



Evaluation of Factors Influencing Maritime Dangerous Cargo Transport Accidents-Induced Crew Fatalities and Serious Injuries

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Abstract

Maritime dangerous cargo transport accidents can lead to crew fatalities and serious injuries. This paper focuses on these accidents to evaluate the factors involved in these losses. To that end, the relevant reports of 2000–2020 maritime dangerous cargo transport accidents recorded in the Marine Casualties and Incidents (MCI) module of the International Maritime Organization's Integrated Shipping Information System (IMO-GISIS) database were analyzed. Six initial events in six basic ship operations were determined. This paper combined the entropy weight and Grey relational analysis methods to analyze the involved factors and evaluate the extent of influences of each initial event in various ship operations. The entropy weight (EW) method was applied to determine the weights of basic ship operations. The grey relational analysis method was applied to calculate the correlational degrees of the initial events. Most crew fatalities and severe injuries occur during bunkering, berthing, and mooring operations. Occupational accidents and fires/explosions are the most influential factors; more specifically, occupational accidents during sailing, cargo loading/unloading, anchoring, berthing, and mooring operations and fires/explosions during bunkering operations are most likely to lead to crew fatalities and serious injuries. The results of this paper can aid stakeholders in improving the required strategies to ensure the safety of seafarers during maritime dangerous cargo transport.

Keywords: Maritime Accident; Maritime Transport; Dangerous Goods; Entropy Weight; Grey Relation.

1. Introduction

Maritime transport enables the economical and safe transport of cargo over long distances and is the preferred method worldwide to carry nearly 2000 dangerous cargoes [1]. Dangerous cargoes are substances with physical and chemical properties that may be hazardous to human health and the marine environment [2]. Accidents may occur during maritime dangerous cargo transport. Previous accidents have had substantial consequences not limited to marine environment pollution and financial losses but also fatalities and serious injuries [3-5]. Moreover, with releases, leakage, fire, and explosions, maritime dangerous cargo transport accidents can be even more devastating [6, 7].

From the starting point to the final destination, maritime dangerous cargo transport needs great care [8]. Identifying contributing factors plays a huge role in preventing and reducing maritime dangerous cargo transport accidents. The human factor is behind 90% of maritime dangerous cargo transport accidents [9]. Some scholars have focused on the human factor in dangerous maritime cargo transport. Khan et al. [8] used Bayesian networks to investigate the human factors in port-related dangerous cargo accidents. They revealed that errors and violations were the most dominant accident causation factors in these accidents. Khan et al. [10] then developed the Human Factors Analysis and

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Classification System for Port Environment Hazardous Cargo Accidents (HFACS-PEHCA) to examine the interrelationships between human factors in dangerous cargo accidents in port environments. They stated that violations, limited intellect, inappropriate supervision, and an inadequate safety culture were the most dominant causal factors. Many scholars have addressed maritime dangerous cargo transport safety. Previous studies on maritime dangerous cargo transport accidents generally focus on their contributing factors.

Zhao [3] discussed the chemical causes of the Tianjin Port fire and explosion accident. Zhou et al. [11] developed the HFACS-Hazardous Chemicals (HC) system to study the human and organizational factors of the Tianjin Port fire and explosion accident. Similarly, Huang and Zhang [12] highlighted this accident's chemical causes, losses, and management deficiencies, while Hua et al. [13] explored the causal factors involved using the fault tree analysis (FTA) method. They handled the environmental, human, management, facility, and cargo factors and remarked that the management factors were key causation factors in this accident. Ellis [14] constructed a generic qualitative model to depict the contributing factors and potential consequences of maritime undeclared dangerous cargo transport accidents. Furthermore, Ellis [15] investigated the contributing factors of maritime packaged dangerous cargo transport accidents and described packaging faults as the primary contributing factor. Ronza et al. [16] offered a quantitative risk analysis method to estimate the frequency of hydrocarbon product handling accidents in harbors. Chen et al. [17] determined the factors involved in dangerous cargo accidents in Chinese ports using formal concept analysis. Xie et al. [18] evaluated the main risk factors of dangerous cargo containers in the port through simulation calculations. Nevertheless, accidents continue to occur despite these studies on maritime dangerous cargo transport safety and International Maritime Organization (IMO) regulations [1].

