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Multi-attribute decision-making method for prioritizing maritime traffic safety influence factors of autonomous ships' maneuvering decisions using grey and fuzzy theories

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Abstract

Ships maneuvering decisions are influenced by several factors, and it is essential to prioritize the main influencing factors for efficient selection of the corresponding maneuvering decisions. Meanwhile, the autonomous ships maneuvering decision-making influence factors constitute a typical grey system, which is suitable for research by grey relational analysis. Furthermore, in the fuzzy approach, linguistic assessment of factors is evaluated to obtain priority numbers. Therefore, this study mainly focuses on the concept of human-like maneuvering for ~~the~~ autonomous ships. Based on ~~the~~ experimental data of experienced seafarers ~~in~~ on a simulation platform, in this paper, we proposed a grey and fuzzy theories based inference model combined with the expert linguistic terms to select the ships maneuvering decision-making main influence factors from multi-source influence factors to study the decision-making prioritization for maritime traffic safety in specific ships maneuvering scenarios. This method can mine the main factors which affect maneuvering decisions and guide an autonomous ship-assisted or automatic maneuvering evaluation system for the research of human-like maneuvering behavior. This study provides a new perspective on the identification of main ships maneuvering decision-making influence factors in theory and practice; it can be utilized for better decision-making concerning maritime traffic safety of autonomous ships maneuvering, which in turn makes shipping ~~more~~ safer and promote the application and spreading of autonomous ships.

Keywords: Maritime safety; grey relational analysis; fuzzy logic; autonomous ships; decision-making; quantitative assessment.

1. Introduction

Maritime shipping is the lifeblood of the global economy, transporting approximately 90% of international merchandise trade (ICS, 2018). According to the statistics, there are over 50,000 merchant ships trading internationally (AGCS, 2018), so the safety of vessels is a critical issue in globe seaborne transport. In addition, with the development of computer science and technology, especially the rapid development of technologies and theories such as The Internet of Things (IoT), Information Technology (IT), and Artificial Intelligence (AI), the world merchandise trade is moving in the direction of informatization and intelligence. Thereupon, the study of Autonomous merchant ships has become a "hot" topic internationally, as this would reduce the need for operators/seafarers onboard, and increase maritime transport as a more environmental-friendly alternative to transport by trucks on land. Several large companies have started to test such vessels, for instance, the Advanced Autonomous Waterborne Applications Initiative (AAWA) project Of Rolls-Royce Holdings plc (Rolls-Royce, 2018). In addition, for the shipping industry, Advancements in Network Technology (NT), Information Technology (IT) and Information and Communication Technology (ICT) create new opportunities for developing the electrical systems such as ships autonomous navigation (Perera et al., 2015), Integrated Bridge System (IBS), and decision support system (Pietrzykowski et al., 2017), and the level of shipping modernization has been rapidly improved. The development of autonomous ships has been technically feasible. Moreover, to the technical factors, the world economy is experiencing a period of slow-moving recovery, and shipping industry falls into the long-term overcapacity. Hence the world's major shipping companies have to shift their development planning to improve the operational efficiency and enhance the safety management of their merchant fleet, thus to reduce the seaborne transport costs and adapt to the market tendency. Moreover, the demands of ship owners and seafarers for safety and economy of shipping are constantly increasing; it is also an essential influence factor for the development of autonomous ships.

Furthermore, since the implementation of the international energy conservation and emission reduction rules and regulations promoted the development of autonomous ships, the EU's Monitoring, Reporting and Verification (MRV) regulations for greenhouse gas emissions of the shipping industry took effect on July 1, 2015, and began to monitor emissions according to MRV regulations on January 1, 2018. In addition, all ships larger than 5,000 gross tons and berthed in EU ports are required to meet MRV regulations. Moreover, the International Maritime Organization (IMO) will also begin emissions monitoring under the Ship Energy Efficiency Management Plan (SEEMP) on January 1, 2019 (IMO, 2018). Besides, the number of seafarers in the world is declining recently, while the wages of seafarers are rising year by year, which has become the second largest expenditure item after the fuel costs of shipping (Lun et al., 2016). At the same time, maritime accidents frequently occur, for instance, there were 2712 reported shipping incidents (casualties) in 2017 (AGCS, 2018), and hull collisions and damages caused by personnel errors account for more than 80% of marine accidents (Hanzu-Pazara et al., 2008; Rothblum, 2000). In addition, the safety of the seafarers in extreme sea conditions in recent years has also become a problem that cannot be ignored (Wang et al., 2014).

In summary, as autonomous ships have outstanding advantages in improving operational efficiency, safety management, decision-making efficiency, and energy consumption management of ships, therefore, the researches for autonomous ships have become an inevitable tendency for future ship development, and gained the interest of many researchers in both academia and private sectors (Goerlandt and Montewka, 2015). Furthermore, although the control technology of ships has gradually begun to change from traditional electromechanical control to the trend of networking, digitization, and automation, moreover, the ship-handling process has become a multi-functional integrated system integrating multiple automation systems, which improves the safety, economy and management efficiency of the shipping. However, the improvement of the degree of automation of ships has a certain gap from the ships with automatic perception, subjective analysis, and autonomous decision-making.

The accuracy of ships maneuvering decisions is directly related to the safety of water traffic. The seafarers onboard vessels, especially the officer on watch (OOW), often perform duties in circumstances where technological, environmental factors, etc., emerge which may lead to the occurrence of human failures and marine accidents (Ugurlu et al., 2015). Likewise, in the process of autonomous ships human-like decision-making, the OOW maneuvering decision-making is also stimulated and influenced by multi-source information, for instance, the other ships in waterways and ports, the natural environmental factors, etc. (Kim et al., 2017), this requires ships maneuvering decision-making procedures expressed along with higher effectiveness. However, due to the limited capacity of information processing, the OOW cannot concurrently achieve knowledge acquisition of the multi-attribute or multi-source information in a certain time and space, thus maneuvering decisions cannot be carried out accurately and quickly, which could lead to water traffic accidents. Furthermore, under high-intensity work pressure, the OOW cannot always ensure to make correct decisions timely when facing constantly changing factors in different navigation scenarios. In addition, the decision mechanisms of different maneuvering behavioral patterns and the execution mechanisms of ships operating modes are two important steps in simulating task aggregation and multi-source information stimulation. Therefore, the automatic acquisition and representation of maneuvering decision-making are essential in ensuring accurate and rapid maneuvering decisions and water traffic safety, moreover, it is also essential to identify, analysis, and prioritize the main maritime traffic safety influencing factors for efficient selection of autonomous ships from the multi-attribute or multi-source information for corresponding maneuvering decisions.

Multi-attribute decision-makings have broad applications in society, economics, military, and engineering technology. As the complexity and uncertainty of decision problems and decision environment, most of the multi-attribute decision-making problems are uncertain and fuzzy, so fuzziness is an important factor to be considered in actual decision-making (Jin and Liu, 2010). In addition, in dealing with the problems with poor information, the decision problems have also shown the characteristics of grey. Therefore, the actual decision-making problems are often fuzzy and grey, which is called the grey fuzzy multiple attribute decision-making problems (Liu et al., 2015). The grey system theory, proposed by Professor Julong Deng (Julong, 1982, 1989), is one of the most widely utilized models of grey system theory. As an effective pattern recognition method, it is mainly utilized to analyze the proximity of the dynamic grey process development situation, determine the primary and secondary factors in the grey system, and control the main factors affecting the system (Huang et al., 2013). Specifically, the Grey Relational Analysis (GRA) is suitable for data with uncertain, multi inputs and discrete properties; it does provide techniques for determining an appropriate solution for real-world problems. The research object of the grey system theory is the uncertain system that “partial information is known and some information is unknown”. Through the research on some known information, the system can be accurately understood (Liu and Forrest, 2010). The GRA method does not require too much sample size and does not require a typical distribution law during analysis. In addition, the GRA method could capture the impact of the relationship between the main factor and influencing factors in the system regardless of whether the system has adequate information (Julong, 1989; Shen and Du, 2005). The results are corresponding to the qualitative analysis results, so the method has wide practicality (Chen and Ting, 2002; Julong, 1989). As a systematic analysis technique, the grey correlation analysis is a quantitative comparative analysis method, by calculating the correlation between the target value and the influencing factors, and the ranking of the relevance, the main factors affecting the target value are sought (Julong, 1982; Liu et al., 2010). After more than twenty years of development, the grey system theory has penetrated many scientific research fields and has been confirmed and developed. It provides a new insight into to solve system problems in the case of poor information (Li, 1996). In order to analyze the system behavior of grey systems with uncertain information, the grey system theory develops a series of comprehensive analysis methods of grey systems, such as GRA (Lee et al., 2018; Rajesh et al., 2013). It is applied to many research domains, for example, it was adapted to study the research output and growth of countries (Javed and Liu, 2017), and it has also been used to effectively study air pollution (Pai et al., 2013) and subsequently utilized to investigate the nonlinear multiple-dimensional model of the social economic activities' impact on the city air pollution (Li et al., 2017). Lu et al. utilized GRA to evaluate the problem of road traffic safety measures (Lu et al., 2010). Kelvin et al. proposed a grey model-based smoothness predictions; the results showed that the model provides promising results and is useful for evaluating the riding quality of pavement performance (Wang et al., 2007). Lu applied a mathematical approach and GRA to analyze the traffic and transport situation trends in China and investigate the potential solutions for enhancing road traffic safety (Lu et al., 2010). Rajesh et al. introduced the optimization steps to investigate the effects of different operations in the Computer Numerical Control (CNC) machine by using the GRA with entropy (Rajesh et al., 2013). Hatefi and Tamošaitienė proposed a novel fuzzy analytic hierarchy process (AHP) and improved grey relational analysis (GRA) method to assess construction projects based on the sustainable development criteria in economic, social, and environmental dimensions using experts' opinions (Hatefi and Tamošaitienė, 2018). Lilly Mercy et al. developed a multi-response optimization algorithm to study the mechanical properties in self-healing glass fiber reinforced plastic using grey relational analysis; the results showed that lesser microcapsule size and concentration with medium catalyst concentration gave better mechanical properties (Lilly Mercy et al., 2017).

The grey relational analysis (Fu et al., 2017; Hao et al., 2017; Lilly Mercy et al., 2017; Rajesh et al., 2013) is an effective algorithm used to resolve uncertainty issues, under discontinuous and partial information (Julong, 1982). However, the traditional GRA has been largely criticized for the reason that it treats different indexes (influence factors) equally and takes no account of the relative importance of them. It does not fit with people's preference for specific index. Furthermore, the fuzzy logic theory has been regarded as being a beneficial method for modeling processes which are too complicated for conventional quantitative analysis or when available information from the process is qualitative, uncertain or inexact (Balin et al., 2018; Tseng and Cullinane, 2018; Zadeh, 1983; Zhou and Thai, 2016a). Moreover, fuzzy numbers are more compatible with phrases and ambiguities; it is better to utilize them in decisions in the real world and reflect human thoughts (Hatefi and Tamošaitienė, 2018). In maritime domain, many studies using fuzzy theories have been implemented. For instance, Zhou and Thai utilized fuzzy and grey theories to evaluate the failure modes and analyze the effect for tanker equipment failure prediction, the priority ranking results show that both fuzzy theory and grey theory are quite similar and the proposed fuzzy and grey Failure Mode and Effects Analysis (FMEA) method is more practical and flexible for risk evaluation for tank shipping (Zhou and Thai, 2016b). Senlo and Sahin used defuzzification process of fuzzy logic to transform the fuzzy numbers from Crisp Failure Possibility (CFP) to Fault Probability (FP), thus, proposed a real-time continuous fuzzy fault tree model for dynamic environment analysis of ship collision and grounding (Senol and Sahin, 2016). Balmat et al. applied a novel fuzzy technique to evaluate maritime risk assessment of the pollution prevention on the open sea based on the decision-making system named MAritime RISk Assessment (MARISA) (Balmat et al., 2011). Yang and Wang developed a approach for analyzing engineering system risks on the basis of a generic Fuzzy Evidential Reasoning (FER) method, and the approach was applied to model the safety of an offshore engineering system, then the failure criticality analysis is carried out in a collision of a Floating, Production, Storage, and Offloading (FPSO) system with a shuttle tanker during tandem offloading operations (Yang and Wang, 2015). Celik et al. proposed a risk-based modeling algorithm based on the fuzzy extended fault tree analysis to enhance the execution process of shipping accident investigation; this approach allows accident investigators to clarify the probability of technical failures, operational misapplications, and legislative shortages leading to the shipping accident (Celik et al., 2010). Ung developed a novel fuzzy Cognitive

Reliability and Error Analysis Methods (CREAM) methodology considering the weight of each Common Performance Condition (CPC), and validated the method using two axioms and demonstrated by the case of an oil tanker (Ung, 2015). Zhou et al. introduced a fuzzy and Bayesian network model for the quantitative analysis of human reliability for the tanker shipping industry; the results show that the proposed model is very promising and is consistent with the original CREAM approach (Zhou et al., 2018). Similarly, Zhou et al. also proposed a quantitative CREAM method to estimate the human error probability in tanker operational safety using Fuzzy Analytic Hierarchy Process (FAHP) to establish a fuzzy congruous matrix (Zhou et al., 2017). Wu et al. developed a fuzzy multiple attribute decision-making approach to select the site of offshore wind farm in the busy waterway of the Eastern China Sea, the proposed method considered the economic feasibility of installation and maritime safety and determined an optimal site selection scheme for the wind farm (Wu et al., 2018).

