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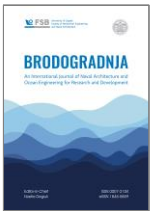

A combined method for the evaluation of contributing factors to maritime dangerous goods transport accidents

Özge Eski[*1], *Leyla Tavacioglu*[2]

[1]*Zonguldak Bulent Ecevit University, Maritime Faculty, Department of Maritime Transportation and Management Engineering, Kdz. Eregli, Zonguldak, Türkiye.*
[2]*Istanbul Technical University, Maritime Faculty, Department of Basic Sciences, Tuzla, Istanbul, Türkiye.*

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ABSTRACT

This paper evaluates the contributing factors to maritime dangerous goods (DG) transport accidents by integrating the Entropy Weight (EW) and Grey Relational Analysis (GRA) methods. For this purpose, investigation reports of maritime DG transport accidents that occurred worldwide between 2000 and 2023 are derived from the International Maritime Organization’s Integrated Shipping Information System (IMO GISIS) database’s Marine Casualties and Incidents (MCI) module. Eleven main ship operations and thirteen primary causes were selected by analysing accident investigation reports. The weights of main ship operations are calculated utilizing the EW method. The correlational degrees of the primary causes are then calculated using the GRA method. Most maritime DG transport accidents occur during unberthing, bunkering, and pilotage operations. The most common contributing factors of maritime DG transport accidents are collisions and occupational accidents. Specifically, maritime DG transport accidents are most likely to be caused by collisions during sailing, passage, maneuvering, and bunkering operations, as well as occupational accidents during cargo loading, anchoring, berthing, and mooring operations. The results of this paper can support stakeholders in developing the needed policies to guarantee the safety of maritime DG transport.

1. Introduction

DG are substances that may pose a hazard to humans, property, and the environment owing to their physical, chemical, and nuclear characteristics [1]. Over the past two decades, the need to handle DG has

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[*] Corresponding author.
E-mail address: ozge.eski@beun.edu.tr

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increased in many industries. As a result, the volume of DG transported in global trade has increased [2]. Maritime transport is more cost-effective than other modes of transport [3]. For this reason, it is now the preferred means of transporting nearly 2,000 DG [1].

During maritime DG transport, accidents can cause serious environmental damage, economic losses, deaths, and serious injuries. Various risk factors for accidents may exist during maritime DG transport [4]. These factors can be independent or have complex connections between them. To logically examine the prevailing factors and types of accidents, we had to efficiently examine these factors and then assess their influences on the accidents depending on accident types or chosen factors. This is the key objective of this study. In this paper, the integration of the EW method and GRA is utilized to evaluate the factors contributing to maritime DG transport accidents around the world. The objective weight of each factor is calculated using the EW method, and the real contribution of each factor is further examined using the GRA approach. Depending on the degree of index variation, the EW method modifies each index’s weight, applying information entropy to provide a more impartial index weight and remove human error from the weight calculation process, making the assessment result more practical and objective. GRA is one of the multifactor statistical methods. By using the grey relational degree, it determines the size, order, and strength of the indicators' association. This approach is quite practical because it is not excessive given the sample size and regularity of the sample [4]. In this study, the integration of the EW method and GRA is employed to construct an assessment system of contributing factors to maritime DG transport accidents. This paper determines the contributing factors to maritime DG transport accidents by analysing worldwide maritime accidents in the past 24 years. This study employs quantitative methods to investigate the issue of maritime DG transport accidents, examine the factors that contribute to the occurrence of accidents, and recommend workable solutions for preventing these accidents. Preventing fatalities and injuries, protecting the marine environment, and advancing the sustainable growth of the world’s maritime DG transport industry are crucial.

The purpose of this study is to develop an assessment framework and research methodology for the evaluation of maritime DG transport accidents worldwide. This study builds up an entropy-weighted grey relation model to assess the contributing factors to maritime DG transport accidents. It then suggests appropriate measurements to reduce these accidents. There are three main ways in which this study contributes. First, the concept of a thorough examination of the factors contributing to maritime DG transport accidents is presented in this study. Secondly, this study offers a useful instrument for examining the factors that contribute to maritime DG transport accidents worldwide. Third, the findings of this study offer a point of reference for stakeholders to improve strategies for reducing accidents involving DG.

This paper consists of six sections. To identify knowledge gaps, related literature is reviewed systematically in Section 2. Section 3 presents a detailed, step-by-step explanation of the model formulation employed in this study. Section 4 presents the data source and explanation of the major contributing factors to maritime DG transport accidents and the model implementation. Section 5 covers the analysis of the results. In Section 6, which is the last section of this paper, the results are outlined and suggestions for further research are discussed.

2. Systematic Literature Review

This paper has employed the systematic literature review method offered by Denyer and Tranfield to determine the studies that handle the contributing factors to maritime DG transport accidents [5]. In this method, a clear and significant question is set at the beginning of the research to select the related studies. The four-step procedure is carried out after the research question has been set. The first step involves searching electronic databases like Elsevier and Scopus to find the most comprehensive source. The second step includes the evaluation of the research relevant to the review question. To accomplish this, a first search is conducted after identifying the eligibility criteria for excluding irrelevant literature. Therefore, keywords should be defined together with the preferred location in which they may be placed, such as in the title, summary, keywords, or all of them. Then the literature that addresses the review questions is gathered and used for additional research. The third step contains a thorough examination of the chosen literature items, during which relevant data is extracted, study findings from related research are compared, and the most important information is gathered. The final step covers a discussion of the major findings from the earlier studies.

The review procedure employed in this study purposes to provide a thorough understanding of the contributing factors to maritime DG transport accidents. The Scopus database was used to examine articles published between 1960 and 2024. The literature search relevant to the contributing factors to maritime DG transport accidents was based on these keywords: dangerous goods, hazardous substances, hazardous materials, dangerous substances, dangerous cargo, dangerous goods transport, accident, maritime, sea, and marine. Thirty-one sub-searches were carried out by altering the word combinations in each query to make sure the collected literature is comprehensive. For instance, the keywords "dangerous goods", "accident", and "maritime" were covered in the title, summary, or keywords section of the database documents.

481 articles, all of which were published after 1960, were obtained in total. After a thorough investigation, the total number of articles examined was significantly lowered because many of the articles found were not relevant to this study. There have been 33 articles reviewed in all. Figure 1 depicts the steps of the systematic literature review for this paper.

The safety of maritime DG transport is one of the most challenging issues in global trade. There is a high degree of uncertainty regarding risk factors and the potential for very serious accidents [6]. Although various scholars have focused on the safety of maritime transport, only a few of them have addressed maritime DG transport safety. Determining contributing factors is essential to preventing and minimizing maritime DG transport accidents [7]. To provide thorough evaluations of the features and causes of accidents, statistical analysis of historical accidents has always been a basic and practical method. Rømer et al. [8] examined 151 maritime transport accidents of DG to estimate the accident frequencies for the different accident types, including fire/explosions, collisions, groundings, and structural damage. They used the F-N curve to indicate the relationship between the number of casualties and the frequency of accidents. They modelled the spill volume using linear regression analysis, depending on the accident type and ship size. For grounding, structural damage, and fire/explosion accidents, spill volume and tanker size were found to be highly correlated. Later, Rømer et al. [9] used a numerical F-N curve to compare the casualty rates of maritime transport accidents involving DG to those of other modes of transport. Collision was determined to be the primary cause of maritime DG transport accidents. Roeleven et al. [10] suggested a generalized linear model to calculate the likelihood of inland waterway transport accidents involving DG. Visibility and wind speed were found to be the most effective factors in these accidents. Ellis [11] examined the records of maritime DG transport accidents, and packaging error was found to be the main risk factor for these accidents.