Despite several attempts to study crew fatalities and serious injuries, few studies address crew fatalities caused by dangerous maritime cargo transport accidents. Rømer et al. [19] analyzed 151 maritime dangerous cargo transport accidents and made accident frequency predictions based on accident types and ship numbers. They demonstrated the relationship between fatality numbers and accident frequency using a numerical F/N curve. Then, Rømer et al. [20] evaluated the fatality numbers during maritime dangerous cargo transport accidents against other transport modes using a numerical F/N curve. Li and Wonham [21] analyzed 5389 maritime accidents to inspect the fatalities among British seafarers. They found that occupational accidents caused 90% of the British seafarers' fatalities. Nielsen and Roberts [22] examined fatal maritime accidents between 1990 and 1994 based on ship flags. They indicated that Greece and Norway were the two countries with the highest number of seafarer fatalities. Li [23] introduced a new method to estimate seafarer fatality rates in maritime accidents. Zheng et al. [24] analyzed maritime accident reports in the database of the U.S. Coast Guard to calculate the probability of crew fatalities and injuries on container ships.

Seafaring is a risky occupation with a high fatality and injury rate. This risk increases even more in maritime dangerous cargo transport. It is required to ensure the crew's safety during dangerous cargo transports. The studies mentioned thus far handle the safety during maritime dangerous cargo transport. However, they mainly explain the human and organizational factors in a specific accident case, focusing on enhancing the safety of port operations or estimating the accident frequency in the port area, with few studies taking into account seafarer fatalities due to dangerous maritime cargo transport accidents. Their contents lack serious injuries. As seen from the review of the maritime literature, it is needed to comprehensively handle the issue of crew fatalities and serious injuries caused by maritime dangerous cargo transport accidents. Initial events in different ship operations in maritime dangerous cargo transport accidents influence the crew fatalities and severe injuries to varying degrees. Therefore, this paper combines the EW method with GRA to evaluate the influencing factors of crew fatalities and serious injuries caused by maritime dangerous cargo transport accidents based on initial events and basic ship operations. The 2000–2020 reports of maritime dangerous cargo transport accidents recorded in the IMO's IMO-GISIS database were analyzed. The initial events and basic ship operations were determined by analyzing accident reports. The weights of basic ship operations were calculated objectively by the EW method. The correlation degrees of initial events were calculated objectively by Grey Relational Analysis. This paper aims to help maritime dangerous cargo transport stakeholders develop strategies to reduce crew fatalities and serious injuries.

2. Materials and Methods

The factors influencing crew fatalities and serious injuries caused by maritime dangerous cargo transport accidents pertain to a grey system. There was partial information. Only some of the data were available. The GRA method can be applied to calculate the correlation degrees between factors [25]. Therefore, the GRA method was used to evaluate the accidents in question that can lead to crew fatalities and severe injuries. This method has the potential to reveal the total contribution of initial events to maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. Also, the EW method was employed to determine the weights of basic ship operations for more objective calculation results (for a more detailed methodology flowchart, see Figure 1).