Although variety of previous studies in academia have been conducted upon impact factors assessment based on the grey and fuzzy theories, they seldom take into consideration the relative importance of different influence factors (just consider different influence factors in the same weight) and in the absence of expertise; just consider the same weight to determine the judgments from different experts; just use the standard fuzzy number functions to evaluate the linguistic terms given from experts. However, the standard fuzzy membership function sometimes cannot determine different linguistic terms from different domain experts reasonably, on some specific situation, it treats different indexes, specifically, the same linguistic term from different domain experts, equally. In our research, the autonomous ship human maneuvering decision factors constitute a typical “grey system”. Besides, the fuzzy numbers of the domain experts are utilized to optimize our proposed model. Therefore, it is suitable to study with GRA method and fuzzy theories. The maritime traffic safety influence factors of autonomous ships maneuvering decision-making, such as the factors of forces parameters, draft, environment, motion, and position, etc., are obtained using the data from the simulation platform. After collecting the judgment knowledge from domain experts, the Delphi method was utilized for comprehensive determining the fuzzy numbers of different linguistic terms combined with different weights of each domain expert. Finally, the novel improved GRA and fuzzy theories based model is proposed for analyzing the final weights and rankings of the influence factors. With computer assistance, the algorithm/model proposed in this paper permits an automatic conversion from the comparative series of maritime traffic safety influence factors and the corresponding maneuvering decisions (the combination of ship telegraph and rudder order) reference series to autonomous ships maneuvering influence factors analysis system.

The remainder of this paper is organized as follows. Firstly, section 2 briefly presents the grey relational analysis and fuzzy theories, describes the specific steps of our proposed model. Secondly, the experimental processes are introduced in Section 3. Thirdly, section 4 details the results of our experiment. Fourthly, the discussions of the results are represented in section 5. Finally, the conclusions are addressed in Section 6.

2. Methodology

This paper utilized the gray and fuzzy theories combined with quantitative and qualitative analysis, and comprehensively evaluates the maritime traffic safety influence factors of autonomous ships maneuvering decisions. On the one hand, it can conduct the problems of imprecise and uncertainty. On the other hand, by giving various weights of different experts can make more rational use of expert knowledge for judging the prioritization of the influence factors. Furthermore, the evaluation results of the specific criteria of different experts on each linguistic term will be more accurate and reasonable by comprehensively utilizing the fuzzy numbers. The specific method is introduced below.

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2.1. Grey relational analysis

Professor J. Deng proposed the grey system theory in 1982 (Julong, 1982, 1989), and then came the concept of a grey set. If white represents completely clear data/information and black represents completely unknown data/information, grey is other data/information that known partially. If a system contains grey information, so it can be called a grey system, Grey system theory is especially suitable for data with multi inputs, uncertain, and it can be utilized to resolve uncertainty issues, under discontinuous data and partial information effectively. A typical grey system concept is shown in Fig.1.

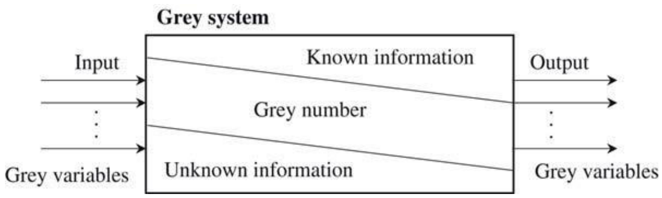

Fig.1. The concept of the grey system.

Grey relational analysis is an analytical method based on the microscopic or macroscopic geometric approach to determine the influence degree between factors or the contribution of factors to the primary system. It is mainly the analysis of a development situation, that is, the quantitative analysis of the dynamic development process of a system, which is represented by the proximity of the geometric shape of the curve, judging by the degree of correlation.

In addition, the GRA can also be regarded as a dynamic quantitative comparison procedure of the relative changes in the factors between/in systems over time. It is usually used to analyze the geometry of the time series curve, and measure the degree of correlation between them by the proximity of their size, direction, and speed.

Grey relational analysis has the characteristics of asymmetry, non-uniqueness, and orderliness, etc. The correlation analysis is essentially the analysis and comparison of the geometric curve graphs associated with the original data, that is, the closer the collection graphs are, the closer their development trends are, then the greater the correlation between them is. Therefore, the reference series should be determined first, and then the geometric similarity between the other series and the curve formed by the reference series should be compared to determine the degree of correlation between the comparative series and the reference series. Before analyzing the degree of correlation, it is necessary to determine the data series, adopt the most suitable data series according to the characteristics of the system, and then calculate the relational coefficient according to the relational grade equations based on the data series.

2.2. Fuzzy sets

Fuzzy logic is a type of many-valued logic in which the truth values of variables considered to be “fuzzy” may be any real number within the unit interval [0,1] (Novk et al., 1999). It is an efficient method for design a decision- making system, and it can be used to solve the problems related to conducting the imprecise and uncertain data (Balmat et al., 2011). Wang et al. (2009) introduced a fuzzy set is a collection of elements in the information world, where the boundary of the set contained is ambiguous, vague and otherwise fuzzy. A membership function specifies and assigns a value between 0 and 1 in the usual case to each element in the universe of discourse. The assigned value is called a membership degree, which specifies the extent to which a given element belongs to the fuzzy set. For instance, if an assigned value is 1, that means the element belongs to the set definitely; if an assigned value is 0, that means the element does not belong to the set. Besides, if the value is within the interval (0, 1), then the elements are just a part of the set. Therefore, any fuzzy set can be uniquely determined by its membership.

Fuzzy numbers are cases of fuzzy sets, and the most commonly used fuzzy numbers are triangular and trapezoidal fuzzy numbers. In addition, the triangular fuzzy numbers have the advantages of promoting representation and processing imprecise information due to its computational simplicity (Pedrycz, 1994). The triangular membership functions are shown in Fig. 2, and respectively defined as follows:

$$\mu_A(X)=\begin{cases} 0, & x<a \\ (x-a)/(b-a), & a\le x\le b \\ (c-x)/(c-a), & b\le x\le c \\ 0, & x>c \end{cases} \tag{1}$$

Zadeh proposed the fuzzy sets in 1965 (Zadeh, 1965), and it provides a useful mathematical tool for reliability analyses and system vagueness and uncertainty (Zadeh, 1983). In practical applications, linguistic estimations are converted into fuzzy numbers using fuzzy membership functions for quantitative evaluation.

Assume $\tilde{a}=(a_1,a_2,a_3)$ and $\tilde{b}=(b_1,b_2,b_3)$ are two triangular fuzzy numbers, then the basic fuzzy arithmetic operations with these fuzzy numbers are defined as follows (Wang et al., 2009)

Addition: $\tilde{a}+\tilde{b}=(a_1+b_1,a_2+b_2,a_3+b_3)$;

Subtraction: $\tilde{a}-\tilde{b}=(a_1-b_1,a_2-b_2,a_3-b_3)$;

Multiplication: $\tilde{a}\times\tilde{b}=(a_1\times b_1,a_2\times b_2,a_3\times b_3)$;

Division: $\tilde{a}\div\tilde{b}=(a_1\div b_1,a_2\div b_2,a_3\div b_3)$.

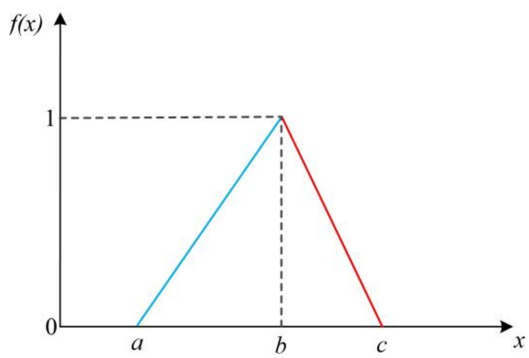

Fig. 2. Triangular membership functions.

2.3. The Proposed Model

Nomenclature	
X	a grey relation factor set (discrete series)
X_0	a reference series
X_i	the comparative series
$X_0^{'}$	the processed reference series
$X_i^{'}$	the processed comparative series

S_0	the standard deviation of the reference series
S_i	the standard deviation of the comparative series
$X^{'}$	the original data series
ω	the number of influence factors plus one
$\Delta_i(k)$	the absolute value of the difference between the reference series and each sub-series at each point
$\Delta_i(\max)$	the first-level maximum range
$\Delta_i(\min)$	the first-level minimum range
$\Delta_{\max}$	the second-level maximum range
$\Delta_{\min}$	the second-level minimum range
$\xi_i(x_0(k), x_i(k))$	the correlation coefficient between the comparative series X_i and the reference series X_0 at point k
ρ	the resolution ratio
$A=(a,b,c)$	the triangular fuzzy number corresponding to the linguistic term
β_i	the relative weights of the experts
A(X)	the crisp value
$\mu_A(x)$	the membership function for linguistic terms from the judgments of domain experts
γ_i	the grey relational grade
λ_k	the weight of each influence factor
$\lambda_i(x_0(k), x_i(k))$	the relational grade between the reference series and comparative series

Step 1 - Data preprocessing

Since there are differences in the dimension and magnitude of each factor in the ship's maneuvering decision system. In order to facilitate data processing, the original data needs to be standardized, the dimension or the order of magnitude needs to be eliminated, and the data series need to be transformed into a comparative series due to the inconsistent dimension of various factors.

Assume X is a grey relation factor set (discrete series), $X_0 = \{x_0(k) \mid k = 1, 2, \cdots, m\}$ as a reference series, representing the ships maneuvering decisions, which is the combination of ship Telegraph and Rudder Order (TRO) in the research (see Fig. 8). $X_i = \{x_i(k) \mid k = 1, 2, \cdots, m\} (i = 1, 2, \cdots, n)$ as comparative series, representing the influence factors, such as wind, current, and waves. Thus, the correlation mechanisms of the reference series and comparative series can be utilized to recognize the influential mechanism of four type of different factors (ship motion, natural environment, forces parameters, and draft & position, shown in Table 3) for autonomous ships maneuvering.

In the analysis and calculation process of the GRA, there are three methods for the non-dimensionalization of the original data, namely, equalization, initialization, and standardization.

Equalization First, the average value of each series is calculated separately, and then the original data in the corresponding series is divided by the average value, that is, the new data column obtained by the mean transformation.

$$X_0' = \left\{ nx_0(k) / \sum_{k=1}^{m} x_0(k) \mid k = 1, 2, \cdots, m \right\} \quad (2)$$

$$X_i' = \left\{ nx_i(k) / \sum_{k=1}^{m} x_i(k) \mid k = 1, 2, \cdots, m \right\} (i = 1, 2, 3, \cdots, n) \quad (3)$$

Initialization The data of the same series is divided by the subsequent original data to obtain new multiple series, which is an initial valued series.

$$X_0' = \{ x_0(k) / x_0(1) \mid k = 1, 2, \cdots, m \} \quad (4)$$

$$X_i' = \{ x_i(k) / x_i(1) \mid k = 1, 2, \cdots, m \} (i = 1, 2, 3, ..., n) \quad (5)$$

Standardization Firstly, the average value and standard deviation of each trait are respectively determined, and then the original data is subtracted from the average value and then divided by the standard deviation so that the new data column obtained is the standardized series.

$$X_0' = \left\{ x_0(k) \text{-} \frac{1}{m} \sum_{k=1}^{m} x_0(k) / S_0 \mid k = 1, 2, \cdots, m \right\} \quad (6)$$

$$X_i' = \left\{ x_i(k) \text{-} \frac{1}{m} \sum_{k=1}^{m} x_i(k) / S_i \mid k = 1, 2, \cdots, m \right\} (i = 1, 2, 3, ..., n) \quad (7)$$

where X'_0 is a non-dimensionalized reference series; X'_i is a dimensionless comparative series; S_0 and S_i are the standard deviation of the reference series and the comparative series, respectively.