Some scholars have studied the risk factors for tanker accidents resulting in oil spills. Silbermann and Weber [12] revealed that mechanical failure is the main cause of oil spill accidents in Maryland. Ventikos and Psaraftis [13] developed an event-decision network to analyse the risk factors for oil spills caused by tanker accidents. Ismail and Karim [14] investigated the causes of tanker accidents resulting in oil spills. Navigation errors, hurricanes, and storms, as well as factors related to mechanical maintenance and failures of machinery, were found to be the leading causes of these accidents. Chen et al. [15] investigated the main causes that contribute to tanker accidents resulting in oil spills. Fire/explosion was determined to be the principal cause of the oil spill.

Some scholars have handled DG accidents in port areas. Ronza et al. [16] estimated the probability of accidents during hydrocarbon handling operations in ports using a quantitative risk analysis method. Martino et al. [17] inspected the effects of fires, explosions, and chemical spills caused by activities involving DG in the port of Brindisi. Chen et al. [18] used formal concept analysis to evaluate the risk factors for accidents during DG operations in the ports of China. Poor warehouse management, cargo record deficiencies, and inappropriate port facilities and equipment were found to be the main factors. Besides, spills and fire/explosions were described as the most common accident types. Khan et al. [19] explored the critical factors for DG accidents in port areas using Bayesian networks. Human and management factors were highlighted as key causal factors in these accidents. Ma et al. [20] investigated critical risk factors for port operations of DG by combining the Hesitant Fuzzy Linguistic Cloud (HFLC) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method.

The human factor in maritime DG transport accidents has been investigated by several scholars. Stirling [21] stated that human error is the main operational cause that leads to marine pollution from the transport of DG. Chen et al. [22] revealed that the human factor was the primary factor leading to the Sanchi tanker accident by performing the fault tree analysis. Khan et al. [23,24] investigated the role of human factors in accidents involving DG in ports. Besides, Zhou et al. [25] and Hua et al. [26] examined the human and organizational factors contributing to the accident at the port of Tianjin. Also, Zhao [27] and Huang and Zhang [28] investigated the cause of this accident in the chemical sense. Wang et al. [29] and Jiang et al. [30] developed a human factors analysis framework based on the Human Factors Analysis Classification System (HFACS) and used it for port operations to determine unsafe behaviours of practitioners.

Maritime DG transport requires considerable attention from the starting point to the last destination [24]. Mullai and Larsson [31] made a comprehensive risk assessment, and the human factor and mechanical failures were found to be the most contributing factors to maritime transport accidents involving DG. Derse and Göçmen [32] stated that cargo factors were the key causes of maritime transport accidents involving DG. Ma et al. [33] examined the risk factors contributing to maritime DG transport accidents by using DEMATEL, Interpretive Structure Modelling (ISM), and Fuzzy Bayesian Network (FBN) integration. Serra et al. [34] used the hierarchical clustering method to examine risk factors for maritime transport accidents involving DG. The human factor was found to be the main factor, and fires and explosions were the most frequent accident types. Ma et al. [35] suggested a hybrid model to conduct a risk assessment of coupling links (CLs) in the maritime DG transport system.

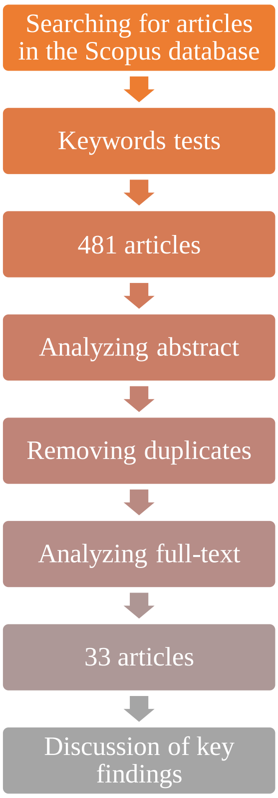

Fig. 1 Stages of the systematic literature review of this paper

Besides, Ellis [36] developed a numerical model to describe the primary risk factors for maritime transport accidents involving undeclared DG. Popek [37] surveyed the contributing factors to maritime transport accidents involving packaged DG. Saruchera [38] examined the factors that affect the efficiency of DG logistics in Namibian ports. While appropriate port equipment and infrastructure were the factors that increased efficiency the most, inadequate port traffic management was the factor that reduced efficiency the most. Eski and Tavacioglu [1] developed a valid and reliable questionnaire to evaluate the factors that affect dock laborers' DG transport awareness. DG training was stated to be the most prominent factor in preventing accidents. Galieriková et al. [39] examined the factors that influence the destruction of the marine environment caused by spillage from maritime accidents involving DG. The amount of spillage and the type of cargo package were determined as the two main factors.

There are still certain gaps in some ways, even though several earlier studies on maritime DG transport accidents examined the risk factors that contributed to these accidents. The contributing factors to maritime DG transport accidents are complex and interrelated, and there is still a lack of thorough evaluations of their hierarchical relationships in the literature. Previous related studies investigated the ranking of contributing factors and did not consider the comprehensive and dynamic correlation of these factors. There are a few comprehensive analyses of different primary causes during ship operations using quantitative methods [4, 40]. This paper aims to close these research gaps. Hence, this paper integrates the EW and GRA methods to analyse and investigate different causes of maritime DG transport accidents, as well as classify and sort them by the degree of influence.

3. Methodology

3.1 Research method

Maritime DG transport accidents can be attributed to numerous complex factors that include every facet of a ship. There are independent and interconnected factors, and the factors have varying degrees of effect on maritime DG transport accidents. For different ship operations, different primary causes have various degrees of effect on maritime DG transport accidents. A thorough analysis of contributing factors to maritime DG transport accidents is required.

Among the objective weighing methods is the EW method. By using this method, it is possible to calculate the weights of the criteria without depending on the expert's subjective assessments and opinions. It is also simple to implement without establishing a hierarchical structure [41]. Therefore, for more objective calculation results, the weights of main ship operations can be determined using the EW method. In general, a factor's weight and importance in evaluating maritime DG transport accidents increase with decreasing information entropy. Information entropy, created by Claude Shannon, is a concept from information theory. It provides the amount of information available about an event. An event will include less information the more certain or deterministic it is. To put it more simply, information is an increase in entropy, or uncertainty [42].

Grey system theory, proposed by Julong Deng, is a novel approach to investigating uncertainty problems with inadequate data and poorly known information. In this theory, white describes known information, while black describes unknown information. Partially known information is described in the grey region in between [43,44]. Contributing factors to maritime DG transport accidents belong to a grey system. There is not enough information available. There is a finite quantity of data available. Therefore, the GRA method can be used for assessment. To determine the comprehensive correlation degrees between factors, the GRA method can be utilized. This method can demonstrate the overall primary cause contribution to maritime transport accidents involving DG.

Considering this, this paper evaluates the contributing factors to maritime DG transport accidents by integrating the EW method with GRA. First, the raw data about the primary causes of maritime DG transport accidents and main ship operation modes is normalized. Next, each ship operation indicator's entropy weights are calculated. Ultimately, the weights are substituted into the grey relation model to calculate the correlation degree to determine the influence extent of different primary causes. Figure 2 depicts the workflow diagram for the research.