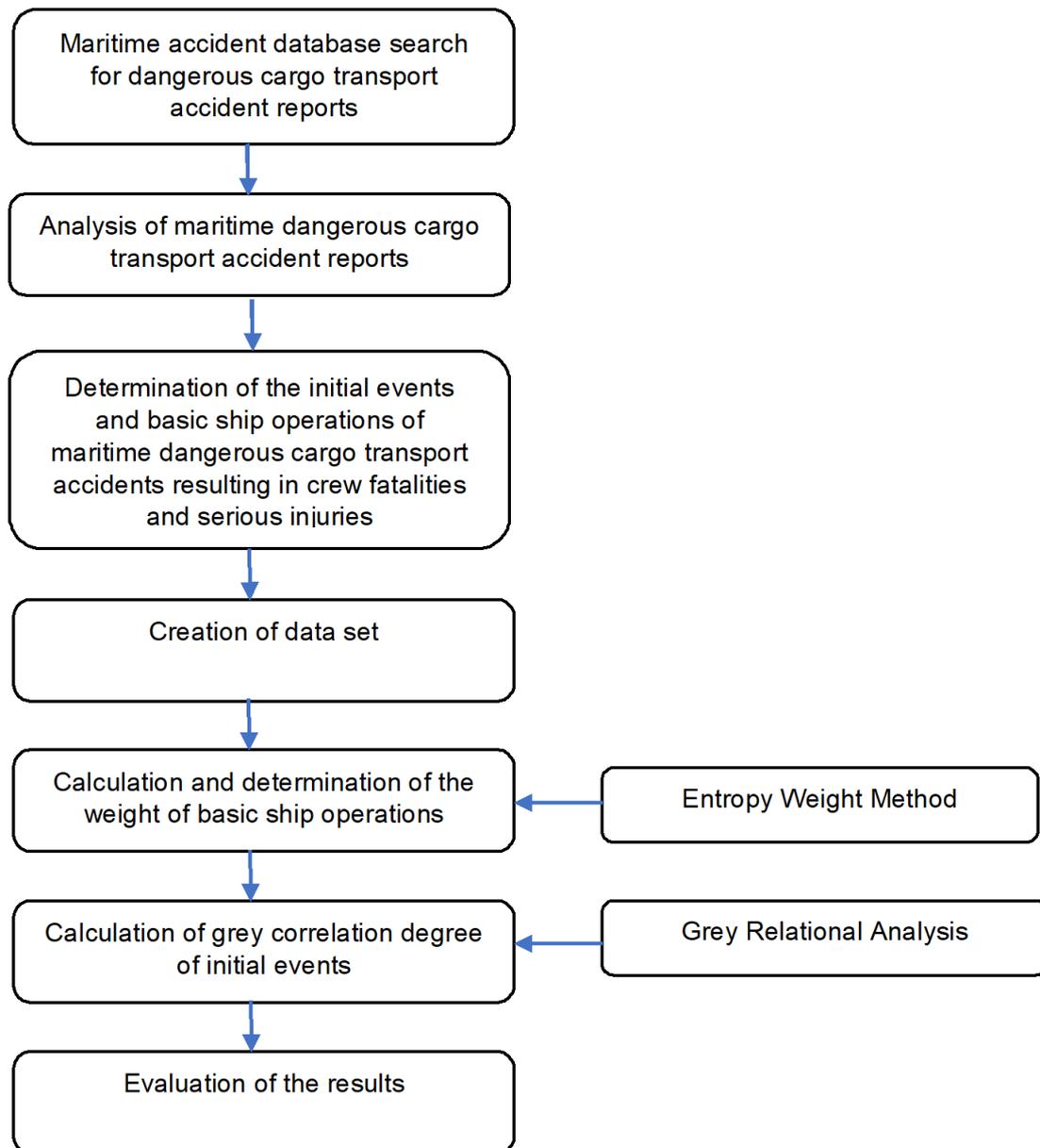


Figure 1. The flowchart of the research methodology

2.1. Entropy Weight Method

In multi-criteria decision-making problems, subjective and objective methods are used to determine the importance weights of the criteria. The entropy method is one of the objective weighting methods. It allows for calculating the importance weights of the criteria without resorting to the subjective judgments and thoughts of the experts. Additionally, it can be applied easily without creating a hierarchical structure. Therefore, it is often used in different disciplines. Rudolf Clausius first defined entropy as a measure of disorder in 1865. Later, Shannon developed the concept of information entropy in 1948 [26]. The information theory defines entropy as a measure of the uncertainty associated with random variables. It is possible to measure the amount of helpful information with the entropy method [27]. The decision matrix is sufficient to use the EW method as it provides the weighting of the evaluation criteria in the decision matrix. A high entropy value indicates that the criterion is fundamental [28].

The EW method consists of 5 stages [26, 28]:

Stage 1: Decision matrix (X) creation. A set of alternatives ($A = \{A_i, i = 1, 2, \dots, n\}$) should be compared with a set of criteria ($C = \{C_j, j = 1, 2, \dots, m\}$). Thus, a $n \times m$ performance matrix (the decision matrix; X) can be obtained as follows, where x_{ij} is a clear value showing the performance grade of each alternative A_i according to each criterion C_j .

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{nm} \end{bmatrix} \quad (1)$$

Stage 2: Data standardization. The decision matrix in Stage 1 is normalized for each criterion to find objective weights with the entropy measure by eliminating the discrepancies in different measurement units. Equation 2 is used for normalization.

$$p_{ij} = \frac{x_{ij}}{\sum_{p=1}^n x_{pj}}, i = 1, 2, \dots, n \quad (2)$$

This normalization process results in obtaining the normalized decision matrix (P).

$$P = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1m} \\ p_{21} & p_{22} & \dots & p_{2m} \\ \dots & \dots & \dots & \dots \\ p_{n1} & p_{n2} & \dots & p_{nm} \end{bmatrix} \quad (3)$$

Stage 3: Entropy measure (e_j) calculation. Equation 4 is used to calculate the entropy measure of each index.

$$e_j = -k \sum_{i=1}^n p_{ij} \ln p_{ij}, k = \frac{1}{\ln(n)} \quad (4)$$

Stage 4: Divergence degree (d_j) calculation. Equation 5 is used to calculate the divergence degree of the entropy measure of each criterion. The greatness of d_j shows the greatness of the importance of the criterion j .th.

$$d_j = 1 - e_j \quad (5)$$

Stage 5: Entropy weight (w_j) calculation. Equation 6 is used to calculate the objective weight of each criterion.

$$w_j = \frac{d_j}{\sum_j d_j} \quad (6)$$

2.2. Grey Relational Analysis

Julong Deng developed the grey system theory in 1982 to quantify uncertainty. White represents known information, and black represents unknown information in grey system theory. The grey area in between represents partially known information. The GRA method is a grading, classification, and decision-making technique in multi-criteria decision-making problems where insufficient, incomplete, or inaccurate data are present [29]. This method explores system behavior by performing correlation analysis and model building. Its straightforward calculations and relatively simple formulas have turned it into a mathematical method with applications in many disciplines [30].

