flow and combustion characteristics of pool fires around a bluff body in the ship engine room. *Case Stud. Therm. Eng.* **2021**, *28*, 101514. [CrossRef]
13. Liu, Z.; Guo, Z.; Li, Y.; Zhu, L.; Yuan, C. An Improved Failure Risk Assessment Method for Bilge System of the Large Luxury Cruise Ship under Fire Accident Conditions. *J. Mar. Sci. Eng.* **2021**, *9*, 957. [CrossRef]
14. Guan, Y.; Zhao, J.; Shi, T.; Zhu, P. Fault tree analysis of fire and explosion accidents for dual fuel (diesel/natural gas) ship engine rooms. *J. Mar. Sci. Appl.* **2016**, *15*, 331–335. [CrossRef]
15. Sarıalioğlu, S.; Uğurlu, O.; Aydin, M. A hybrid model for human-factor analysis of engine-room fires on ships: HFACS-PV&FFTA. *Ocean. Eng.* **2020**, *217*, 107992.
16. Jia, J.; Lu, S.X. A mission-oriented risk assessment methodology for naval vessel fire caused by non-contact explosions using Bayesian Networks. *Procedia Eng.* **2013**, *62*, 573–580. [CrossRef]
17. Ahn, S.I.; Kurt, R.E. Application of a CREAM based framework to assess human reliability in emergency response to engine room fires on ships. *Ocean. Eng.* **2020**, *216*, 108078. [CrossRef]
18. Spyrou, K.J.; Koromila, I.A. A risk model of passenger ship fire safety and its application. *Reliab. Eng. Syst. Saf.* **2020**, *200*, 106937. [CrossRef]
19. Li, H.; Soares, C. Assessment of failure rates and reliability of floating offshore wind turbines. *Reliab. Eng. Syst. Saf.* **2022**, *228*, 108777. [CrossRef]
20. Reniers, G.; Cozzani, V. *Domino Effects in the Process Industries, Modeling, Prevention and Managing*; Elsevier: Amsterdam, The Netherlands, 2013.
21. Zarei, E.; Gholamizadeh, K.; Khan, F.; Khakzad, N. A dynamic domino effect risk analysis model for rail transport of hazardous material. *J. Loss Prev. Process Ind.* **2022**, *74*, 104666. [CrossRef]
22. Huang, K.X.; Chen, G.H.; Khan, F.; Yang, Y.F. Dynamic analysis for fire-induced domino effects in chemical process industries. *Process Saf. Environ. Prot.* **2021**, *148*, 686–697. [CrossRef]
23. Li, M.; Jiang, X.; Carroll, J.; Negenborn, R.R. A multi-objective maintenance strategy optimization framework for offshore wind farms considering uncertainty. *Appl. Energy* **2022**, *321*, 119284. [CrossRef]
24. ClassNK. *Guidelines for the Prevention of Human Error Aboard Ships*; ClassNK: Tokyo, Japan, 2010.
25. Li, Y.L.; Wang, Y.H.; Lu, S.X. Ignition of the leaked diesel on a heated horizontal surface. *Fire Saf. J.* **2010**, *45*, 58–68. [CrossRef]
26. Panama Maritime Authority (PMA). *Ocean Star Pacific-Marine Casualty*; Panama Maritime Authority: Panama City, Panama, 2011.
27. Dai, X.; Gamba, A.; Liu, C.; Anderson, J.; Charlier, M.; Rush, D.; Welch, S. An engineering CFD model for fire spread on wood cribs for travelling fires. *Adv. Eng. Softw.* **2022**, *173*, 103213. [CrossRef]
28. Huang, K.; Chen, G.; Yang, Y.; Chen, P. An innovative quantitative analysis methodology for Natech events triggered by earthquakes in chemical tank farms. *Saf. Sci.* **2020**, *128*, 104744. [CrossRef]
29. Chen, C.; Reniers, G.; Zhang, L. An innovative methodology for quickly modeling the spatial-temporal evolution of domino accidents triggered by fire. *J. Loss Prev. Process Ind.* **2018**, *54*, 312–324. [CrossRef]
30. Zhou, J.; Reniers, G. A matrix-based modeling and analysis approach for fire-induced domino effects. *Process Saf. Environ. Prot.* **2018**, *116*, 347–353. [CrossRef]
31. Cozzani, V.; Gubinelli, G.; Antonioni, G.; Spadoni, G.; Zanelli, S. The assessment of risk caused by domino effect in quantitative area risk analysis. *J. Hazard. Mater.* **2005**, *127*, 14–30. [CrossRef]
32. Landucci, G.; Gubinelli, G.; Antonioni, G.; Cozzani, V. The assessment of the damage probability of storage tanks in domino events triggered by fire. *Accid. Anal. Prev.* **2009**, *41*, 1206–1215. [CrossRef]
33. Khakzad, N. Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. *Reliab. Eng. Syst. Saf.* **2015**, *138*, 263–272. [CrossRef]
34. Bukowski, R.W.; Budnick, E.; Schemel, C. Estimates of the operational reliability of fire protection systems. In Proceedings of the 3rd International Conference on Fire Research and Engineering, Chicago, IL, USA, 4–8 October 2022; CRC Press: Boca Raton, FL, USA, 1999; pp. 87–98.
35. Wang, J.H.; Zhang, R.Q.; Wang, Y.C.; Shi, L.; Zhang, S.G.; Li, C.C.; Zhang, Y.; Zhang, Q.J. Smoke filling and entrainment behaviors of fire in a sealed ship engine room. *Ocean. Eng.* **2022**, *245*, 110521. [CrossRef]