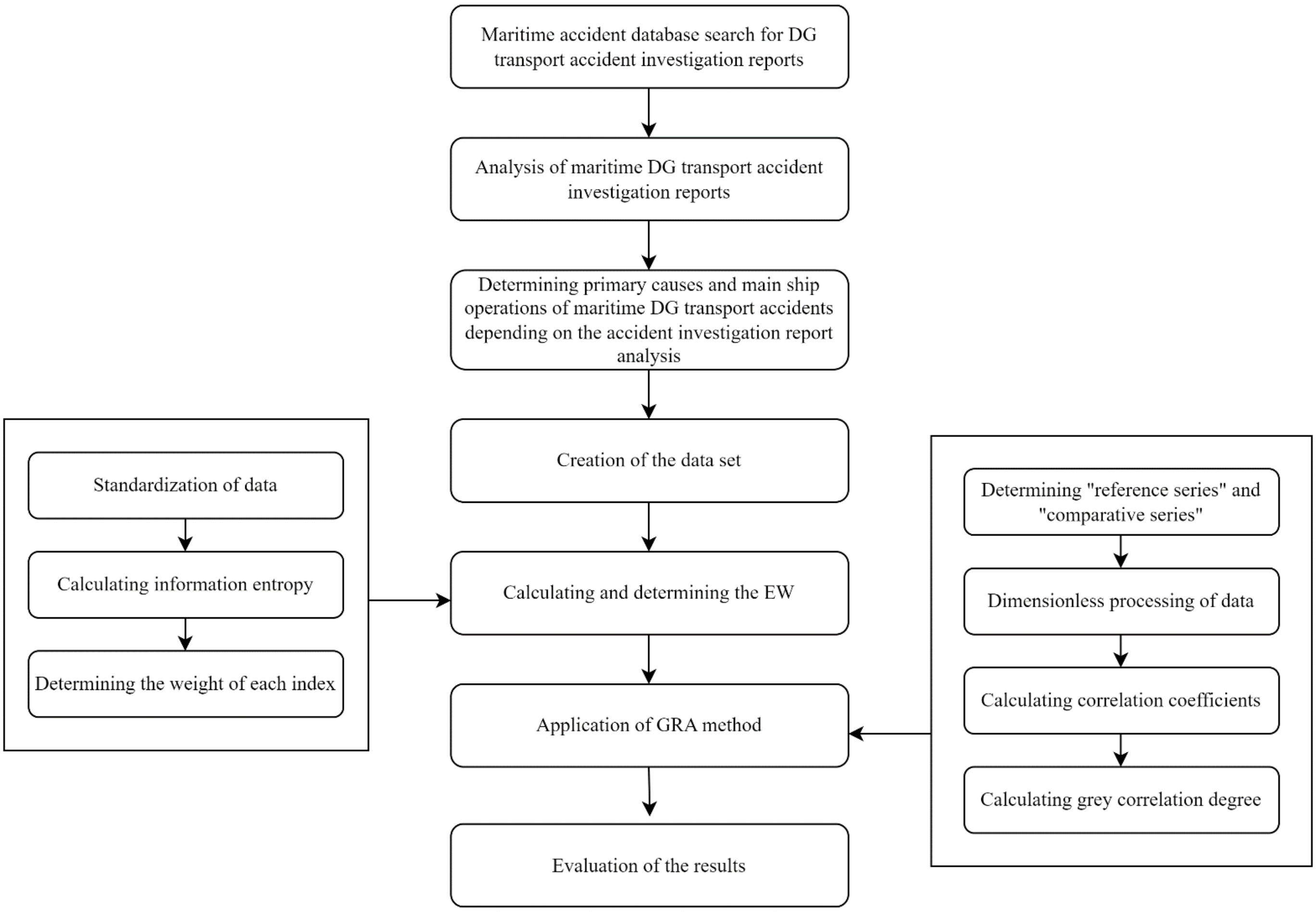

Fig. 2 The workflow diagram for the research

3.2 Entropy weight method

In multi-criteria decision-making problems, the significance weights of the criteria are calculated by applying both objective and subjective methods. The entropy method is an example of an objective approach that allows the calculation of significant weights without considering the subjective views of experts. Furthermore, it is simple to implement without the need for a hierarchical structure. Thus, it is frequently employed in a variety of fields of study [40]. In 1865, Rudolf Clausius described entropy as the degree of chaos [45]. In 1948, Shannon created the idea of information entropy [42]. Entropy is described in information theory as an indicator of the ambiguity related to random variables. The entropy approach is used to determine the amount of useful knowledge [41]. The decision matrix provides an adequate basis for the utilization of EW since it contains weighting criteria for the assessment. A high degree of entropy suggests that this criterion is essential [46]. In this paper, the EW method is used to calculate the weights of main ship operations involved in maritime DG transport accidents. According to the principle of the EW method, the phases involved are as follows [40]:

Phase 1: Establishment of a decision matrix

The primary causes and main ship operations are determined. As mentioned below, this paper selected thirteen primary causes (X_1 to X_{13}, see Table 1) and eleven main ship operation modes (A_1 to A_{11}, see Table 2) involved in maritime DG transport accidents. The decision matrix X is created. According to raw data about the primary causes of maritime DG transport accidents and main ship operation modes, the $m \times n$ order evaluation indicator matrix can be obtained:

$$Xmn = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

where x_{ij} is the value of the j-th ship operation indicator for the i-th cause and $i = 1, 2, ..., m$, $j = 1, 2, \ldots, n$.

Phase 2: Standardization of data

Using the averaging method, the data is normalized. Then the j-th ship operation indicator of the i-th primary cause is demonstrated by p_{ij}, and $i = 1, 2, ..., m$, $j = 1, 2, \ldots, n$. Equation 2 is utilized for normalization.

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2}$$

The normalized decision matrix P is obtained from this normalization procedure.

$$Pmn = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix} \tag{3}$$

Phase 3: Entropy measure calculation

The information entropy e_j of main ship operation modes can be calculated in accordance with the description of information entropy in information theory, and $j = 1, 2, \ldots, n$. The calculation formula is given in Equation 4.

$$e_j = -\frac{\sum_{i=1}^{m} p_{ij} \ln p_{ij}}{\ln m} \tag{4}$$

If $p_{ij} = 0$, $\lim_{p_{ij} \to 0} p_{ij} \ln p_{ij} = 0$ can be described to obtain the information entropy of main ship operation modes $e_1, e_2, \ldots, e_n$.

Phase 4: Divergence degree calculation

The divergence degree d_j calculation formula is given in Equation 5.

$$d_j = 1 - e_j \tag{5}$$

where $1-e_j$ is the deviation coefficient, stating the significance of the indicator in the system. The more significant the role of the indicator, the higher its value.

Phase 5: Entropy weight calculation

In the end, the entropy weight w_j of main ship operation modes can be calculated using Equation 6.

$$w_j = \frac{d_j}{\sum_j d_j} \tag{6}$$

3.3 Grey Relational Analysis

When there is inadequate, deficient, or partial data available for multi-criteria decision-making problems, the GRA method can be used as a grading, categorization, and decision-making approach [43,44]. This approach investigates system behavior by applying correlation analysis and performing model construction. Its clear calculations and plain formulas make it useful for various study fields [47]. In this paper, the GRA method is adopted to calculate the correlational degrees of the primary causes involved in maritime DG transport accidents. The phases involved in the GRA method are as follows [40]:

Phase 1: Construction of the decision matrix

$$X=\begin{bmatrix} x_1(1) & x_1(2) & \dots & x_1(n) \\ x_2(1) & x_2(2) & \dots & x_2(n) \\ \dots & \dots & \dots & \dots \\ x_m(1) & x_m(2) & \dots & x_m(n) \end{bmatrix} \tag{7}$$

According to raw data about the primary causes (X_1 to X_{13}, see Table 1) of maritime DG transport accidents and main ship operation modes (A_1 to A_{11}, see Table 2), the decision matrix X is built.