The GRA method consists of six stages [31]:

Stage 1: Decision matrix (X) preparation, where m is the number of alternatives and n is the number of criteria, $x_i(j)$ shows the performance of the i^{th} alternative's j^{th} criterion value:

$$X = \begin{bmatrix} x_1(1) & x_1(2) & \dots & x_1(m) \\ x_2(1) & x_2(2) & \dots & x_2(m) \\ \dots & \dots & \dots & \dots \\ x_n(1) & x_n(2) & \dots & x_n(m) \end{bmatrix} \quad (7)$$

Stage 2: Data set normalization. There are three formulas for data conversion.

Larger-the-better:

$$x_i^+(j) = \frac{x_i(j) - \min_{i=1}^n [x_i(j)]}{\max_{i=1}^n [x_i(j)] - \min_{i=1}^n [x_i(j)]} \quad (8)$$

The maximum sequence factor is the ideal factor in the larger-the-better grey-relational generation.

Smaller-the-better:

$$x_i^-(j) = \frac{\max_{i=1}^n [x_i(j)] - x_i(j)}{\max_{i=1}^n [x_i(j)] - \min_{i=1}^n [x_i(j)]} \quad (9)$$

The minimum of the sequence factors is ideal in the smaller-the-better grey-relational generation.

Nominal-the-better:

$$x_i^0(j) = 1 - \frac{|x_i(j) - x_{obj}(j)|}{\max\{\max_{i=1}^n [x_i(j)] - x_{obj}(j), x_{obj}(j) - \min_{i=1}^n x_i(j)\}} \tag{10}$$

where $x_{obj}(j)$ is the target value. The one compatible with the target value of the sequence factors is the ideal factor in the nominal-the-better grey relational generation.

Stage 3: Normalized matrix construction and reference series generation based on Equations 8-10.

Normalized Matrix

$$X' = \begin{bmatrix} x'_1(1) & x'_1(2) & \dots & x'_1(m) \\ x'_2(1) & x'_2(2) & \dots & x'_2(m) \\ \dots & \dots & \dots & \dots \\ x'_n(1) & x'_n(2) & \dots & x'_n(m) \end{bmatrix} \tag{11}$$

Reference Series

$$X'_0 = x'_0(1), x'_0(2), \dots, x'_0(m) \tag{12}$$

The reference value ($x'_0(j)$) is determined as below:

$$x'_0(j) = \max_{i=1}^n [x'_i(j)] \tag{13}$$

Stage 4: Distance calculation and absolute value matrix preparation.

The distance between the normalized values with the reference series is measured using Equation 14.

$$\Delta_{oi}(j) = |x'_0(j) - x'_i(j)| \tag{14}$$

Absolute Value Matrix:

$$\Delta = \begin{bmatrix} \Delta_{o1}(1) & \Delta_{o1}(2) & \dots & \Delta_{o1}(m) \\ \Delta_{o2}(1) & \Delta_{o2}(2) & \dots & \Delta_{o2}(m) \\ \dots & \dots & \dots & \dots \\ \Delta_{on}(1) & \Delta_{on}(2) & \dots & \Delta_{on}(m) \end{bmatrix} \tag{15}$$

Stage 5: Grey relational coefficient calculation.

The grey relational coefficient is calculated using Equation 16.

$$\gamma_{oi}(j) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(j) + \zeta \Delta_{max}} \tag{16}$$

where $\Delta_{max} = \max_i \max_j \Delta_{oi}(j)$, $\Delta_{min} = \min_i \min_j \Delta_{oi}(j)$ and $\zeta \in [0,1]$, ζ is the distinguishing coefficient.

The value is generally considered 0.5.

Stage 6: Grey relational degree calculation.

The grey relational degree is calculated using Equation 17:

$$\Gamma_{oi} = \sum_{j=1}^m [w_i(j) * \gamma_{oi}(j)], \sum_{j=1}^m w(j) = 1 \tag{17}$$

2.3. Data Set Preparation

IMO-GISIS is an international database system. It includes the Maritime Casualties and Incidents (MCI) module. This module contains reports on worldwide maritime accidents. These accident investigation reports are reliable sources for data set preparation and provide detailed information. A report's main elements are ship name and type, accident date, location and severity, accident initial event and consequences, ship operation, voyage segment, cargo's nature, and event summary. This paper analyzed 347 dangerous cargo transport accident reports between 2000 and 2020 that resulted in crew fatalities and serious injuries. Basic ship operations and initial events were determined depending on the report analysis. Basic ship operations were as follows: sailing (shown as A₁), cargo loading/unloading (shown as A₂), anchoring (shown as A₃), berthing (shown as A₄), mooring (shown as A₅), and bunkering (shown as A₆). Initial events of accidents were as follows: collision (shown as X₁), stranding/grounding (shown as X₂), fire/explosion (shown as X₃), equipment failure (shown as X₄), capsizing/listing (shown as X₅), and occupational accidents (shown as X₆). Table 1 illustrates the descriptions of initial events.