The original data series can be described by:

$$X' = \begin{pmatrix} X_0' \\ X_1' \\ X_2' \\ \vdots \\ X_\omega' \end{pmatrix} = \begin{bmatrix} x_{01}' & x_{02}' & \cdots & x_{0m}' \\ x_{11}' & x_{12}' & \cdots & x_{1m}' \\ x_{21}' & x_{22}' & \cdots & x_{2m}' \\ \vdots & \vdots & \ddots & \vdots \\ x_{\omega 1}' & x_{\omega 2}' & \cdots & x_{\omega m}' \end{bmatrix} \Rightarrow \begin{bmatrix} \text{TRO} \\ \text{Influence Factor 1} \\ \text{Influence Factor 2} \\ \vdots \\ \text{Influence Factor } (\omega\text{-1}) \end{bmatrix} \quad (8)$$

where ω is the number of influence factors plus one (the ships maneuvering decision-making factor TRO).

Step 2 - Range analyzing

First, calculate $\Delta_i(k)$, that is, the absolute value of the difference between the reference series and each sub-series at each point:

$$\Delta_i(k) = \left| x_0(k) - x_i(k) \right| \quad (9)$$

among them, $k=1,2,\cdots,m$, $i=1,2,\cdots,n$.

Then find the two-level maximum range and the two-level minimum range. First, calculate the first-level maximum range and the first-level minimum range:

$$\Delta_i(\max)=\max_k \Delta_i(k) \tag{10}$$

$$\Delta_i(\min)=\min_k \Delta_i(k) \tag{11}$$

Then calculate the second-level maximum range:

$$\Delta_{\max}=\max_i \max_k \Delta_i(k) \tag{12}$$

Similarly, the second-level minimum range is calculated:

$$\Delta_{\min}=\min_i \min_k \Delta_i(k) \tag{13}$$

Step 3- Relational coefficient calculating

The relational coefficient is used to measure the geometric difference between the comparative series and the reference series at each point. The relational coefficient of X_i to X_0 is:

$$\xi_i(x_0(k),x_i(k))=\frac{\Delta_{\min}+\rho\cdot\Delta_{\max}}{\Delta_i(k)+\rho\cdot\Delta_{\max}} \tag{14}$$

where $\xi_i(x_0(k),x_i(k))$ represents the correlation coefficient between the comparative series X_i and the reference series X_0 at point k; ρ is a resolution ratio, in $(0,1)$, if ρ is small, the greater the difference between the relationship coefficient, the stronger the ability to distinguish, and ρ usually takes a value of 0.5 (Wang et al., 2014). $k=1,2,\cdots,m$, $i=1,2,\cdots,n$.

Step 4 – Fuzzy membership functions of linguistic terms establishing

The traditional GRA has been largely criticized for the reason that it treats different indexes (influence factors) equally and takes no account of the relative importance of them. It does not fit with people's preference for a specific index. To overcome this drawback, the relative importance weights of the influence factors are considered in this paper, but they are not easy to be precisely determined. Moreover, in many situations, the information and experts' expertise are uncertain or vague. However, fussy sets provides a useful mathematical tool for directly working with the linguistic expression in reliability analyses (Lin and Wang, 1997; Page and Perry, 1994), and fuzzy numbers are more compatible with phrases and ambiguities, it is better to utilize them in decisions in the real world and reflect human thoughts (Hatefi and Tamošaitienė, 2018). Therefore, we utilize fuzzy numbers of the domain experts to optimize our proposed model. And the information of four domain experts is listed as follows:

•**Expert No.1**: An experienced captain with more than 15 years of experience on the operation of board ships (classes of certificates: class A, ≥ 3000 gross tons, unlimited voyages).

•**Expert No.2**: A professor engaged in maritime research for more than ten years with particular reference to the ship operations.

•**Expert No.3**: A senior officer in charge of safety management of port operations of Yangtze River Three Gorges Navigation Authority.

•**Expert No.4**: A senior officer in charge of safety regulation of Shanghai Port from China Maritime Safety Administration.

The triangular fuzzy number, corresponding to linguistic terms, can be determined from domain expert knowledge and experience based Delphi method (Ishikawa et al., 1993). Assuming that there are *n* experts, the *i*-th expert are assigned with the relative weights β_i (*i*= 1,. . . ,m), satisfying $\sum_{i=1}^{m}\beta_i = 1$ and β_i > 0 for *i* = 1,. . . ,m. And the fuzzy judgment linguistic term for the specific influence factors is $x_i = (a_i, b_i, c_i)$, then according to the expert' judgment, the triangular fuzzy number $A = (a, b, c)$ corresponding to the fuzzy linguistic term of the variable can be summarized according to Eq. (15) to Eq. (17).

$$a = \sum_{i=1}^{n}\beta_i a_i \tag{15}$$

$$b = \sum_{i=1}^{n}\beta_i b_i \tag{16}$$

$$c = \sum_{i=1}^{n}\beta_i c_i \tag{17}$$

This study defines the maritime traffic safety influence factors of autonomous ships maneuvering using five linguistic terms, namely, Very Low (VL), Low (L), Medium (M), High (H), Very High (VH). Different from each linguistic term utilized in the same separation distance, for instance, the corresponding midpoint or the *b* in triangular fuzzy number *A* of each linguistic term Very Low (VL), Low (L), Medium (M), High (H), Very High (VH) is 0, 0.25, 0.5, 0.75, 1, respectively (Wang et al., 2009; Wu et al., 2018). In this research, the triangular fuzzy number of different linguistic terms is determined by the domain expert knowledge, and the weight of each expert is taken into consideration, as shown in Table 1. Hence, the fuzzy membership function of each linguistic term can be represented more rationally because we take into account the different evaluation criteria of each expert for various linguistic terms comprehensively. Fuzzy membership degrees of quantitative indexes can be obtained from Fig. 3. Experts are invited to define the triangular fuzzy number of each linguistic term based their judgment, then the triangular fuzzy numbers of different linguistic terms are calculated through Eq. (15) to Eq. (17), and the results are shown in Table 1.

Table 1 Triangular fuzzy numbers of different linguistic terms.

Expert No.	**Weights(β_i)**	**Triangular fuzzy numbers of different linguistic terms**				
		Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
1	0.30	(0, 0, 0.25)	(0, 0.25, 0.50)	(0.25, 0.50, 0.75)	(0.50, 0.75, 1)	(0.75, 1, 1)
2	0.25	(0, 0, 0.20)	(0, 0.20, 0.40)	(0.20, 0.40, 0.60)	(0.40, 0.60,0.80)	(0.80, 1, 1)
3	0.20	(0, 0, 0.25)	(0.10, 0.30, 0.50)	(0.30, 0.50, 0.70)	(0.70, 0.90, 1)	(0.90, 1, 1)
4	0.25	(0, 0, 0.30)	(0.20, 0.40, 0.50)	(0.30, 0.50, 0.65)	(0.60, 0.70, 0.90)	(0.85, 1, 1)
Total	1	(0, 0, 0.25)	(0.07, 0.29, 0.48)	(0.26, 0.48，0.68)	(0.54, 0.73, 0.93)	(0.82, 1, 1)

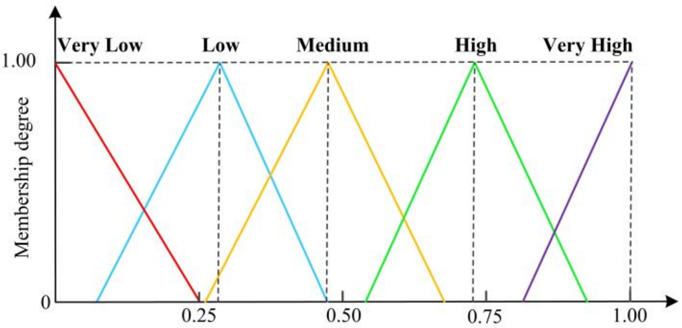

Fig. 3. Triangular membership functions of different linguistic terms.

The specific process of utilizing fuzzy logic of this step is as follows:

(i) The maritime traffic safety influence factors of autonomous ships maneuvering decisions are evaluated by the experts using the linguistic terms defined in Table 1;

(ii) The linguistic terms based the judgments of domain expert are represented by the triangular fuzzy numbers, then the comprehensive evaluation fuzzy set of the weight of each influence factor is established;

(iii) The relative weights β_i for each domain expert are taken into consideration. Specifically, the relative weights of experts are assigned based on their experience with the following relative weights: 0.30, 0.25, 0.20, and 0.25, respectively, then the optimized comprehensive evaluation fuzzy set is obtained ;

(iv) The comprehensive evaluation weight of each influence factor of autonomous ships maneuvering decisions is calculated.

Step 5 – Defuzzification

The linguistic terms from the judgments of domain experts need to be converted into crisp values before further calculation. In other words, the fuzzy numbers need to be transformed into crisp numbers for priority ranking or comparison purpose, this process of transformation is called defuzzification. The defuzzification of fuzzy numbers is an important process, and it is the basis of applying the grey relational theory. Defuzzification can be conducted in many different ways, such as max criterion, center of gravity (COG), mean of maximum (MOM) methods, etc (Akyuz et al., 2016; Balmat et al., 2011; Braae and Rutherford, 1978; Lee, 1990; Senol and Sahin, 2016)

The center of gravity (COG) method, which also is known as center of area (COA), is the most extensively used technique developed by Sugeno (Sugeno, 1999) as it is relatively accurate and takes the total output distribution into consideration (Patel and Mohan, 2002). Hence, the COG method can yield a better steady-state performance (Lee, 1990). This COG method can be articulated as a centroid defuzzification approach finding the center of gravity point of the fuzzy set, on the fuzzy interval (Kumar et al., 2018).

The linguistic terms from the judgments of domain experts for maritime traffic safety influence factors of autonomous ships maneuvering decisions can be defuzzified according to the fuzzy membership function; the crisp number can be calculated as follows:

$$A(X) = \frac{\int_X x\mu_A(x)dx}{\int_X \mu_A(x)dx} \tag{18}$$

Where A(X) denotes the crisp value, x is the output variable, and $\mu_A(x)$ is the membership function for linguistic terms from the judgments of domain experts, as shown in Fig. 3.

Specifically, the defuzzification of a triangular fuzzy number based the Eq. (18) can be calculated as follows:

$$A(X)=\frac{\int_a^b x\frac{x-a}{b-a}dx+\int_b^c x\frac{c-x}{c-b}dx}{\int_a^b \frac{x-a}{b-a}dx+\int_b^c \frac{c-x}{c-b}dx}=\frac{1}{3}(a+b+c) \quad (19)$$

Then, we can get a crisp number of different linguistic terms as shown in Table 2.

Table 2 The crisp number of different linguistic terms.

Name	**The triangular fuzzy number and crisp number of different linguistic terms**				
Linguistic term	Very Low (VL)	Low (L)	Meium (M)	High (H)	Very High (VH)
Fuzzy number	(0, 0, 0.25)	(0.07, 0.29, 0.48)	(0.26, 0.48, 0.68)	(0.54, 0.73, 0.93)	(0.82, 1, 1)
crisp number	0.0833	0.2800	0.4733	0.7333	0.9400

Step 6 - Relational Grade Ranking

Calculating the traditional grey relational grade according to the Eq. (20):

$$\gamma_i=\frac{1}{m}\sum_{k=1}^{m}\xi_i(x_0(k),x_i(k)) \quad (20)$$

where $k=1,2,\cdots,m$, $i=1,2,\cdots,n$.

Since the influence degree is various from each maritime traffic safety influence factor of autonomous ships maneuvering decisions, assuming that the weight of each influence factor is λ_k, then the relational grade between the reference series and comparative series can be obtained by the Eq. (21):

$$\lambda_i(x_0(k),x_i(k))=\sum_{k=1}^{m}\lambda_k(\xi_i(x_0(k),x_i(k)) \quad (21)$$

where $\sum_{k=1}^{m}\lambda_k=1$, λ_k can be determined by fuzzy sets based the domain expert knowledge.