Phase 2: Construction of reference series and comparison series

The “reference series” that represents the features of the maritime DG transport accidents is identified, and the “comparison series” that impacts the maritime DG transport accidents is identified. The data series that represents the features of the maritime DG transport accidents is referred to as the reference series, which displays the total number of maritime DG transport accidents in this paper. The data series constituted by maritime DG transport accidents primary causes is named comparison series, which displays the certain number of maritime DG transport accidents caused by certain primary cause. X_0 is set to be the reference series, and X_i is set to be the comparison series.

$$X_0=\{x_0(k)|k=1, 2, \dots, n\}\ , X_i=\{x_i(k)|k=1, 2, \dots, n\}\ (i = 1, 2, ..., m) \tag{8}$$

Phase 3: Normalization of the data set

In the grey relational model, different scales and measure units may be used, resulting in different dimensions. This situation makes direct data comparison impracticable. Therefore, raw data conversion is needed for healthier scientific evaluation results. The dimensionless value $y_i(k)$ can be obtained using Equation 9.

$$y_i(k)= \frac{x_i(k)\ -\ \min\limits_i x_i(k)}{\max\limits_i x_i(k) -\ \min\limits_i x_i(k)}\ \ (i = 1, 2, ..., m, k =1, 2, \dots, n) \tag{9}$$

Phase 4: Calculation of the correlation coefficient

The correlation coefficient between the primary causes of maritime DG transport accidents and main ship operation modes is calculated. After the normalization,

The reference series is $Y_0=\{y_0(k)|\ k=1, 2, \dots, n\}$, and

The comparison series is $Y_i=\{y_i(k)|k=1, 2, \dots, n\}$ $(i = 1, 2, ..., m)$.

ξ_i(k) (i = 1, 2, ..., m, k =1, 2, …, n) is the calculation for the correlation coefficient between the k-th ship operation indicator of the i-th primary cause and the k-th optimal indicator. The specific formula is as follows:

$$\xi_i(k)= \frac{\min\limits_i \min\limits_k |y_0(k)\text{-}y_i(k)|+\rho \max\limits_i \max\limits_k |y_0(k)\text{-}y_i(k)|}{|y_0(k)\text{-}y_i(k)|+\rho \max\limits_i \max\limits_k |y_0(k)\text{-}y_i(k)|} \tag{10}$$

where ρ is the distinguishing coefficient and $\rho \in [0, 1]$. In general, the value is regarded as 0.5.

Phase 5: Grey relational degree calculation

The grey correlation degree of the primary causes of maritime DG transport accidents is calculated. The grey relation degree between the reference series and comparison series of different primary causes is calculated as regards the main ship operation weights set by the EW method. The grey correlation degree Γ_i (i = 1, 2, ..., m) is calculated using Equation 11.

$$\Gamma_i= \sum_{k=1}^{n} \omega_k \times \xi_i(k) \tag{11}$$

If the grey correlation degree Γ_i of a definite primary cause is the highest, it demonstrates that the cause has the greatest impact on maritime DG transport accidents.

4. Application

4.1 Preparation of the data set

The Maritime Casualties and Incidents (MCI) module is available in the global database known as the International Maritime Organization's Integrated Shipping Information System (IMO GISIS). Investigation reports on international maritime accidents are included in the MCI module. These investigation reports offer a thorough examination of international maritime accidents and are reliable resources for creating data sets. The name and type of the ship, the accident date, the location and severity, the journey segment, the type of cargo, the accident summary and consequences, the ship's operation, and the accident's primary cause are the fundamental elements of an investigative report. In this paper, the main ship operations and primary causes were determined by examining the investigation reports of 1144 maritime DG transport accidents that happened worldwide between 2000 and 2023. Sailing (illustrated as A_1), cargo loading (illustrated as A_2), cargo unloading (illustrated as A_3), anchoring (illustrated as A_4), berthing (illustrated as A_5), passage (illustrated as A_6), maneuvering (illustrated as A_7), mooring (illustrated as A_8), unberthing (illustrated as A_9), pilotage (illustrated as A_{10}), and bunkering (illustrated as A_{11}) were the basic ship operations. Collision (illustrated as X_1), stranding/grounding (illustrated as X_2), contact (illustrated as X_3), fire/explosion (illustrated as X_4), hull failure (illustrated as X_5), machinery damage (illustrated as X_6), damages to ship or equipment (illustrated as X_7), capsizing/listing (illustrated as X_8), foundering (illustrated as X_9), accidents with life-saving appliances (illustrated as X_{10}), occupational accidents (illustrated as X_{11}), other factors (illustrated as X_{12}), and unknown factors (illustrated as X_{13}) were the initial events of accidents. Table 1 depicts the definitions of the primary causes.

Table 1 Definitions of the primary causes

Series No.	Primary Causes	Definitions
X_1	Collision	Collision refers to the crash between at least two ships, whether sailing or not [48].
X_2	Stranding/grounding	Stranding/grounding refers to the ship that touches the bottom of the sea, rendering it unfit to sail on [49].
X_3	Contact	Contact refers to the ship hitting fixed or floating items, excluding collisions and stranding/groundings [50].
X_4	Fire/explosion	Fire/explosion refers to the unrestrained inflammation of combustible substances on board for different reasons [51].
X_5	Hull failure	Hull failure refers to damage to the hull, depending on several reasons, and affects the structural strength of the ship [52].
X_6	Machinery damage	Machinery damage refers to the devastation and disorders of the ship's machinery [53].
X_7	Damages to ship or equipment	Damages to the ship or equipment refer to destruction to the ship's systems and overall structures [15].
X_8	Capsizing/listing	Capsizing/listing refers to when the ship overturns or lies steadily at an angle [54].
X_9	Foundering	Foundering refers to the ship being flooded [55].
X_{10}	Accidents with life-saving appliances	Accidents with life-saving appliances refer to the accidents that happen during drills [56].
X_{11}	Occupational accidents	Occupational accidents refer to work-related accidents caused by human negligence, errors in reaction, or poor perception [57].
X_{12}	Other factors	Other factors encompass stormy weather, rough seas, and piracy.
X_{13}	Unknown factors	Unknown factors include uncategorized circumstances due to a lack of information.

Table 2 depicts the descriptions of the main ship operations [58].