Table 1. Descriptions of initial events

Series No.	Initial Events	Descriptions
X ₁	Collision	Collision states the strike between two or more ships regardless of whether moored, anchored, or underway [32].
X ₂	Stranding/grounding	Stranding/grounding states the ship is aground in a shallow water area. It hits/touches the bottom of the sea, underwater objects, beach, or riverbed. So, the ship renders unfit to proceed [33].
X ₃	Fire/explosion	Fire/explosion states the uncontrolled ignition of flammable chemicals and other materials on board for several reasons [34].
X ₄	Equipment failure	Equipment failure states the damages to the on-board equipment, systems, and the ship itself [25].
X ₅	Capsizing/listing	Capsizing/listing states the ship capsizes or lies permanently at a certain angle [35].
X ₆	Occupational accidents	Occupational accidents state the work-related accidents that occur due to human violations, failure to respond and error in judgment [36].

Paper selects six initial events (X₁ to X₆) and six ship operations (A₁ to A₆). Table 2 illustrates the decision matrix employed.

Table 2. Decision matrix

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₁	28	1	1	1	0	0
X ₂	3	0	3	0	0	0
X ₃	29	19	4	0	3	1
X ₄	15	15	2	4	2	0
X ₅	23	3	3	0	0	0
X ₆	87	38	25	27	10	0

3. Application

3.1. Entropy Weights Calculation of Basic Ship Operations

The decision matrix was normalized using Equation 2. Table 3 illustrates the normalized decision matrix.

Table 3. Normalized decision matrix

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₁	0.1514	0.0132	0.0263	0.0313	0.0000	0.0000
X ₂	0.0162	0.0000	0.0789	0.0000	0.0000	0.0000
X ₃	0.1568	0.2500	0.1053	0.0000	0.2000	1.0000
X ₄	0.0811	0.1974	0.0526	0.1250	0.1333	0.0000
X ₅	0.1243	0.0395	0.0789	0.0000	0.0000	0.0000
X ₆	0.4703	0.5000	0.6579	0.8438	0.6667	0.0000

The ship operations' entropy measures were calculated using Equation 4. Table 4 illustrates the $p_{ij} \ln p_{ij}$ values of the normalized data.

Table 4. The $p_{ij} \ln p_{ij}$ values

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₁	-0.2858	-0.0570	-0.0957	-0.1083	0.0000	0.0000
X ₂	-0.0668	0.0000	-0.2004	0.0000	0.0000	0.0000
X ₃	-0.2905	-0.3466	-0.2370	0.0000	-0.3219	0.0000
X ₄	-0.2037	-0.3203	-0.1550	-0.2599	-0.2687	0.0000
X ₅	-0.2592	-0.1276	-0.2004	0.0000	0.0000	0.0000
X ₆	-0.3548	-0.3466	-0.2755	-0.1434	-0.2703	0.0000

The ship operations' divergence degrees were calculated using Equation 5. The ship operations' entropy weight values were calculated using Equation 6. Table 5 illustrates the ship operations' entropy measures, divergence degrees, and entropy weight values.

Table 5. The entropy measures, divergence degrees, and entropy weight values

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
e _j	0.8153	0.6686	0.6497	0.2855	0.4805	0.0000
d _j	0.1847	0.3314	0.3503	0.7145	0.5195	1.0000
w _j	0.0596	0.1069	0.1130	0.2304	0.1676	0.3225

3.2. Grey Relational Analysis of Initial Events

The decision matrix created for the Entropy Weight Method is also the decision matrix of the Grey Relational Analysis. The normalized decision matrix is illustrated in Table 3. The ship operations were considered based on size: larger operations were more favoured. Therefore, Equation 8 was used to perform the normalization process. Table 6 illustrates the normalized comparison series.

Table 6. Normalized comparison series

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₀	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X ₁	0.2976	0.0263	0.0000	0.0370	0.0000	0.0000
X ₂	0.0000	0.0000	0.0833	0.0000	0.0000	0.0000
X ₃	0.3095	0.5000	0.1250	0.0000	0.3000	1.0000
X ₄	0.1429	0.3947	0.0417	0.1481	0.2000	0.0000
X ₅	0.2381	0.0789	0.0833	0.0000	0.0000	0.0000
X ₆	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000

The absolute value matrix was created using Equation 14. Table 7 illustrates the absolute value matrix.