When determining the relational grade, each sub-series of Y1~Y33 is compared to the reference series of TRO. Hence, the relationship between each sub-series and the reference series is sorted. Thereby, the main maritime traffic safety influence factors of the autonomous ships maneuvering decisions in the specific navigational scenario are prioritized and identified.

The framework of our proposed model is shown graphically in Fig. 4, it briefly illustrate the maritime traffic safety influence factors of autonomous ships maneuvering decisions prioritizing procedure of the proposed GRA and fuzzy theories based methodology. The right-hand part of Fig. 4 shows the steps of obtaining the weights for different influence factors; the middle part presents the process of applying the traditional GRA theory, while the left-hand part provides the priority ranking and analyzing procedure of the maritime traffic safety influence factors analysis system for autonomous ships maneuvering.

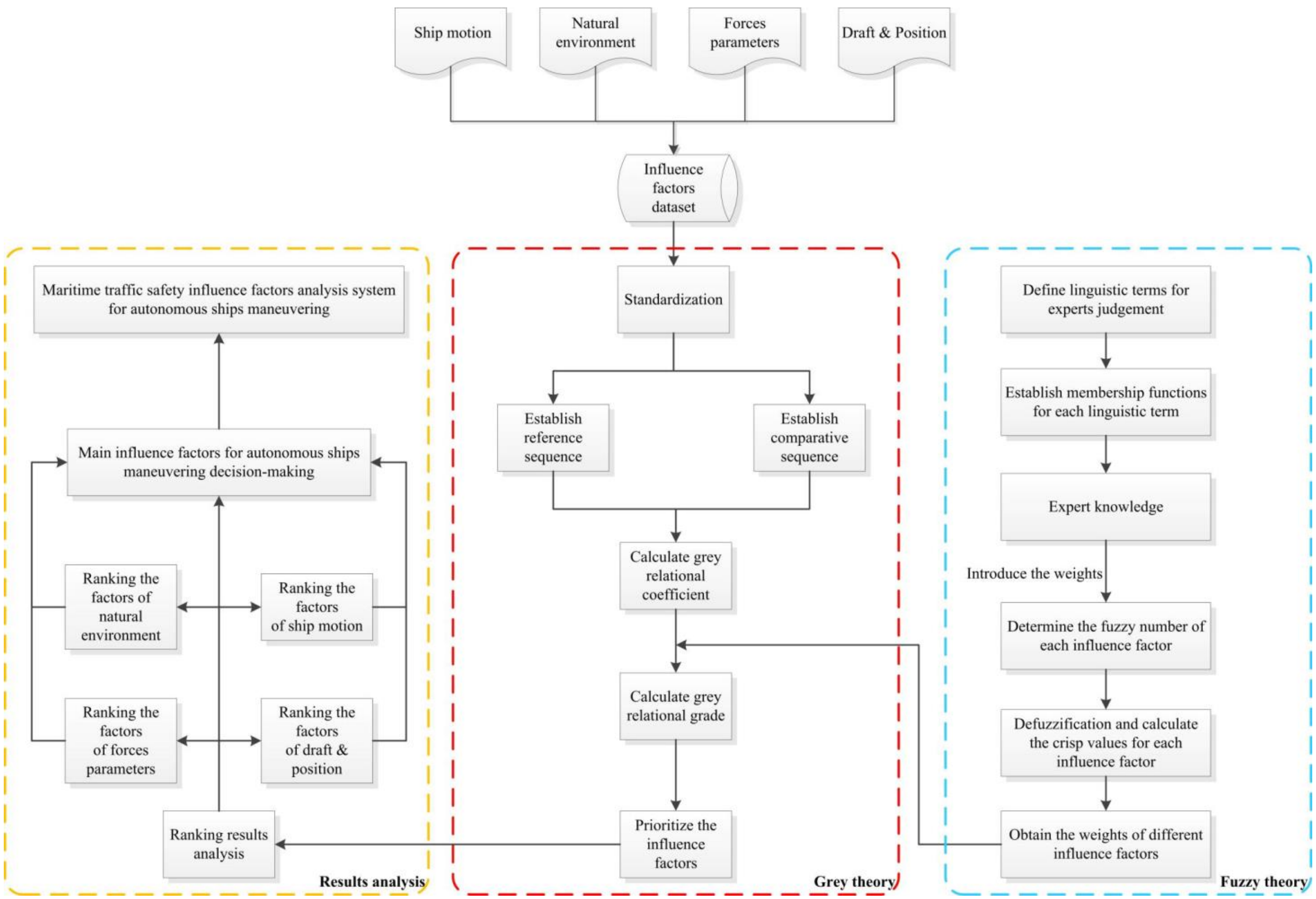

Fig. 4. The framework of the proposed model using grey and fuzzy theory.

3. Experiments

3.1. Scenario design

In our experiment, the simulator scenario was the Shanghai Waigaoqiao wharf, and the ship was downstream of the berthing into the port. We use a Liquefied Natural Gas (LNG) ship as our experimental ship (name: OS1; displacement: 171705.0 tons; length: 345.3 meters; breadth: 53.8 meters). We define the process as when the ship's stern leaves the main channel near the port side of the boundary line in the electronic chart (Fig. 5(b) shows the initial boundary) to the ship berths docked at the end of the cable (Fig. 5(c) shows the end boundary) as a complete berthing process. The experimental scene is shown in Fig. 5.

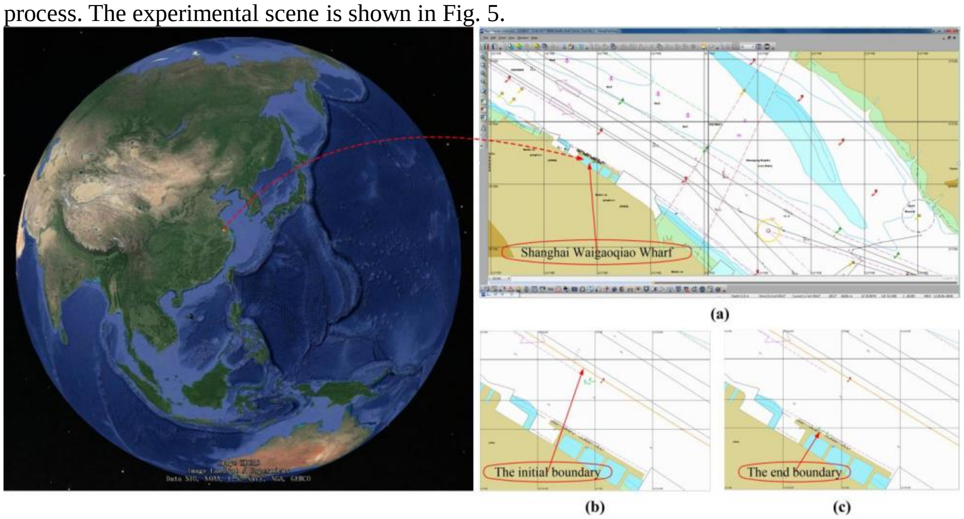

Fig. 5. The designed experimental scenario.

3.2. Data collection and processing

We collect the data from the full-task handling simulation platform (Navi-Trainer Professional 5000, which conforms to the IMO STCW78/10 convention and the Det Norske Veritas (DNV)) from the Maneuvering Simulator Laboratory in Wuhan University of Technology Waterway Road Traffic Safety Control and Equipment Ministry of Education Engineering Research Center. Fig.6 represents the experimental data collection process.

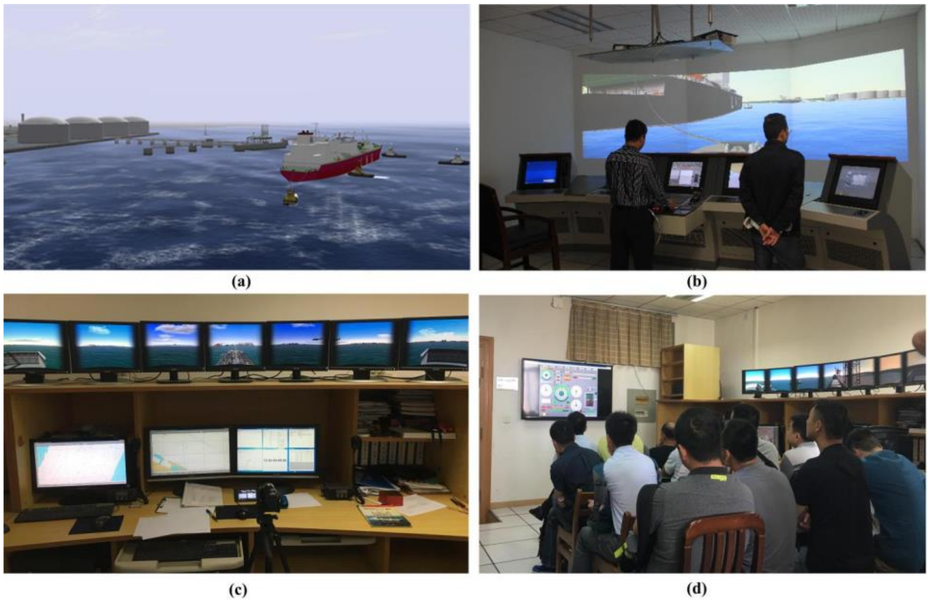

Fig. 6. The experimental data collection process.

We collect the operational data of the exercises and assessment exams as our experimental data (unlimited navigational class seafarers, 96 people, 32-45 years old, skilled maneuvering level, captain/chief officer). The ship maneuvering traffic environment, including inside and outside multisource information, were collected on the ship's berthing process. For instance, the location (longitude, latitude), environment (wind, flow, current, etc.), control (rudder order, marine telegraph), ship movement (ship heading, steering rate, etc.), the ship's draft, tugs, mechanical contact force-related parameters, and other related parameters. These above factors, such as the ship movement, the environment, the control, location and the relevant parameters of the tug and other factors, were extracted from fixed factors and the weakly related parameters. Fig. 7 shows the participants' information; Table 4 lists some of the training samples.

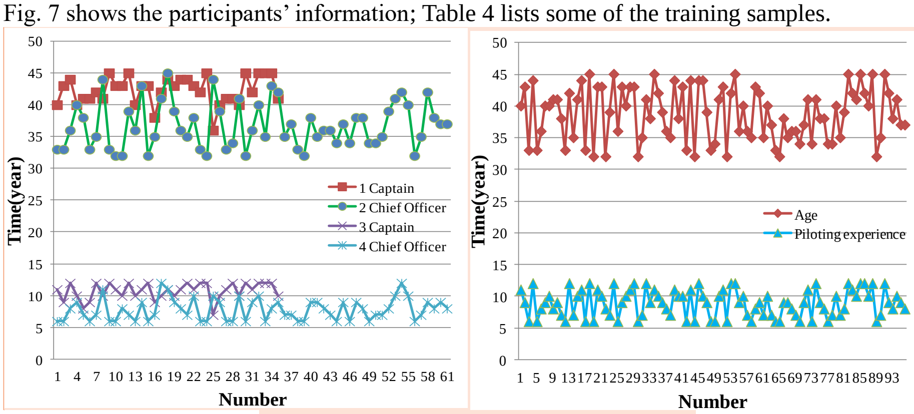

Fig. 7. Analysis of participants' information.

Commented [PvG-T2]: This figure can be removed. Please summarize the information as: Mean age of captains = 40 years, Min. age = 32 years, Max age = 45 years; the sam,e for OOW and for the piloting experience (Mean number of years of piloting experience for captains = 11 years, etc., Mean piloting experience for OOW = 7 years, …)

Table 3 The category of influence factors.