Table 2 Descriptions of the main ship operations

Series No.	Ship Operations	Descriptions
A_1	Sailing	Sailing refers to the ship being underway and moving through water, neither berthed alongside, at anchor, nor aground.
A_2	Cargo loading	Cargo loading refers to the transport of cargo from the shore terminal onto a ship.
A_3	Cargo unloading	Cargo unloading refers to the transport of cargo from a ship to the shore terminal.
A_4	Anchoring	Anchoring refers to the process by which a ship is secured in place in the water using an anchor.
A_5	Berthing	Berthing refers to the process of navigating a ship into a designated position alongside a dock, quay, or pier to secure it for loading, unloading, or other port activities.
A_6	Passage	Passage refers to the process of navigating a ship from one point to another through confined waterways such as canals, rivers, or straits.
A_7	Maneuvering	Maneuvering refers to the process of controlling and directing a ship's movements, often in confined or challenging environments, to achieve specific positioning or navigational objectives.
A_8	Mooring	Mooring refers to the process of securing a ship to a fixed point or floating element to keep it stationary in the water.
A_9	Unberthing	Unberthing refers to the process of releasing the mooring lines that secure the ship to the berth, allowing it to move away from a designated position alongside a dock, quay, or pier.
A_{10}	Pilotage	Pilotage refers to the practice of employing a local maritime pilot to assist in navigating a ship through challenging or unfamiliar waters.
A_{11}	Bunkering	Bunkering refers to the process of supplying fuel to a ship.

Table 3 Decision matrix

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_1	137	5	6	22	11	27	11	1	2	25	1
X_2	114	2	0	25	8	13	9	2	0	38	0
X_3	12	0	5	3	15	5	3	1	3	8	0
X_4	81	14	26	12	18	5	1	6	0	2	1
X_5	17	2	1	2	1	1	0	0	0	0	1
X_6	30	1	3	3	3	5	1	0	1	2	0
X_7	30	10	15	4	8	1	1	6	0	2	1
X_8	43	2	3	4	0	3	0	1	0	0	0
X_9	7	1	0	0	0	3	0	0	0	0	0
X_{10}	9	2	2	0	1	0	0	0	0	0	0
X_{11}	79	23	24	26	26	12	1	12	1	9	0
X_{12}	3	0	0	0	0	2	0	0	0	0	0
X_{13}	8	0	3	1	0	0	0	1	0	0	0

This paper selects thirteen primary causes (X_1 to X_{13}) and eleven ship operations (A_1 to A_{11}). Corresponding to the thirteen primary causes and eleven ship operation modes, the decision matrix is set utilizing Equation 1. The decision matrix is depicted in Table 3.

4.2 Calculation of entropy weights of main ship operations

Based on the decision matrix, the normalized data p_{ij} is calculated using Equation 2, as displayed in Table 4. The normalized data in Table 4 is substituted into Equations 4-6 to calculate the entropy weights of main ship operations. The $p_{ij} \ln p_{ij}$ value of the normalized data is calculated as displayed in Table 5. Table 6 displays the information entropy e_j , the divergence degree d_j , and the entropy weight w_j values.

Table 4 Normalized p_{ij} values of the decision matrix for primary contributors of maritime DG transport accidents and main ship operation modes

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_1	0.2404	0.0806	0.0682	0.2157	0.1209	0.3506	0.4074	0.0333	0.2857	0.2907	0.2500
X_2	0.2000	0.0323	0.0000	0.2451	0.0879	0.1688	0.3333	0.0667	0.0000	0.4419	0.0000
X_3	0.0211	0.0000	0.0568	0.0294	0.1648	0.0649	0.1111	0.0333	0.4286	0.0930	0.0000
X_4	0.1421	0.2258	0.2955	0.1176	0.1978	0.0649	0.0370	0.2000	0.0000	0.0233	0.2500
X_5	0.0298	0.0323	0.0114	0.0196	0.0110	0.0130	0.0000	0.0000	0.0000	0.0000	0.2500
X_6	0.0526	0.0161	0.0341	0.0294	0.0330	0.0649	0.0370	0.0000	0.1429	0.0233	0.0000
X_7	0.0526	0.1613	0.1705	0.0392	0.0879	0.0130	0.0370	0.2000	0.0000	0.0233	0.2500
X_8	0.0754	0.0323	0.0341	0.0392	0.0000	0.0390	0.0000	0.0333	0.0000	0.0000	0.0000
X_9	0.0123	0.0161	0.0000	0.0000	0.0000	0.0390	0.0000	0.0000	0.0000	0.0000	0.0000
X_{10}	0.0158	0.0323	0.0227	0.0000	0.0110	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
X_{11}	0.1386	0.3710	0.2727	0.2549	0.2857	0.1558	0.0370	0.4000	0.1429	0.1047	0.0000
X_{12}	0.0053	0.0000	0.0000	0.0000	0.0000	0.0260	0.0000	0.0000	0.0000	0.0000	0.0000
X_{13}	0.0140	0.0000	0.0341	0.0098	0.0000	0.0000	0.0000	0.0333	0.0000	0.0000	0.0000

Table 5 The $p_{ij} \ln p_{ij}$ value of the normalized data

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_1	-0.3427	-0.2030	-0.1831	-0.3308	-0.2554	-0.3675	-0.3658	-0.1134	-0.3579	-0.3591	-0.3466
X_2	-0.3219	-0.1108	0.0000	-0.3446	-0.2138	-0.3003	-0.3662	-0.1805	0.0000	-0.3609	0.0000
X_3	-0.0813	0.0000	-0.1629	-0.1037	-0.2972	-0.1776	-0.2441	-0.1134	-0.3631	-0.2209	0.0000
X_4	-0.2773	-0.3360	-0.3602	-0.2518	-0.3205	-0.1776	-0.1221	-0.3219	0.0000	-0.0875	-0.3466
X_5	-0.1048	-0.1108	-0.0509	-0.0771	-0.0496	-0.0564	0.0000	0.0000	0.0000	0.0000	-0.3466
X_6	-0.1550	-0.0666	-0.1152	-0.1037	-0.1125	-0.1776	-0.1221	0.0000	-0.2780	-0.0875	0.0000
X_7	-0.1550	-0.2943	-0.3016	-0.1270	-0.2138	-0.0564	-0.1221	-0.3219	0.0000	-0.0875	-0.3466
X_8	-0.1950	-0.1108	-0.1152	-0.1270	0.0000	-0.1264	0.0000	-0.1134	0.0000	0.0000	0.0000
X_9	-0.0540	-0.0666	0.0000	0.0000	0.0000	-0.1264	0.0000	0.0000	0.0000	0.0000	0.0000
X_{10}	-0.0655	-0.1108	-0.0860	0.0000	-0.0496	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
X_{11}	-0.2739	-0.3679	-0.3543	-0.3484	-0.3579	-0.2897	-0.1221	-0.3665	-0.2780	-0.2362	0.0000
X_{12}	-0.0276	0.0000	0.0000	0.0000	0.0000	-0.0948	0.0000	0.0000	0.0000	0.0000	0.0000
X_{13}	-0.0599	0.0000	-0.1152	-0.0453	0.0000	0.0000	0.0000	-0.1134	0.0000	0.0000	0.0000

Table 6 The information entropy e_j , the divergence degree d_j , and the entropy weight w_j values of main ship operations

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
e_j	0.8241	0.6930	0.7192	0.7250	0.7291	0.7605	0.5709	0.6411	0.4979	0.5613	0.5405
d_j	0.1759	0.3070	0.2808	0.2750	0.2709	0.2395	0.4291	0.3589	0.5021	0.4387	0.4595
w_j	0.0471	0.0821	0.0751	0.0736	0.0725	0.0641	0.1148	0.0960	0.1343	0.1174	0.1229

4.3 Grey relational analysis of the primary causes of maritime DG transport accidents

The generated decision matrix for the EW method, displayed in Table 3, is also the decision matrix of the GRA. The reference series and the comparison series are determined based on Equation 8. Using Equation 9, the raw data is nondimensionalized to get the dimensionless value $y_i(k)$. Table 7 displays the dimensionless values $y_i(k)$.