Table 7. Absolute value matrix

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₀	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X ₁	0.7024	0.9737	1.0000	0.9630	1.0000	1.0000
X ₂	1.0000	1.0000	0.9167	1.0000	1.0000	1.0000
X ₃	0.6905	0.5000	0.8750	1.0000	0.7000	0.0000
X ₄	0.8571	0.6053	0.9583	0.8519	0.8000	1.0000
X ₅	0.7619	0.9211	0.9167	1.0000	1.0000	1.0000
X ₆	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Grey relational coefficients were calculated using Equation 16. Table 8 illustrates grey relational coefficients.

Table 8. Grey relational coefficients

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆
X ₁	0.4158	0.3393	0.3333	0.3418	0.3333	0.3333
X ₂	0.3333	0.3333	0.3529	0.3333	0.3333	0.3333
X ₃	0.4200	0.5000	0.3636	0.3333	0.4167	1.0000
X ₄	0.3684	0.4524	0.3429	0.3699	0.3846	0.3333
X ₅	0.3962	0.3519	0.3529	0.3333	0.3333	0.3333
X ₆	1.0000	1.0000	1.0000	1.0000	1.0000	0.3333

The grey relational degrees of initial events were calculated using Equation 17. The ship operations' entropy weights are in Table 5. Table 9 illustrates the grey relational degrees and rankings.

Table 9. Relational degrees and rankings of the initial events

	Relational degree	Ranking
X ₁	0.3408	5
X ₂	0.3355	6
X ₃	0.5887	2
X ₄	0.3662	3
X ₅	0.3413	4
X ₆	0.7850	1

4. Results and Discussion

This paper evaluates the influencing factors of maritime dangerous cargo transport accidents that lead to crew fatalities and severe injuries. Table 5 illustrates the influence of basic ship operations on maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. Table 9 illustrates the results of grey relational calculation for various initial events of maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries.

Table 5 and Figure 2 indicate that the weight of bunkering is 32.25%, the weight of berthing is 23.04%, the weight of mooring is 16.76%, the weight of anchoring is 11.30%, the weight of cargo loading/unloading is 10.69%, and the weight of sailing is 5.96%. Bunkering has the maximum weight. It demonstrates that maritime dangerous cargo transport accidents with crew fatalities and serious injuries occur mainly during bunkering operations. At the same time, sailing has the minimum weight, which indicates that these accidents have the lowest fatalities and injuries during sailing operations.

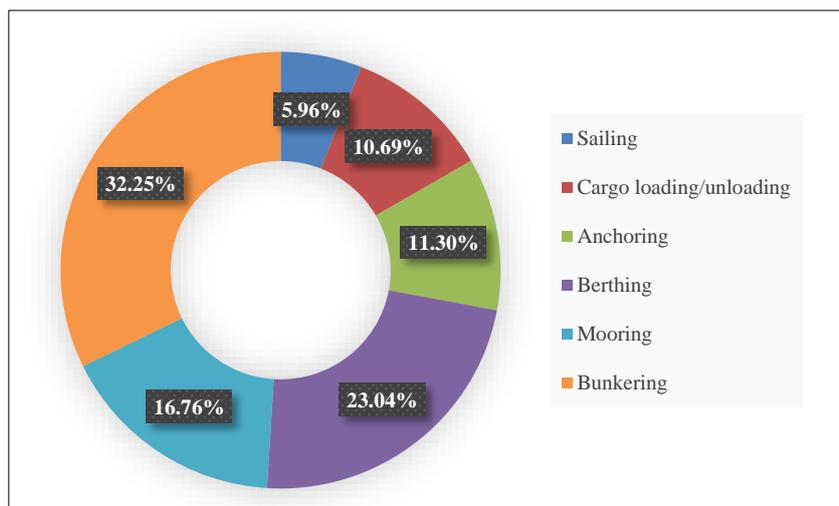


Figure 2. The weights of basic ship operations

The total weight of bunkering, berthing, and mooring operations constitutes more than 70% of the total. It means maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries are more probable to occur during these three operations. Stakeholders of maritime dangerous goods transport need to be much more careful in the management of these three operations can be inferred. The weight of the anchoring, cargo loading/unloading, and sailing operations comprise less than 30% of the total. It refers that maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries are less probable to occur during these three operations.

According to Table 9 and Figure 3, the correlation degree of occupational accidents is 0.7850, the correlation degree of fire/explosion is 0.5887, the correlation degree of equipment failure is 0.3662, the correlation degree of capsizing / listing is 0.3413, the correlation degree of collision is 0.3408, and the correlation degree of stranding/grounding is 0.3355. Occupational accidents occupy the highest correlation degree. It shows that occupational accidents are the most influential factor in maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. On the other hand, stranding/grounding occupies the lowest correlation degree. It shows that stranding/grounding is the lowest influential factor in maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. Since they take the lion's share, occupational accidents and fire/explosion are the most critical factors of maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. Occupational accidents and fire/explosion are the most significant factors that should be considered by the stakeholders of maritime dangerous cargo transport for developing accident management procedures.