Influence factors	Meaning	Units	Category	Influence factors	Meaning	Units	Category
Y1	Current draft at ship bow	Meters	Draft	**Y18**	Longitudinal force of mooring lines	Tonne-force	Forces Parameters
Y2	Current draft at ship stern	Meters	Draft	**Y19**	Summary force of mooring lines:	Tonne-force	Forces Parameters
Y3	Under keel clearance aft	Meters	Draft	**Y20**	Vertical force of mooring lines	Tonne-force	Forces Parameters
Y4	Under keel clearance fwd	Meters	Draft	**Y21**	Heading	Degrees	Motion
Y5	Current direction	Degrees	Environment	**Y22**	Height above the water	Meters	Motion
Y6	Current speed	Knots	Environment	**Y23**	Lateral speed	Knots	Motion
Y7	Relative current direction	Degrees	Environment	**Y24**	Longitudinal speed	Knots	Motion
Y8	Relative wave direction	Degrees	Environment	**Y25**	Pitch angle	Degrees	Motion
Y9	Relative wind direction	Degrees	Environment	**Y26**	Pitch rate	Degrees/min	Motion
Y10	Relative wind speed	Knots	Environment	**Y27**	Rate of turn	Degrees/min	Motion
Y11	Water depth	Meters	Environment	**Y28**	Roll angle	Degrees	Motion
Y12	Wave height	Meters	Environment	**Y29**	Roll rate	Degrees/min	Motion
Y13	Lateral force	Tonne-force	Forces Parameters	**Y30**	Vertical speed	Knots	Motion
Y14	Longitudinal force	Tonne-force	Forces Parameters	**Y31**	Yaw rate	Degrees/min	Motion
Y15	Summary force	Tonne-force	Forces Parameters	**Y32**	Latitude	Degrees	Position
Y16	Vertical force	Tonne-force	Forces Parameters	**Y33**	Longitude	Degrees	Position
Y17	Lateral force of mooring lines	Tonne-force	Forces Parameters	-	-	-	-

It should be noted that, in our case, the OOW is the captain or chief officer, although, in the real situation, the captain is not on duty. The captain will go to the bridge only in special circumstances, and if necessary, the captain may take over the duty of the OOW to maneuver the ship, but it is an assessment and evaluation scenario in our experiment; therefore, the captain also acts as the OOW. In addition, we regard the tugboat as a power plant system of target ship OS1 to facilitate the ship's overall situation of a simplified analysis.

Table 4 Original data of the studied area (partially).

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No.	X		Y1	Y2	Y3	Y4	…	Y33
	Rudders Order	Telegraphs Order						
1	-1.0000	50.0000	10.1766	10.8138	4.2631	4.8818	…	121.6474
2	-1.0000	50.0000	10.1812	10.8184	4.2574	4.8783	…	121.6474
3	-1.0000	50.0000	10.1898	10.8270	4.2478	4.8706	…	121.6474
4	-1.0000	50.0000	10.2095	10.8468	4.2267	4.8523	…	121.6473
5	-1.0000	50.0000	10.2152	10.8526	4.2200	4.8474	…	121.6473
6	-1.0000	46.2955	10.1926	10.8300	4.2411	4.8714	…	121.6473
7	-1.0000	40.0000	10.1809	10.8183	4.2521	4.8837	…	121.6473
8	-1.0000	40.0000	10.1915	10.8290	4.2398	4.8748	…	121.6473
9	-1.0000	40.0000	10.2082	10.8457	4.2220	4.8591	…	121.6473
10	-1.0000	40.0000	10.2006	10.8381	4.2284	4.8678	…	121.6472
11	-3.3119	40.0000	10.1846	10.8221	4.2431	4.8849	…	121.6472
12	-11.2792	40.0000	10.1958	10.8334	4.2307	4.8747	…	121.6472
13	-11.9016	40.0000	10.2208	10.8584	4.2045	4.8507	…	121.6472
14	-11.0000	40.0000	10.2157	10.8532	4.2090	4.8564	…	121.6472
15	-11.0000	40.0000	10.1831	10.8207	4.2405	4.8899	…	121.6472
16	-11.0000	40.0000	10.1789	10.8165	4.2445	4.8944	…	121.6472
17	-11.0000	40.0000	10.2266	10.8642	4.1939	4.8490	…	121.6471
18	-11.0000	40.0000	10.1998	10.8373	4.2196	4.8769	…	121.6471
19	-11.0000	40.0000	10.1749	10.8125	4.2432	4.9028	…	121.6471
20	-11.0000	40.0000	10.2083	10.8460	4.2084	4.8704	…	121.6471
21	-11.0000	40.0000	10.2140	10.8518	4.2014	4.8658	…	121.6471
22	-11.0000	40.0000	10.2140	10.8518	4.2014	4.8658	…	121.6471
23	-11.0000	40.0000	10.1741	10.8121	4.2386	4.9077	…	121.6471
24	-11.0000	40.0000	10.2186	10.8567	4.1933	4.8641	…	121.6470
25	-11.0000	40.0000	10.2214	10.8595	4.1913	4.8618	…	121.6470
26	-11.0000	40.0000	10.1926	10.8307	4.2227	4.8922	…	121.6470
27	-11.0000	40.0000	10.1999	10.8380	4.2170	4.8858	…	121.6470
28	-11.0000	40.0000	10.2018	10.8399	4.2159	4.8844	…	121.6470
29	-11.0000	40.0000	10.1767	10.8148	4.2435	4.9109	…	121.6470
30	-11.0000	40.0000	10.2035	10.8416	4.2183	4.8850	…	121.6470
…	…	…	…	…	…	…	…	…

According to the simulation scenario shown in Fig. 5 and Fig. 6, the size of the rudder angle and the propeller speed are defined according to the navigation experience and the situation of data collection from the emulator. When the output power ≥ 50%, it is defined as the propeller rapid rotation state, the value range is $[-100\%,\ -50\%]\cup[50\%,\ 100\%]$. When the output power $<50\%$, it is defined as the propeller slow rotation state, the value range is $(-50\%,\ 0)\cup(0,\ 50\%)$. When the rudder angle value belongs to the interval $(-10,\ 0)\cup(0,\ 10)$, it is defined as the small steering angle. When the value of the rudder angle belongs to the interval $[-35,\ -10]\cup[10,35]$, it is defined as the large steering angle. See Fig. 8 and Table 5 (showing 64 possible maneuvering decisions).

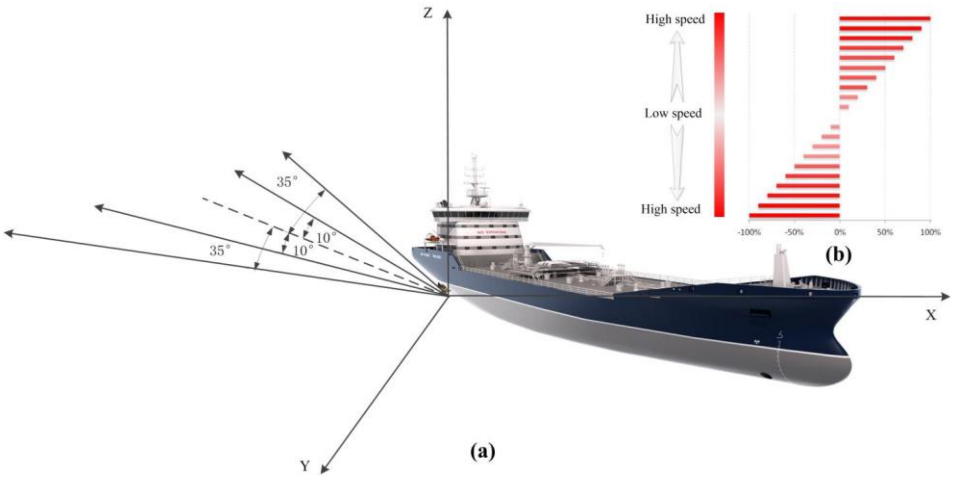

Fig. 8. The telegraph and rudder orders of ship OS1.

The OOW maneuvers the ship by operating different TROs to change ship's speed and direction then to complete the ship's control. Fig. 8 shows TROs of ship OS1 and the Table 5 shows the combining TROs; this control is a multi-dynamic process. Moreover, it should be noted that, in combination with the actual situation of the experimental scenario. Unlike the ship sailing on the open sea, the OOW needs to call the TROs frequently in the inbound decision-making ship handing process; therefore, in this paper, we do not consider "Midships" and "Stop engine" regardless of the rudder angle and if the power output is 0. Table 5 shows the standardization principle for the output maneuvering decision-making factor.

Table 5 ships maneuvering decision-making factors and standardization principle.

Attributes	Speed control			Course control		
	Symbolic principle	**Status**	**Symbol**	**Symbolic principle**	**Status**	**Symbol**
Variety	$a_{i+1}-a_i \neq 0$	Changed	C1	$b_{i+1}-b_i \neq 0$	Changed	C2
	$a_{i+1}-a_i = 0$	Unchanged	U1	$b_{i+1}-b_i = 0$	Unchanged	U2
Value	$[-100\%, -50\%] \cup [50\%, 100\%]$	Fast	F1	$[-35, -10] \cup [10, 35]$	Large	L2
	$(-50\%, 0) \cup (0, 50\%)$	Slow	S1	$(-10, 0) \cup (0, 10)$	Small	S2
Direction	$a_i > 0$	Ahead	D1	$b_i > 0$	Starboard	D2
	$a_i < 0$	Astern	T1	$b_i < 0$	Port	T2
Influence factors	**Decisions**		**Symbols**	**Decisions**		**symbol**
X(Dimensionless)	U1F1D1U2L2T2		X1	U1F1D1C2L2T2		X33
	U1F1D1U2S2T2		X2	U1F1D1C2S2T2		X34
	U1S1D1U2L2T2		X3	U1S1D1C2L2T2		X35
	U1S1D1U2S2T2		X4	U1S1D1C2S2T2		X36
	U1F1T1U2L2T2		X5	U1F1T1C2L2T2		X37
	U1F1T1U2S2T2		X6	U1F1T1C2S2T2		X38
	U1S1T1U2L2T2		X7	U1S1T1C2L2T2		X39
	U1S1T1U2S2T2		X8	U1S1T1C2S2T2		X40
	U1F1D1U2L2D2		X9	U1F1D1C2L2D2		X41
	U1F1D1U2S2D2		X10	U1F1D1C2S2D2		X42
	U1S1D1U2L2D2		X11	U1S1D1C2L2D2		X43

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U1S1D1U2S2D2	X12	U1S1D1C2S2D2	X44
U1F1T1U2L2D2	X13	U1F1T1C2L2D2	X45
U1F1T1U2S2D2	X14	U1F1T1C2S2D2	X46
U1S1T1U2L2D2	X15	U1S1T1C2L2D2	X47
U1S1T1U2S2D2	X16	U1S1T1C2S2D2	X48
C1F1D1C2L2T2	X17	C1F1D1U2L2T2	X49
C1F1D1C2S2T2	X18	C1F1D1U2S2T2	X50
C1S1D1C2L2T2	X19	C1S1D1U2L2T2	X51
C1S1D1C2S2T2	X20	C1S1D1U2S2T2	X52
C1F1T1C2L2T2	X21	C1F1T1U2L2T2	X53
C1F1T1C2S2T2	X22	C1F1T1U2S2T2	X54
C1S1T1C2L2T2	X23	C1S1T1U2L2T2	X55
C1S1T1C2S2T2	X24	C1S1T1U2S2T2	X56
C1F1D1C2L2D2	X25	C1F1D1U2L2D2	X57
C1F1D1C2S2D2	X26	C1F1D1U2S2D2	X58
U1S1D1C2L2D2	X27	C1S1D1U2L2D2	X59
C1S1D1C2S2D2	X28	C1S1D1U2S2D2	X60
C1F1T1C2L2D2	X29	C1F1T1U2L2D2	X61
C1F1T1C2S2D2	X30	C1F1T1U2S2D2	X62
C1D1T1C2L2D2	X31	C1S1T1U2L2D2	X63
C1D1T1C2S2D2	X32	C1S1T1U2S2D2	X64

4. Results

In our experiment, we select X and the related parameters Y1 ~ Y33 to apply the proposed model, among them, X is the main factor and reference series, which is the 64 possible maneuvering decisions (the OOW's actual operation in the simulator, a different combination of TROs, see Table 5). Y1 ~ Y33 is the influencing factors, and their values constitute the comparative series, such as the environment, ships, and other influencing factors. In addition, we collected a total of 60,716 samples as our data sets.

4.1. Standardizing of the original data set

In this paper, X presents the percentage of the number of each maneuvering decision of X1 ~ X64 in a total number of the data set records. Limited to space, Table 6 lists only a part of multiple measured data. The data in Table 6 are standardized according to the principle of standardization of maneuvering decision influence factors in Table 5.

Table 6 Dataset with the principle of standardization (partially).