Table 7 The dimensionless values $y_i(k)$

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X_1	1.0000	0.2174	0.2308	0.8462	0.4231	1.0000	1.0000	0.0833	0.6667	0.6579	1.0000
X_2	0.8284	0.0870	0.0000	0.9615	0.3077	0.4815	0.8182	0.1667	0.0000	1.0000	0.0000
X_3	0.0672	0.0000	0.1923	0.1154	0.5769	0.1852	0.2727	0.0833	1.0000	0.2105	0.0000
X_4	0.5821	0.6087	1.0000	0.4615	0.6923	0.1852	0.0909	0.5000	0.0000	0.0526	1.0000
X_5	0.1045	0.0870	0.0385	0.0769	0.0385	0.0370	0.0000	0.0000	0.0000	0.0000	1.0000
X_6	0.2015	0.0435	0.1154	0.1154	0.1154	0.1852	0.0909	0.0000	0.3333	0.0526	0.0000
X_7	0.2015	0.4348	0.5769	0.1538	0.3077	0.0370	0.0909	0.5000	0.0000	0.0526	1.0000
X_8	0.2985	0.0870	0.1154	0.1538	0.0000	0.1111	0.0000	0.0833	0.0000	0.0000	0.0000
X_9	0.0299	0.0435	0.0000	0.0000	0.0000	0.1111	0.0000	0.0000	0.0000	0.0000	0.0000
X_{10}	0.0448	0.0870	0.0769	0.0000	0.0385	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
X_{11}	0.5672	1.0000	0.9231	1.0000	1.0000	0.4444	0.0909	1.0000	0.3333	0.2368	0.0000
X_{12}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0741	0.0000	0.0000	0.0000	0.0000	0.0000
X_{13}	0.0373	0.0000	0.1154	0.0385	0.0000	0.0000	0.0000	0.0833	0.0000	0.0000	0.0000

Table 8 The range values

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X_1	0.0000	0.7826	0.7692	0.1538	0.5769	0.0000	0.0000	0.9167	0.3333	0.3421	0.0000
X_2	0.1716	0.9130	1.0000	0.0385	0.6923	0.5185	0.1818	0.8333	1.0000	0.0000	1.0000
X_3	0.9328	1.0000	0.8077	0.8846	0.4231	0.8148	0.7273	0.9167	0.0000	0.7895	1.0000
X_4	0.4179	0.3913	0.0000	0.5385	0.3077	0.8148	0.9091	0.5000	1.0000	0.9474	0.0000
X_5	0.8955	0.9130	0.9615	0.9231	0.9615	0.9630	1.0000	1.0000	1.0000	1.0000	0.0000
X_6	0.7985	0.9565	0.8846	0.8846	0.8846	0.8148	0.9091	1.0000	0.6667	0.9474	1.0000
X_7	0.7985	0.5652	0.4231	0.8462	0.6923	0.9630	0.9091	0.5000	1.0000	0.9474	0.0000
X_8	0.7015	0.9130	0.8846	0.8462	1.0000	0.8889	1.0000	0.9167	1.0000	1.0000	1.0000
X_9	0.9701	0.9565	1.0000	1.0000	1.0000	0.8889	1.0000	1.0000	1.0000	1.0000	1.0000
X_{10}	0.9552	0.9130	0.9231	1.0000	0.9615	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X_{11}	0.4328	0.0000	0.0769	0.0000	0.0000	0.5556	0.9091	0.0000	0.6667	0.7632	1.0000
X_{12}	1.0000	1.0000	1.0000	1.0000	1.0000	0.9259	1.0000	1.0000	1.0000	1.0000	1.0000
X_{13}	0.9627	1.0000	0.8846	0.9615	1.0000	1.0000	1.0000	0.9167	1.0000	1.0000	1.0000

The correlation coefficient $\xi_i(k)$ between the extreme values and the primary causes of maritime DG transport accidents and between the extreme values and main ship operations is calculated using Equation 10. For instance, the range minimum value $\min_i \min_k |y_0(k)\text{-}y_i(k)|$ is 0, and the range maximum value $\max_i \max_k |y_0(k)\text{-}y_i(k)|$ is 1. The grey correlation coefficient $\xi_1(1)$ of X_1 collision in the A_1 operation of sailing ship will be calculated as follows:

$$\xi_1(1)=\frac{0.0000+0.5\times1.0000}{(1.0000\text{-}1.0000)+0.5\times1.0000}=1.0000$$

All the grey correlation coefficients are calculated in the same way. Tables 8 and 9 display the calculation results.

The entropy weights of main ship operations in Table 6 and the correlation coefficient data in Equation 10 are substituted into Equation 11. Table 10 displays the grey relation degree Γ_i calculation results of different primary causes with different main ship operation weights.

Table 9 The correlation coefficients ξ_i(k) of primary causes and main ship operations

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
X_1	1.0000	0.3898	0.3939	0.7647	0.4643	1.0000	1.0000	0.3529	0.6000	0.5938	1.0000
X_2	0.7444	0.3538	0.3333	0.9286	0.4194	0.4909	0.7333	0.3750	0.3333	1.0000	0.3333
X_3	0.3490	0.3333	0.3824	0.3611	0.5417	0.3803	0.4074	0.3529	1.0000	0.3878	0.3333
X_4	0.5447	0.5610	1.0000	0.4815	0.6190	0.3803	0.3548	0.5000	0.3333	0.3455	1.0000
X_5	0.3583	0.3538	0.3421	0.3514	0.3421	0.3418	0.3333	0.3333	0.3333	0.3333	1.0000
X_6	0.3851	0.3433	0.3611	0.3611	0.3611	0.3803	0.3548	0.3333	0.4286	0.3455	0.3333
X_7	0.3851	0.4694	0.5417	0.3714	0.4194	0.3418	0.3548	0.5000	0.3333	0.3455	1.0000
X_8	0.4161	0.3538	0.3611	0.3714	0.3333	0.3600	0.3333	0.3529	0.3333	0.3333	0.3333
X_9	0.3401	0.3433	0.3333	0.3333	0.3333	0.3600	0.3333	0.3333	0.3333	0.3333	0.3333
X_{10}	0.3436	0.3538	0.3514	0.3333	0.3421	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333
X_{11}	0.5360	1.0000	0.8667	1.0000	1.0000	0.4737	0.3548	1.0000	0.4286	0.3958	0.3333
X_{12}	0.3333	0.3333	0.3333	0.3333	0.3333	0.3506	0.3333	0.3333	0.3333	0.3333	0.3333
X_{13}	0.3418	0.3333	0.3611	0.3421	0.3333	0.3333	0.3333	0.3529	0.3333	0.3333	0.3333

Table 10 Grey relation degree Γ_i values and rankings of the primary causes

Primary Cause	Correlation degree	Ranking
X_1	0.6846	1
X_2	0.5427	4
X_3	0.4642	6
X_4	0.5485	3
X_5	0.4212	7
X_6	0.3624	8
X_7	0.4740	5
X_8	0.3473	9
X_9	0.3361	12
X_{10}	0.3374	11
X_{11}	0.6306	2
X_{12}	0.3344	13
X_{13}	0.3383	10

5. Result and Discussion

The calculation process is implemented in compliance with the research workflow diagram depicted in Figure 2. Tables 4-8 depict the calculation process of the EW and grey correlation coefficient of maritime DG transport accident evaluation. Table 6 depicts the impact of the main ship operation mode on maritime DG transport accidents. The results of the grey correlation calculation for several primary causes are depicted in Table 10. According to the results of Tables 6 and 10, the contributing factors to maritime DG transport accidents can be examined in more detail.