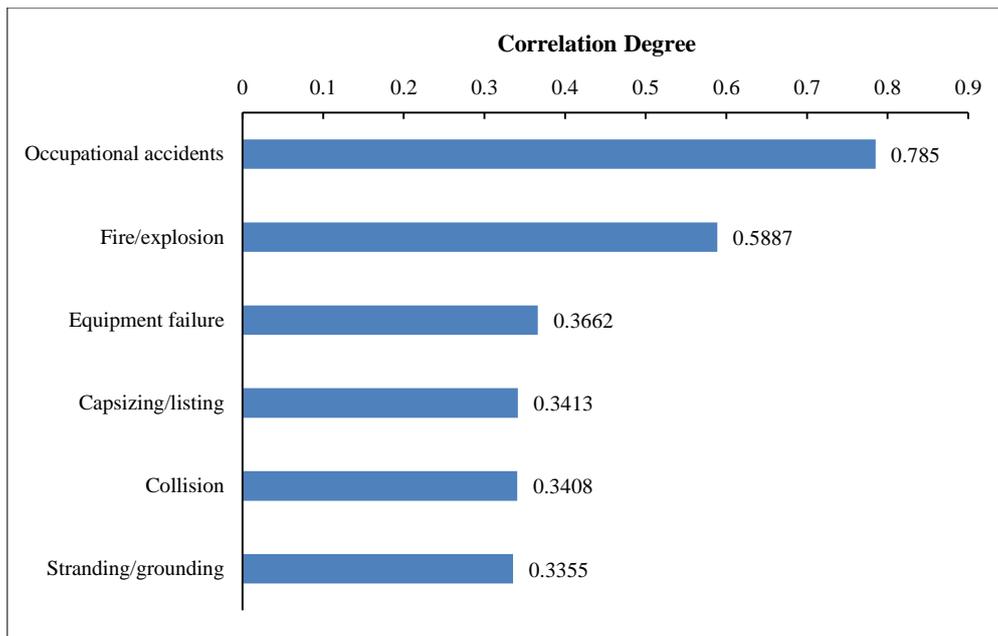


Figure 3. Correlation of initial events

Table 8 and Figure 4 illustrate the correlation coefficients of initial events and basic ship operations of maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. According to Table 8 and Figure 4, occupational accidents during basic ship operations, except for bunkering operations, and fire/explosion during bunkering operations are the most prone to cause maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries.

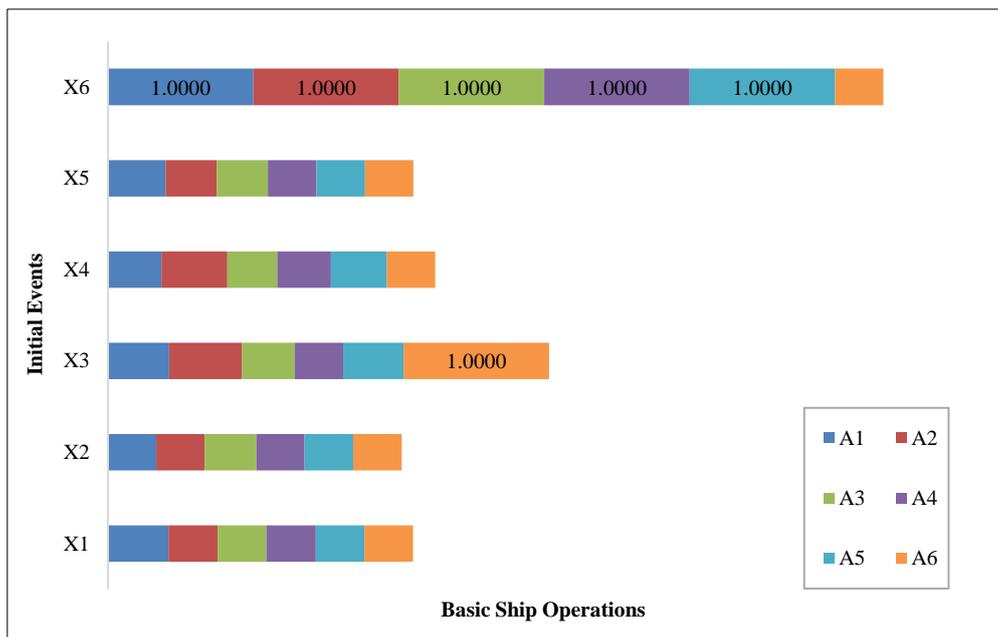


Figure 4. Correlation coefficients between basic ship operations and initial events