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No.	**X**		**Y1**	**Y2**	**Y3**	**Y4**	**…**	**Y33**
	Standardized	**Proportion**						
1	X2	0.0300	10.1766	10.8138	4.2631	4.8818	**…**	121.6474
2	X2	0.0300	10.1812	10.8184	4.2574	4.8783	**…**	121.6474
3	X2	0.0300	10.1898	10.8270	4.2478	4.8706	**…**	121.6474
4	X2	0.0300	10.2095	10.8468	4.2267	4.8523	**…**	121.6473
5	X52	0.0196	10.2152	10.8526	4.2200	4.8474	**…**	121.6473
6	X52	0.0196	10.1926	10.8300	4.2411	4.8714	**…**	121.6473
7	X4	0.2955	10.1809	10.8183	4.2521	4.8837	**…**	121.6473
8	X4	0.2955	10.1915	10.8290	4.2398	4.8748	**…**	121.6473
9	X4	0.2955	10.2082	10.8457	4.2220	4.8591	**…**	121.6473
10	X36	0.0098	10.2006	10.8381	4.2284	4.8678	**…**	121.6472
11	X35	0.0062	10.1846	10.8221	4.2431	4.8849	**…**	121.6472
~~**12**~~	~~X35~~	~~0.0062~~	~~10.1958~~	~~10.8334~~	~~4.2307~~	~~4.8747~~	~~**…**~~	~~121.6472~~

~~13~~	~~X35~~	~~0.0062~~	~~10.2208~~	~~10.8584~~	~~4.2045~~	~~4.8507~~	~~…~~	~~121.6472~~
~~14~~	~~X3~~	~~0.0818~~	~~10.2157~~	~~10.8532~~	~~4.2090~~	~~4.8564~~	~~…~~	~~121.6472~~
~~15~~	~~X3~~	~~0.0818~~	~~10.1831~~	~~10.8207~~	~~4.2405~~	~~4.8899~~	~~…~~	~~121.6472~~
~~16~~	~~X3~~	~~0.0818~~	~~10.1789~~	~~10.8165~~	~~4.2445~~	~~4.8944~~	~~…~~	~~121.6472~~
~~17~~	~~X3~~	~~0.0818~~	~~10.2266~~	~~10.8642~~	~~4.1939~~	~~4.8490~~	~~…~~	~~121.6471~~
~~18~~	~~X3~~	~~0.0818~~	~~10.1998~~	~~10.8373~~	~~4.2196~~	~~4.8769~~	~~…~~	~~121.6471~~
~~19~~	~~X3~~	~~0.0818~~	~~10.1749~~	~~10.8125~~	~~4.2432~~	~~4.9028~~	~~…~~	~~121.6471~~
~~20~~	~~X3~~	~~0.0818~~	~~10.2083~~	~~10.8460~~	~~4.2084~~	~~4.8704~~	~~…~~	~~121.6471~~
~~21~~	~~X3~~	~~0.0818~~	~~10.2140~~	~~10.8518~~	~~4.2014~~	~~4.8658~~	~~…~~	~~121.6471~~
~~22~~	~~X3~~	~~0.0818~~	~~10.2140~~	~~10.8518~~	~~4.2014~~	~~4.8658~~	~~…~~	~~121.6471~~
~~23~~	~~X3~~	~~0.0818~~	~~10.1741~~	~~10.8121~~	~~4.2386~~	~~4.9077~~	~~…~~	~~121.6471~~
~~24~~	~~X3~~	~~0.0818~~	~~10.2186~~	~~10.8567~~	~~4.1933~~	~~4.8641~~	~~…~~	~~121.6470~~
~~25~~	~~X3~~	~~0.0818~~	~~10.2214~~	~~10.8595~~	~~4.1913~~	~~4.8618~~	~~…~~	~~121.6470~~
~~26~~	~~X3~~	~~0.0818~~	~~10.1926~~	~~10.8307~~	~~4.2227~~	~~4.8922~~	~~…~~	~~121.6470~~
~~27~~	~~X3~~	~~0.0818~~	~~10.1999~~	~~10.8380~~	~~4.2170~~	~~4.8858~~	~~…~~	~~121.6470~~
~~28~~	~~X3~~	~~0.0818~~	~~10.2018~~	~~10.8399~~	~~4.2159~~	~~4.8844~~	~~…~~	~~121.6470~~
~~29~~	~~X3~~	~~0.0818~~	~~10.1767~~	~~10.8148~~	~~4.2435~~	~~4.9109~~	~~…~~	~~121.6470~~
~~30~~	~~X3~~	~~0.0818~~	~~10.2035~~	~~10.8416~~	~~4.2183~~	~~4.8850~~	~~…~~	~~121.6470~~
…	…	…	…	…	…	…	…	…

4.2. Applying the proposed analysis model

According to the ranking criteria of the grey relational grade, the greater the grey relational grade of the comparative series, the greater the relevance of the comparative series to the reference series, the greater the degree of influence on the reference series, and the higher the ranking of the influencing factors. The GRA method could quantitatively describe the similarity and consistency degree between each comparative series and reference series and uses relational grade to complete the matching order of influencing factors. We use the original data matrix are defined by

$$X^{'} = \begin{pmatrix} X_0^{'} \\ X_1^{'} \\ X_2^{'} \\ \vdots \\ X_\omega^{'} \end{pmatrix} = \begin{bmatrix} x_{01}^{'} & x_{02}^{'} & \cdots & x_{0m}^{'} \\ x_{11}^{'} & x_{12}^{'} & \cdots & x_{1m}^{'} \\ x_{21}^{'} & x_{22}^{'} & \cdots & x_{2m}^{'} \\ \vdots & \vdots & \ddots & \vdots \\ x_{\omega 1}^{'} & x_{\omega 2}^{'} & \cdots & x_{\omega m}^{'} \end{bmatrix} \Rightarrow \begin{bmatrix} \text{TRO} \\ \text{Influence Factor 1} \\ \text{Influence Factor 2} \\ \vdots \\ \text{Influence Factor } (\omega\text{-1}) \end{bmatrix} \Rightarrow \begin{bmatrix} \text{X} \\ \text{Y1} \\ \text{Y2} \\ \vdots \\ \text{Y33} \end{bmatrix}. \quad (15)$$

Then we could get the original data series. Because there is a case where the initial value is zero in the influencing factors, that is not suitable for the calculation based Eq. (5), besides, the standardization method could truly reflect the relevance of the influencing factors to ships maneuvering decisions. Therefore, we use the standardization methods to explore the results of the interaction between ships maneuvering decisions and various influencing factors.

Table 7 The extreme values of our data set.

Influence factors	Equalization		Standardization	
	Δ_i(max)	Δ_i(min)	Δ_i(max)	Δ_i(min)
Y1	1.159057797	0.075983629	10.75723437	0.000149400
Y2	1.158443208	0.073212015	9.286000215	2.97525E-05
Y3	1.965814768	**5.75977E-06**	6.670632875	0.000162331
Y4	1.604604842	6.15456E-05	4.939213846	0.000240429
Y5	1.131585247	0.099651830	2.677718534	0.001937135
Y6	1.167868355	0.058848769	2.607298241	0.002782460

Y7	3.459486901	9.17383E-05	4.896570329	4.70016E-05
Y8	3.396453057	0.000148308	6.238392243	0.000341300
Y9	4.608587952	1.5976E-050	5.742657263	0.000149654
Y10	2.051199481	4.07302E-05	2.699055325	4.80284E-05
Y11	1.305196174	0.063251989	6.230599999	0.000794324
Y12	3061.141971	0.004551440	8.023167652	0.000179697
Y13	2861.027993	0.000350111	45.23686934	0.001040272
Y14	596.5071506	0.000350111	37.19534450	0.010007617
Y15	476.2396287	0.000350111	36.16702220	0.006453297
Y16	**5563.973892**	0.000350111	**56.71438286**	0.005779491
Y17	305.5604219	0.000238480	26.88140323	0.001041084
Y18	1484.848362	1.48048E-05	26.76096695	0.029507153
Y19	270.5740189	0.000104256	25.52296248	0.005543666
Y20	339.0575745	4.31526E-05	31.57740192	0.041646945
Y21	2.337030342	0.000312376	6.406334561	3.47088E-05
Y22	1.652125364	1.87345E-05	4.576141174	0.000154554
Y23	3.931954781	4.06807E-05	4.212766847	0.000149660
Y24	5.047346851	0.000220488	5.285008067	0.000186862
Y25	1.493240834	0.000226185	13.21063113	7.98433E-05
Y26	1792.386867	5.46493E-05	24.45508796	0.001488166
Y27	13.72025889	0.000238689	6.267063219	0.000109524
Y28	13.60897251	0.000105072	10.38202823	9.73156E-05
Y29	1186.532019	8.10925E-05	12.12034909	6.66299E-05
Y30	938.6543926	0.006868735	8.602456594	0.000166826
Y31	13.72029730	0.000238571	6.267064612	0.000108035
Y32	1.124228306	0.106850537	3.862857951	**6.03501E-06**
Y33	1.124158218	0.107035204	4.661142861	2.04946E-05

From Table 7, we can get the extreme values $\Delta_{\max 1} = \mathbf{5563.973892}$, $\Delta_{\min 1} = \mathbf{5.75977E-06}$. And $\Delta_{\max 2} = \mathbf{56.71438286}$, $\Delta_{\min 2} = \mathbf{6.03501E-06}$. Then we can calculate the grey relational coefficient and grey grades from Table 8.

Table 8 The grey relational coefficient and grey grade (partially).

Influence factors	Grey Relational Coefficient (Standardization)							Grey Grade
	No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**…**	
Y1	0.948821333	0.944800559	0.935685389	0.933054446	0.940548179	0.945995493	…	0.963331321
Y2	0.944422670	0.941285170	0.934169836	0.932105721	0.937298072	0.941518452	…	0.963022501
Y3	0.980756009	0.981198262	0.982182514	0.982491117	0.978341825	0.977832987	…	0.964702382
Y4	0.984269772	0.984635896	0.985511601	0.985748630	0.981409613	0.980825559	…	0.964360060
....								
~~**Y5**~~	~~0.958719718~~	~~0.958719718~~	~~0.958719718~~	~~0.958719718~~	~~0.955695626~~	~~0.955695626~~	~~…~~	~~0.962321061~~
~~**Y6**~~	~~0.940306134~~	~~0.940306134~~	~~0.940306134~~	~~0.940306134~~	~~0.937396914~~	~~0.937396914~~	~~…~~	~~0.962607649~~
~~**Y7**~~	~~0.977801220~~	~~0.977891825~~	~~0.977931508~~	~~0.977993022~~	~~0.974925396~~	~~0.974957017~~	~~…~~	~~0.964744459~~
~~**Y8**~~	~~0.971251135~~	~~0.971392017~~	~~0.971608734~~	~~0.971735174~~	~~0.974998194~~	~~0.975095592~~	~~…~~	~~0.967877544~~
~~**Y9**~~	~~0.841280242~~	~~0.841106931~~	~~0.840896531~~	~~0.840735405~~	~~0.838168367~~	~~0.838051112~~	~~…~~	~~0.962919694~~
~~**Y10**~~	~~0.998257956~~	~~0.998169573~~	~~0.998126221~~	~~0.998081209~~	~~0.998665148~~	~~0.998728818~~	~~…~~	~~0.964861416~~
~~**Y11**~~	~~0.983231411~~	~~0.983231411~~	~~0.983231411~~	~~0.983231411~~	~~0.980050964~~	~~0.980050964~~	~~…~~	~~0.964247007~~
~~**Y12**~~	~~0.944235511~~	~~0.944220127~~	~~0.994048723~~	~~0.977953994~~	~~0.934740041~~	~~0.944328861~~	~~…~~	~~0.961966953~~
~~**Y13**~~	~~0.965904865~~	~~0.965904865~~	~~0.965904865~~	~~0.965904865~~	~~0.962835347~~	~~0.962835347~~	~~…~~	~~0.968696019~~
~~**Y14**~~	~~0.964395151~~	~~0.964395151~~	~~0.964395151~~	~~0.964395151~~	~~0.961335205~~	~~0.961335205~~	~~…~~	~~0.968659475~~
~~**Y15**~~	~~0.968953428~~	~~0.968953428~~	~~0.968953428~~	~~0.968953428~~	~~0.965864535~~	~~0.965864535~~	~~…~~	~~0.969245754~~
~~**Y16**~~	~~0.966102022~~	~~0.966102022~~	~~0.966102022~~	~~0.966102022~~	~~0.963031252~~	~~0.963031252~~	~~…~~	~~0.969236192~~
~~**Y17**~~	~~0.969356693~~	~~0.969356693~~	~~0.969356693~~	~~0.969356693~~	~~0.966265232~~	~~0.966265232~~	~~…~~	~~0.968609094~~
~~**Y18**~~	~~0.967033754~~	~~0.967033754~~	~~0.967033754~~	~~0.967033754~~	~~0.963957068~~	~~0.963957068~~	~~…~~	~~0.968266306~~
~~**Y19**~~	~~0.969568983~~	~~0.969568983~~	~~0.969568983~~	~~0.969568983~~	~~0.966476170~~	~~0.966476170~~	~~…~~	~~0.968451261~~
~~**Y20**~~	~~0.963392954~~	~~0.963392954~~	~~0.963392954~~	~~0.963392954~~	~~0.960339355~~	~~0.960339355~~	~~…~~	~~0.967668141~~
~~**Y21**~~	~~0.909889805~~	~~0.910028713~~	~~0.910145804~~	~~0.910297183~~	~~0.907701868~~	~~0.907830373~~	~~…~~	~~0.957594808~~
~~**Y22**~~	~~0.954178672~~	~~0.955252886~~	~~0.956159522~~	~~0.956445868~~	~~0.951069799~~	~~0.950563470~~	~~…~~	~~0.957995484~~
~~**Y23**~~	~~0.907782183~~	~~0.907409168~~	~~0.908501406~~	~~0.908865794~~	~~0.906425201~~	~~0.906429648~~	~~…~~	~~0.957976209~~
~~**Y24**~~	~~0.950643723~~	~~0.950755541~~	~~0.950572988~~	~~0.950536360~~	~~0.947538063~~	~~0.947567799~~	~~…~~	~~0.955638214~~
~~**Y25**~~	~~0.938662153~~	~~0.938578234~~	~~0.938563640~~	~~0.938505272~~	~~0.935552791~~	~~0.935516544~~	~~…~~	~~0.962322084~~
~~**Y26**~~	~~0.965855204~~	~~0.965856724~~	~~0.965923488~~	~~0.965894714~~	~~0.962822040~~	~~0.962898655~~	~~…~~	~~0.964491499~~
~~**Y27**~~	~~0.993807782~~	~~0.993415855~~	~~0.992347703~~	~~0.991987082~~	~~0.988237198~~	~~0.987176771~~	~~…~~	~~0.963209744~~
~~**Y28**~~	~~0.966142965~~	~~0.966234013~~	~~0.966354440~~	~~0.966462437~~	~~0.963518894~~	~~0.963701914~~	~~…~~	~~0.964126732~~
~~**Y29**~~	~~0.966915878~~	~~0.966277561~~	~~0.966579003~~	~~0.966698608~~	~~0.963888008~~	~~0.964242401~~	~~…~~	~~0.965110499~~
~~**Y30**~~	~~0.970562344~~	~~0.972582036~~	~~0.973802135~~	~~0.958892072~~	~~0.950538172~~	~~0.968438806~~	~~…~~	~~0.961761784~~
Y31	0.993807833	0.993415906	0.992347753	0.991987132	0.988237248	0.987176821	…	0.963209766
Y32	0.902638993	0.902687368	0.902726071	0.902784132	0.900150231	0.900198339	…	0.955548915
Y33	0.941088142	0.941467051	0.941775139	0.942178328	0.939634966	0.939989087	…	0.962805458