It can be seen from the comparison of different ship operation indicators at maritime DG transport accidents (see Table 6 and Figure 3) that the unberthing's weight is 13.43%, the bunkering's weight is 12.29%, the pilotage's weight is 11.74%, the maneuvering's weight is 11.48%, the mooring's weight is 9.60%, the cargo loading's weight is 8.21%, the cargo unloading's weight is 7.51%, the anchoring's weight is 7.36%, the berthing's weight is 7.25%, the passage's weight is 6.41%, and the sailing's weight is 4.71%. Particularly, unberthing has the highest weight, demonstrating that maritime DG transport accidents happen mainly during this operation. Sailing has the smallest weight, demonstrating the reduced probability of maritime DG transport accident occurrence during this operation.

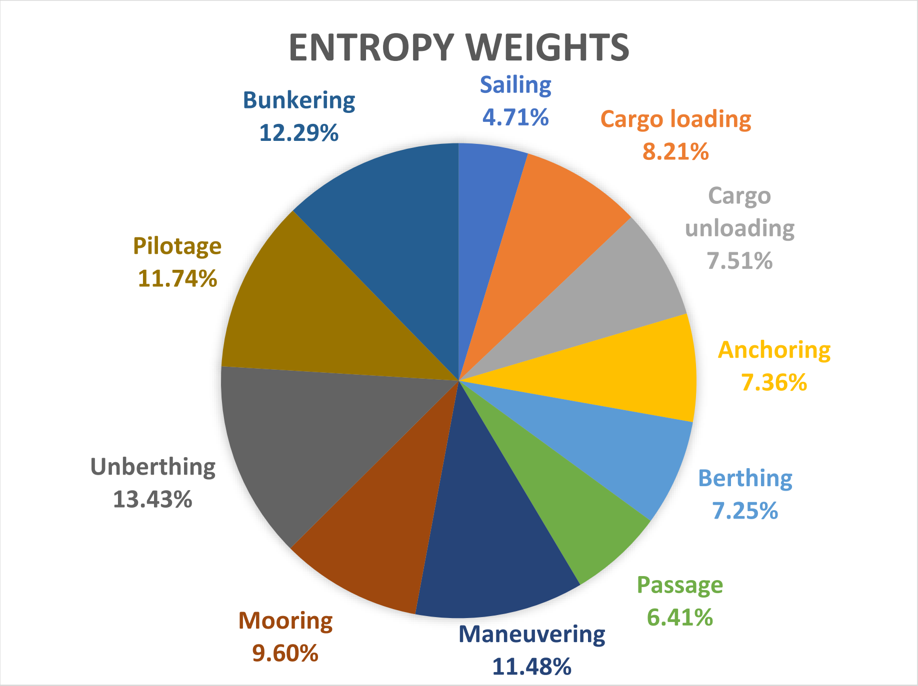

Fig. 3 The weights of main ship operations

Nearly 60% of the entire weight is accounted for by the operations of unberthing, bunkering, pilotage, maneuvering, and mooring, demonstrating a higher probability of maritime DG transport accidents happening during these five operations than during other operations. Stakeholders in maritime DG transport need to handle these five operations with far more caution and seriousness considering this information. In contrast, berthing, passage, and sailing operations constitute fewer than 20% of the whole, demonstrating the reduced probability of maritime DG transport accidents during these operations. Maritime DG shipping companies should establish rational measures for accident prevention. Especially, they should concentrate on the five operation modes of the ships, such as unberthing, bunkering, pilotage, maneuvering, and mooring, to manage and prevent the occurrence of maritime DG transport accidents during these five operations.

The correlation (see Table 10 and Figure 4) of primary causes in the ultimate calculation result indicates that the collision's correlation degree is 0.6846, the occupational accidents' correlation degree is 0.6306, the fire/explosion's correlation degree is 0.5485, the stranding/grounding's correlation degree is 0.5427, the damages to ship or equipment's correlation degree is 0.4740, the contact's correlation degree is 0.4642, the hull failure's correlation degree is 0.4212, the machinery damage's correlation degree is 0.3624, the capsizing/listing’s correlation degree is 0.3473, the unknown factors’ correlation degree is 0.3383, the accidents with life-saving appliances’ correlation degree is 0.3374, the foundering’s correlation degree is 0.3361, and the other factors’ correlation degree is 0.3344. Unobtainable accident information is defined as unknown factors, and other factors encompass stormy weather, rough seas, and piracy. Collision indicates the highest correlation value, demonstrating that collision has the highest degree of influence on maritime DG transport accidents. Other factors occupy the smallest degree of correlation, demonstrating their smallest influence on maritime DG transport accidents. Specifically, collisions and occupational accidents have a greater influence on maritime DG transport accidents. The influence of these causes on maritime DG transport accidents needs to be given great attention. Decision-making bodies should enhance preventative strategies going forward. For maritime DG shipping companies, it is essential to focus on the management of DG transport accidents, particularly to take extra precautions to avoid the influence of key causes.

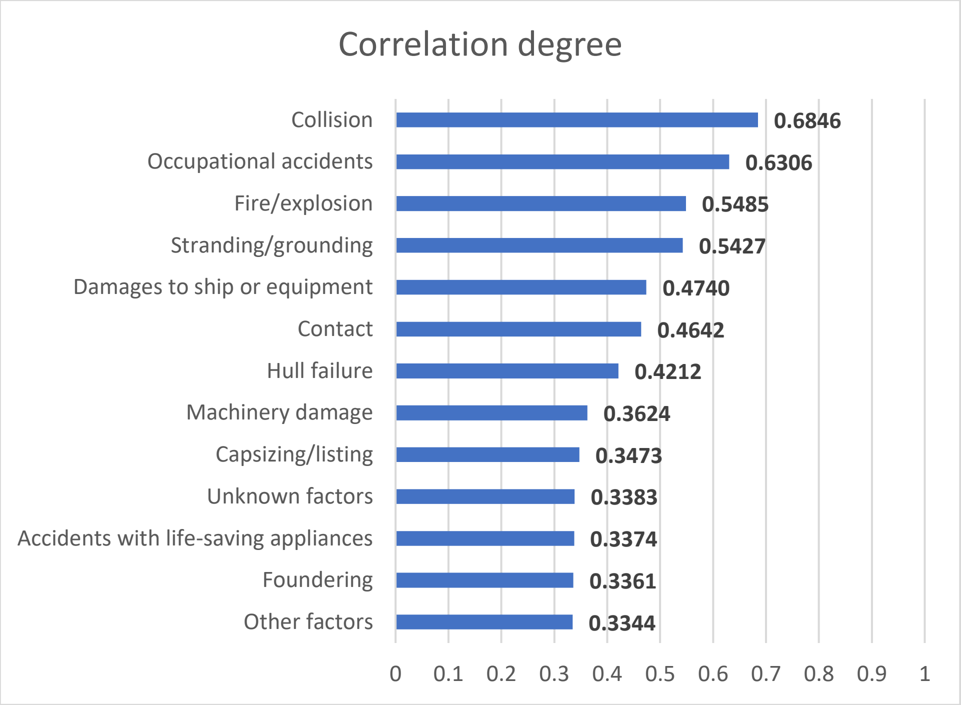

Fig. 4 Correlation of primary causes

Table 9 and Figure 5 depict the correlation coefficients between main ship operations and the primary causes of maritime DG transport accidents. According to Table 9 and Figure 5, collisions during sailing, passage, maneuvering, and bunkering operations, and occupational accidents during cargo loading, anchoring, berthing, and mooring operations are the most likely to cause maritime DG transport accidents.