Rømer et al. [19] estimated accident frequencies of tankers transporting dangerous cargo based on accident type and tanker size. Fire/explosion was the primary factor leading to fatalities in ports, coastal waters, and the sea. Rømer et al. [20] examined fatal maritime dangerous cargo transport accidents based on accident type and transport phase consisting of sailing, cargo transfer, and empty tanks. Collisions between tankers and ferries during sailing were the most likely to lead to fatal maritime accidents. Dead passengers increased the total fatality numbers. Li and Wonham [21] analyzed the fatal accidents of British seafarers according to four accident types. Occupational accidents were the primary accident type leading to the highest fatalities. Li [23] analyzed Lloyd’s Register of Shipping’s accident reports to predict the fatality rates of seafarers worldwide by using a new approach. Occupational accidents have caused the most fatalities on ships. Zheng et al. [24] analyzed the U.S. Coast Guard’s reports to calculate the probability of seafarers’ fatalities and injuries on container ships. Fire/explosion was the most likely to occur a fatality on container ships.

This paper highlights those occupational accidents during sailing, cargo loading/unloading, anchoring, berthing and mooring operations, and fire/explosion during bunkering operations are the most likely to lead to maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. Chen et al. [25] stated that fire/explosion during bunkering operations is the most likely to cause an oil spill. It is not surprising when considered fire/explosion is most prone to happen during the bunkering process. Seafaring is a dangerous occupation considering the working environment and conditions. Occupational accidents with fatality and severe injury may likely occur during many ship operations [37]. Li and Wonham [21] stated that occupational accidents were the root cause of nearly 90% of all fatal marine accidents. Li [23] stated that 76% of ship fatalities occurred due to occupational accidents. The rest of the fatalities in ships occurred due to ship accidents, such as sinking, collisions, and grounding. With the intent of reducing these accidents, some precautions can be recommended as follows:

- Increasing safety training is compulsory for the prevention of occupational accidents;
- In particular, IMDG Code refresher training should be taken not only by seafarers but also by all shore-based personnel;
- Seafarers should be treated as human resources, not as the workforce;
- The working conditions of seafarers should be improved, and their working environments should be safer;
- Occupational accidents' root causes should be determined. Risk assessments should be carried out. The ship safety management system should be revised;
- The usage of personal protective equipment should be encouraged;
- Applied occupational health and safety rules should be monitored.

5. Conclusions

Maritime dangerous cargo transport leads to crew fatalities and serious injuries. Comprehensive analysis of influencing factors of crew fatalities and serious injuries caused by maritime dangerous cargo transport accidents is critical for their prevention and minimization. This paper has evaluated the influencing factors of maritime dangerous cargo transport accidents resulting in crew fatalities and serious injuries. The data set, consisting of initial events and basic ship operations, was based on accident reports from 2000 to 2020 retrieved from the MCI module of the IMO-GISIS database. This paper has combined the EW method and GRA to analyze the influencing factors objectively. The main results were as follows:

- The total weight of bunkering, berthing, and mooring operations explains more than 70% of the total. This result indicates that most crew fatalities and serious injuries happen during the three basic ship operations;
- The higher correlation shows the higher impact. Occupational accidents and fire/explosions have a more considerable influence on crew fatalities and serious injuries;
- Specifically, occupational accidents during sailing, cargo loading/unloading, anchoring, berthing, and mooring operations, and fire/explosion during bunkering operations are the most likely to incur crew fatalities and serious injuries. These extended results are appropriate for the stakeholders to develop effective strategies to reduce crew fatalities and serious injuries.

The main novelty of this study is the combination of the EW with GRA methods to analyze the influencing factors involved in crew fatalities and severe injuries due to maritime dangerous cargo transport accidents. This paper contributes to the literature in the following aspects. First, the comprehensive analysis of influencing factors of crew fatalities and serious injuries caused by maritime dangerous cargo accidents is an original idea. Second, this paper applies a rational and effective mathematical tool. Third, the results of this paper can aid stakeholders in taking precautions and formulating strategies to reduce crew fatalities and serious injuries. This paper, however, is subject to several limitations.

The assessment model can be extended by adding more ship operations and initial events. Besides, an integrated evaluation model including ship types, flag states, accident locations, and ship ages can provide a more thorough and realistic analysis in future studies. Moreover, it can be interesting to integrate a probability method into the evaluation model to enable it to predict the potential future factors and trends associated with fatal maritime dangerous cargo transport accidents.

6. Declarations

6.1. Author Contributions

Conceptualization, Ö.E., and L.T.; methodology, Ö.E., and L.T.; formal analysis, Ö.E., and L.T.; data curation, Ö.E., and L.T.; writing—original draft preparation, Ö.E., and L.T.; writing—review and editing, Ö.E., and L.T. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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