The convenient fuzzy numbers are defined for making pairwise comparisons shown in Table 1. And Table 9 shows the linguistic terms survey results from the four experts. Then the defuzzification procedure is conducted based on the Eq. (19) and Table 2, the crisp number of different influence factors are calculated with the relative weights β_i, then the λ_k weights of maneuvering influence factors can be determined, the results are shown in Table 10. Finally, using Eqs. (20) and (21), the priority ranking results of comparing grey algorithm with our proposed model is obtained, as shown in Table 11.

Table 9 The linguistic terms from the experts for different maneuvering influence factors.

Influence factors	**Expert No.**			
	1	2	3	4
Y1	M	M	H	M
Y2	H	M	H	H
Y3	H	H	H	H
Y4	H	M	H	M
Y5	M	M	M	H
… **Y6**	M	M	H	M
Y7	VH	H	H	VH
Y8	VH	VH	VH	VH
Y9	VH	VH	VH	H
Y10	VH	VH	VH	VH
Y11	H	VH	H	H
Y12	M	L	VL	L
Y13	VH	VH	VH	H
Y14	VH	VH	VH	H
Y15	VH	VH	VH	VH
Y16	H	H	VH	H
Y17	VH	VH	H	VH
Y18	VH	VH	H	VH
Y19	VH	VH	VH	VH
Y20	H	H	M	H
Y21	VL	L	L	VL
Y22	L	VL	L	VL
Y23	H	VH	H	VH
Y24	H	VH	H	VH
Y25	H	H	M	H
Y26	H	VH	H	VH
Y27	H	H	M	H
Y28	H	H	M	H
Y29	H	H	H	H
Y30	M	M	M	L
Y31	H	M	M	H
Y32	M	L	L	M
Y33	M	L	M	M
Weights (β_i)	0.30	0.25	0.20	0.25

Table 10 The crisp number and weights of maneuvering influence factors.

Influence factors	**Expert No.**				**Crisp number**	**Weights**
	1	2	3	4		**(λ_k)**
Y1	0.4733	0.4733	0.7333	0.4733	0.4733	0.0231
Y2	0.7333	0.4733	0.7333	0.7333	0.7333	0.0294
Y3	0.7333	0.7333	0.7333	0.7333	0.7333	0.0323
Y4	0.7333	0.4733	0.7333	0.4733	0.7333	0.0266
Y5	0.4733	0.4733	0.4733	0.7333	0.4733	0.0237

…. Y6	0.4733	0.4733	0.7333	0.4733	0.4733	0.0231
Y7	0.9400	0.7333	0.7333	0.9400	0.9400	0.0373
Y8	0.9400	0.9400	0.9400	0.9400	0.9400	0.0414
Y9	0.9400	0.9400	0.9400	0.7333	0.9400	0.0391
Y10	0.9400	0.9400	0.9400	0.9400	0.9400	0.0414
Y11	0.7333	0.9400	0.7333	0.7333	0.7333	0.0346
Y12	0.4733	0.2800	0.0833	0.2800	0.4733	0.0132
Y13	0.9400	0.9400	0.9400	0.7333	0.9400	0.0391
Y14	0.9400	0.9400	0.9400	0.7333	0.9400	0.0391
Y15	0.9400	0.9400	0.9400	0.9400	0.9400	0.0414
Y16	0.7333	0.7333	0.9400	0.7333	0.7333	0.0341
Y17	0.9400	0.9400	0.7333	0.9400	0.9400	0.0396
Y18	0.9400	0.9400	0.7333	0.9400	0.9400	0.0396
Y19	0.9400	0.9400	0.9400	0.9400	0.9400	0.0414
Y20	0.7333	0.7333	0.4733	0.7333	0.7333	0.0300
Y21	0.0833	0.2800	0.2800	0.0833	0.0833	0.0076
Y22	0.2800	0.0833	0.2800	0.0833	0.2800	0.0080
Y23	0.7333	0.9400	0.7333	0.9400	0.7333	0.0369
Y24	0.7333	0.9400	0.7333	0.9400	0.7333	0.0369
Y25	0.7333	0.7333	0.4733	0.7333	0.7333	0.0300
Y26	0.7333	0.9400	0.7333	0.9400	0.7333	0.0369
Y27	0.7333	0.7333	0.4733	0.7333	0.7333	0.0300
Y28	0.7333	0.7333	0.4733	0.7333	0.7333	0.0300
Y29	0.7333	0.7333	0.7333	0.7333	0.7333	0.0323
Y30	0.4733	0.4733	0.4733	0.2800	0.4733	0.0187
Y31	0.7333	0.4733	0.4733	0.7333	0.7333	0.0272
Y32	0.4733	0.2800	0.2800	0.4733	0.4733	0.0170
Y33	0.4733	0.2800	0.4733	0.4733	0.4733	0.0187
Weights (β_i)	0.30	0.25	0.20	0.25	-	**Sum=1**

Table 11 Results of comparing grey method with our proposed model.

Influence factors	Grey method				Our proposed model			
	Grey Grade	Rank No. 1	Category	Rank No. 2	Model grade	Rank No. 3	Category	Rank No. 4
Y1	0.963331321	18	Draft	3	0.022296521	26	Draft	4
Y2	0.963022501	21	Draft	4	0.028357107	22	Draft	2
Y3	0.964702382	13	Draft	1	0.031169444	17	Draft	1
Y4	0.964360060	15	Draft	2	0.025634601	24	Draft	3
Y32	0.955548915	33	Position	6	0.016264792	30	Position	6
Y33	0.962805458	23	Position	5	0.018028349	28	Position	5
Y5	0.962321061	26	Environment	7	0.022824349	25	Environment	6
Y6	0.962607649	24	Environment	6	0.022279772	27	Environment	7
Y7	0.964744459	12	Environment	3	0.036003278	10	Environment	4
Y8	0.967877544	8	Environment	1	0.040086883	3	Environment	1
Y9	0.962919694	22	Environment	5	0.037689118	9	Environment	3
Y10	0.964861416	11	Environment	2	0.039961964	4	Environment	2
Y11	0.964247007	16	Environment	4	0.033350178	14	Environment	5
Y12	0.961966953	27	Environment	8	0.012658338	31	Environment	8
Y13	0.968696019	3	Forces	3	0.037915206	7	Forces	5
Y14	0.968659475	4	Forces	4	0.037913776	8	Forces	6
Y15	0.969245754	1	Forces	1	0.040143551	1	Forces	1
Y16	0.969236192	2	Forces	2	0.033081376	15	Forces	7
Y17	0.968609094	5	Forces	5	0.038352880	5	Forces	3
Y18	0.968266306	7	Forces	7	0.038339307	6	Forces	4
Y19	0.968451261	6	Forces	6	0.040110645	2	Forces	2
Y20	0.967668141	9	Forces	8	0.029048175	18	Forces	8
Y21	0.957594808	31	Motion	10	0.007249314	33	Motion	11
Y22	0.957995484	29	Motion	8	0.007667484	32	Motion	10
Y23	0.957976209	30	Motion	9	0.035314460	12	Motion	2
Y24	0.955638214	32	Motion	11	0.035228273	13	Motion	3
Y25	0.962322084	25	Motion	6	0.028887693	21	Motion	7
Y26	0.964491499	14	Motion	2	0.035554637	11	Motion	1
Y27	0.963209744	20	Motion	5	0.028914340	20	Motion	6
Y28	0.964126732	17	Motion	3	0.028941867	19	Motion	5
Y29	0.965110499	10	Motion	1	0.031182631	16	Motion	4
Y30	0.961761784	28	Motion	7	0.018008806	29	Motion	9
Y31	0.963209766	19	Motion	4	0.026155744	23	Motion	8

The rankings of ships maneuvering decision influence factors are shown in Table 11, ranking result number 3: Y15 > Y19 >Y8 > Y10 > Y17 > Y18> Y13 > Y14 > Y9 > Y7 > Y26 > Y23 > Y24 > Y11 > Y16 > Y29 > Y3 > Y20 > Y28 > Y27 > Y25 > Y2 > Y31 > Y4 > Y5 > Y1 > Y6 > Y33> Y30 > Y32 > Y12 > Y22> Y21. Furthermore, the result of grey method are sorted based the ranking result number 1: Y15 > Y16 > Y13 > Y14 > Y17 > Y19 > Y18 > Y8 > Y20 > Y29 > Y10 > Y7 > Y3 > Y26 > Y4 > Y11 > Y28 > Y1 > Y31 > Y27 > Y2 > Y9 > Y33 > Y6 > Y25 > Y5 > Y12 > Y30 > Y22 > Y23 > Y21 > Y24 > Y32. As can be observed that the common seven influence factors in the top ten most influential factors of both two methods are: Y15 (Summary force), Y19 (Summary force of mooring lines), Y8 (Relative wave direction), Y17 (Lateral force of mooring lines), Y18 (Longitudinal force of mooring lines), Y13 (Lateral force), Y14 (Longitudinal force), which should be taken more attention when making decisions in ships maneuvering process. Furthermore, the result of top ten most influential factors sorted through our optimal model shows that: Y19 (Summary force of mooring lines) has risen four places to second place; Y8 (Relative wave direction) has risen five places to third place; Y10 (Relative wind speed) has risen seven places to fourth place; Y9 (Relative wind direction) has risen thirteen places to ninth place; Y7 (Relative current direction) has risen tow places to tenth place. Y10, Y9, and Y7 became the new factors in top ten of in autonomous ships maneuvering decision process, which is corresponding to the judgment/operation of experienced seafarers in the real word shipping: when the seafarer (OOW) maneuvering the ship inbound the port, they need to pay more attention to the influence factors of forces (e.g. forces of mooring lines and tugs), relative wave direction, relative wind direction, relative current direction, relative wind speed etc., so as to ensure the safety of ship and cargo. Therefore, the results indicate that our proposed model can identify the influence factors of autonomous ships maneuvering decisions under real word maritime traffic safety context, and the priority ranking results are more reasonable than the original GRA method.