These results essentially align with those of a few earlier researchers. Collisions are the most prevalent sort of maritime accident [59]. In collision accidents, the human element is the most significant contributing factor [60]. Therefore, several researchers have investigated the human factor in collisions [22, 61-67]. A few scholars have researched the factors that contribute to collision accidents. Chauvin et al. [68] applied the Human Factors Analysis and Classification System to inspect 38 collision accidents. They discovered nine factors that were effective in leading to these accidents. Ship operational factors were the most influential in collision accidents. Ugurlu and Cicek [69] investigated 513 ship collisions. Using fault tree analysis, they investigated 39 key causes of collisions. Maneuvering and perceptual problems were the most critical components of collisions. Furthermore, Chen et al. [15] asserted that an underway ship is the most vulnerable to collisions.

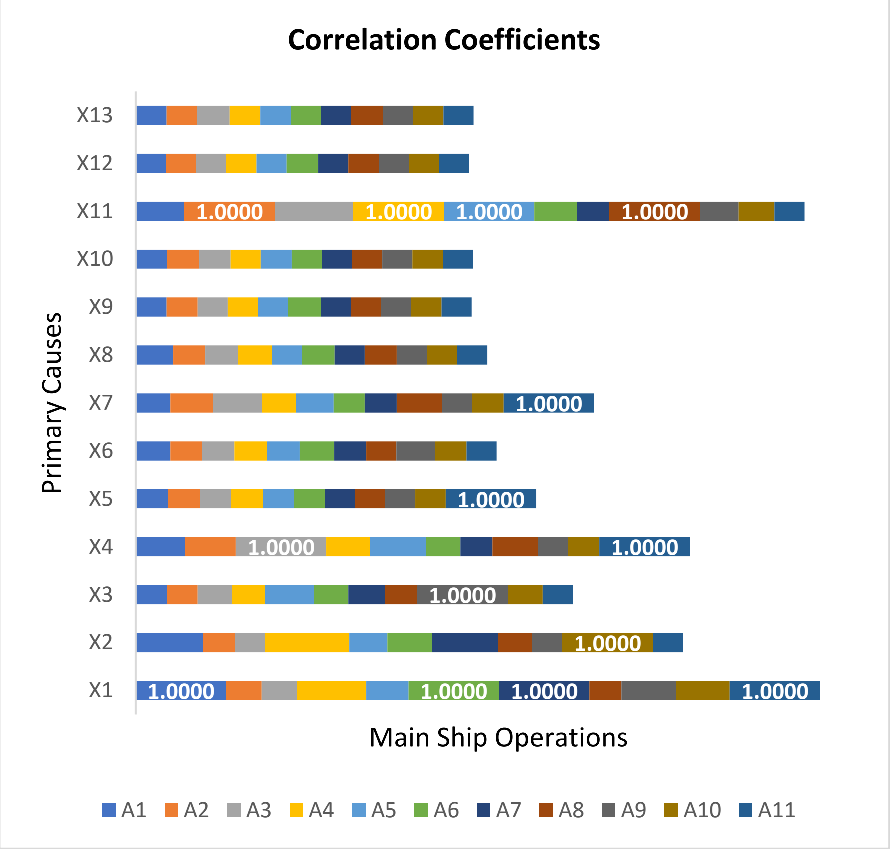

Fig. 5 Correlation coefficients between main ship operations and different primary causes

International and national maritime authorities endeavor in a targeted manner to reduce maritime DG transport accidents. Determining the contributing factors to maritime DG transport accidents is essential to enhancing safety management efficiency. This paper emphasizes that collisions during sailing, passage, maneuvering, and bunkering operations, and occupational accidents during cargo loading, anchoring, berthing, and mooring operations are the most likely to lead to maritime DG transport accidents. Given the working environment and conditions, seafaring is a perilous profession. Fatalities or serious injuries are a potential consequence of occupational accidents occurring during several ship operations [70]. Li and Wonham [71] revealed that occupational accidents accounted for almost 90% of maritime fatalities, and Li [72] concluded that 76% of ship fatalities were the result of occupational accidents. Maritime accidents such as sinkings, collisions, and groundings caused the remaining ship fatalities. On the contrary, many fatalities and injuries happen in port areas because of occupational accidents [73]. Hastiness, inappropriate equipment uses, unqualified staff, insufficient apron sizes and equipment, and violations of regulations and rules may cause occupational accidents during port handling operations [4]. The following measures can be suggested to reduce these accidents:

- Increasing safety training is required to prevent occupational accidents.
- Both seafarers and all shore-based personnel should take IMDG Code refresher training.
- Instead of being considered labor, seafarers should be considered human resources.
- The safety of seafarers' work environments should be improved, and their working conditions should be enhanced.
- It is important for seafarers to avoid working long and exhausting hours.
- The root cause analysis should be performed for occupational accidents.
- It is critical to promote the use of personal protective equipment.
- Rules for occupational health and safety should be strictly enforced.
- The COLREG Rule training should include greater application.

6. Conclusions

To prevent and reduce maritime DG transport accidents, a thorough analysis of the contributing factors is crucial. To that end, the current study offers a combined method that integrates EW and GRA. Depending on the accident investigation reports from 2000 to 2023 obtained from the MCI module of the IMO GISIS database, this paper found thirteen primary causes and eleven main ship operations of maritime DG transport accidents for assessment and created an entropy-weighted grey relational model method for assessing accident-incurring factors. The model method considers the total and dynamic correlation of accident-contributing factors and is simple to calculate, practical, and effective. The main results are as follows:

- Approximately 60% of the entire weight is accounted for by the activities of unberthing, bunkering, pilotage, maneuvering, and mooring, indicating that these five main ship operations are responsible for a significant number of maritime DG transport accidents.
- The higher the correlation, the greater the influence. Maritime DG transport accidents are more significantly impacted by collisions and occupational accidents.
- Particularly, collisions during sailing, passage, maneuvering, and bunkering operations, and occupational accidents during cargo loading, anchoring, berthing, and mooring operations are the most likely to incur maritime DG transport accidents. Stakeholders can enhance effective strategies to reduce these accidents by using these extended results.

A proper evaluation of the contributing factors to maritime DG transport accidents is useful as a scientific basis for stakeholders. The primary innovation in this research is the integration of the EW and GRA methods to examine the contributing factors in maritime DG transport accidents. There are three ways that this study contributes to literature. First, it is an original idea to perform a comprehensive analysis of the contributing factors to maritime DG transport accidents. A thorough analytical framework is constructed to determine the main factors in these accidents. Second, a logical and practical mathematical tool for determining the factors of maritime DG transport accidents is presented in this paper. Third, this paper's results can support the stakeholders in developing strategies and taking preventative measures to lessen maritime DG transport accidents.

Analyzing maritime DG transport accidents using the combination of EW and GRA is a creative endeavor. Nevertheless, this study has various limitations. More ship operations and primary causes can be added to the evaluation model. Beyond that, a more useful and realistic analysis in subsequent research can be obtained by utilizing an integrated evaluation model that incorporates ship types, flag states, accident sites, and ship ages. Additionally, this paper's evaluation model can be enhanced by incorporating a probability method, which would allow it to forecast future trends and factors related to maritime DG transport accidents.

Acknowledgement

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