To compare the results from the proposed method and the GRA method more intuitively and clearly, we settle different coordinate systems in the same specific figure to compare the trend of different graphics. The x-axis denotes the number of influence factors, and the y-axis represents the grey grade get from grey method or the grade get from our proposed method. The ranking results of comparing grey algorithm with our proposed model are visualized in Fig. 9. Meanwhile, the priority ranking analysis for four type of influence factors is shown in Fig. 10.

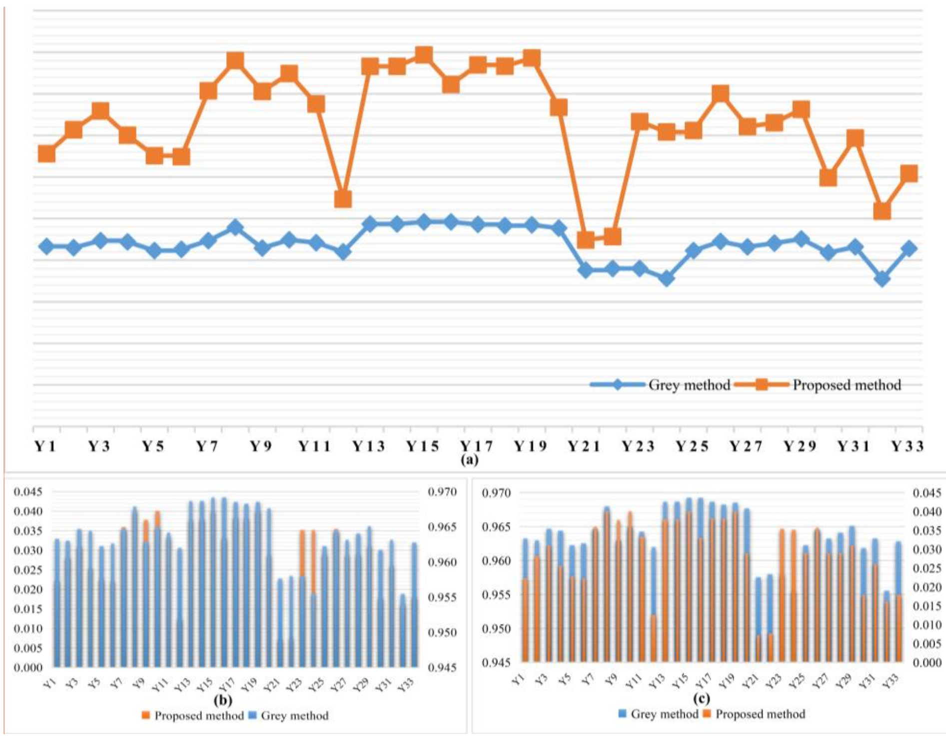

Fig. 9. The results of comparing the grey method with our proposed model.

Commented [PvG-T5]: Add vertical scale.

As can be seen from Fig. 9(a), the changing tendency of the curves for the GRA method and our proposed model are the same basically, however the fluctuation trend of the curve of our proposed model is more obvious than the GRA method, which means that the sensitivity of the prediction result of each influencing factor of our proposed model is higher than GRA method. Meanwhile, the curve of the original GRA method is relatively flat, which also proves the drawbacks of the traditional GRA method: it treats different indexes (influence factors) equally and takes no account of the relative importance of them. Moreover, it does not fit with people's preference for a specific index.

As shown in Fig. 9(b), ~~comparing~~ the results of the histogram heights of the maritime traffic safety influence factors Y9 (Relative wind direction), Y10 (Relative wind speed), Y23 (Lateral speed), and Y24 (Longitudinal speed) of our proposed method are obviously higher than the GRA method, ~~that~~ which indicates that the OOW needs to take more attention about relative wind direction, relative wind speed, lateral speed, and longitudinal speed when ~~they~~ maneuvering the ship ~~than the original priority ranking got from the grey method~~. In other words, when we design the programme for the analysis system of the autonomous ships maneuvering decision in the specific scenarios, we should ~~endow with~~assign a larger weight for the influence factors of relative wind direction, relative wind speed, lateral speed, and longitudinal speed than the original weight ~~got~~ obtained from the grey method.

Meanwhile, Fig. 9(c) shows that the comparing results of the histogram heights of the influence factors Y12 (Wave height), Y21 (Heading), Y22 (Height above the water), Y30 (Vertical speed), and Y33 (Longitude) of our proposed method are obviously lower than the GRA method, ~~that~~ which indicates the OOW needs to take less attention about wave height, heading, height above the water, vertical speed, and longitude when ~~they~~ maneuvering the ship than the original ranking ~~got~~ obtained from the grey method. In other words, when we design the programme for the analysis system of the autonomous ships maneuvering decision in the specific scenarios, we should ~~endow with~~assign a smaller weight for the influence factors of wave height, heading, height above the water, vertical speed, and longitude than the original weight ~~got~~ obtained from the grey method.

It should be noted that, for the influence factors of the same property, we may get different grey grades in different maritime traffic scenarios. For instance, in the specific experimental navigation scenario: Shanghai Waigaoqiao wharf, and the ship was berthing into the port. The ship's position of longitude did not change basically, and it's just a change in the position of latitude, so the grey method gives us the different grey grades for the same property of longitude and latitude. However, when it is extended to the real general word maritime traffic scenarios or other domains, in common sense, the change of longitude and latitude always happens at the same time. Thus the results are consistent with the proposed model. Therefore, the results get from Fig. 9 are reasonable and meaningful, the traditional GRA can sort the driving influencing factors efficiently so that the OOW can get the main maritime traffic safety influence factors intuitively through the correction and optimization of expert judgment knowledge and fuzzy theory. Then through the proposed model, the influencing factors affecting the ships maneuvering decision are obtained in a more general widespread applicability way.

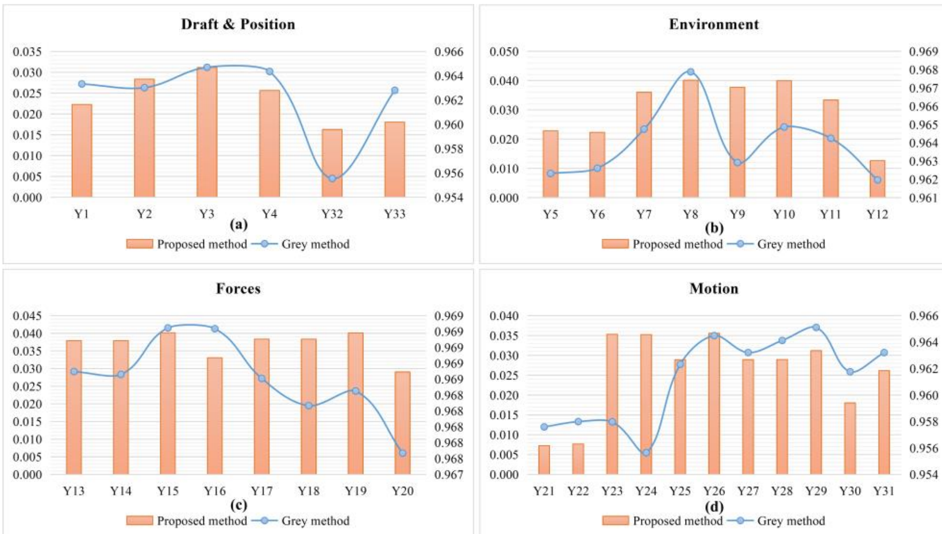

Fig. 10. The ranking results analysis for four type of influence factors.

As shown in Fig. 10, the diagrams of four categories of influence factors are drawn independently (the histogram depicts the variation tendency of the proposed method and the scatter diagram in the form of a smooth curve represents the variation tendency of the GRA method). Overall, the changing tendency of each diagram for the GRA method and our proposed model are the same basically, but there are some details/differences need to be described and explained.

Draft & Position: It can be seen from Fig. 10(a), compared with the diagram of the grey method and the proposed method, the most influential factor within draft and position aspects is Y3 (Under keel clearance aft), it indicates that the OOW needs to take more attention about the under-keel clearance aft within the influence factors of draft and position. Meanwhile, when we design the programme for the analysis system of the autonomous ships maneuvering decision in the specific scenarios considering maritime traffic safety, we should endow withassign a larger weight for the keel clearance aft. Similarly, when it comes to the influence factors longitude and latitude, the specific weight of Y32 (Latitude) has been increased, and the weight of Y33 (Longitude) has been reduced. As the above analysis, in the proposed method, the weight of latitude is higher, and the weight of longitude is lower than the original weight got obtained from the grey method, that indicates the proposed model has a property of general flexibility for the analysis of the maritime traffic safety influencing factors for the ships maneuvering decisions.

Natural environment: As shown in Fig. 10(b), Y8 (Relative wave direction) and Y10 (Relative wind speed) are the top two most influential factors in both the grey method and the proposed method, which indicates the OOW need to focus on the relative wave direction and relative wind speed when it comes to the natural environment. In addition, the Y9 (Relative wind direction), Y10 (Relative wind speed), and Y11 (Water depth) have been increased in the results of proposed method. Among them the increase of Y9 is greatest, which indicates that, in the scope of natural environment, according to the judgments of domain experts based the fuzzy theory, the OOW should pay more attention to the relative wind direction when they maneuvering the ship. Furthermore, it is similar to the programme design for the analysis system, the heavy weight of relative wave direction and relative wind speed need to be given. Moreover, the weight of influence factor of relative wind direction needs to be increased.

Forces parameters: According to Fig. 10(c) and Fig. 9(a), the ranking and grade of forces parameters maintain a relatively stable trend in various influence factors, meanwhile, all the forces parameters keep a high ranking and grade in both two methods (all remain in the top 18, seen from Table 11). It indicates that all the forces parameters play a crucial role in autonomous ships maneuvering decision making in the specific scenario, besides, it is also corresponding to the operation of experienced seafarers in the real world shipping, the forces parameters is the crucial and direct influence factors for the maneuvering of ships and maritime traffic safety. Furthermore, we can see that the most influential factor of forces parameters is Y15 (Summary force); Y17 (Lateral force of mooring lines), Y18 (Lateral force of mooring lines), and Y19 (Lateral force of mooring lines) has been increased and occupy a heavyweight, and Y16 (Vertical force) has been decreased. Similarly, it is reasonable for the real word shipping, especially for the inbound scenario. For instance, when a ship inbound a port, the pilots always call the tugs for assistance, the tugs push (there is no vertical force in this procedure) or pull through the mooring lines then assist the ship get into the port, this has great influence on the maneuvering of ships. For another example, when the ship is close to the berth, the ship usually use the mooring winch to assist the berthing, so the forces from mooring lines is the main influence factors for ships maneuvering and maritime traffic safety. Therefore, when the programme design for the analysis system of the influence factors of autonomous ships maneuvering decision in the specific scenario, the forces parameters should take into consideration and attach the heavyweights.

Ship motion: It is observed from Fig. 10(d) that the most influential factor of ship motion is Y26 (Pitch rate); Y23 (Lateral speed) and Y24 (Longitudinal speed) has been increased, and Y30 (Vertical speed) has been decreased. In addition, the changing tendency of each influence factor for the GRA method and our proposed model are the same basically, except Y 23 and Y24. The changes are reasonable and meaningful in the real word shipping and traffic safety domain. When the ship berthing to the port, the OOW/pilot need to pay attention to the lateral and longitudinal speed at all times, thus to ensure the safety of ship an cargo. For instance, if the ship has an obvious lateral speed, it would do damage for the berth and port; if the ship has a greater longitudinal speed, it will cause the collision with the ships before, and after the berth. However, the vertical speed is not so significant for the safety consider. Hence, when the OOW maneuvering the ship, the lateral and longitudinal speed as well as pitch rate should be taken more attention, as the same to the programme design for the analysis system of the autonomous ships maneuvering decision for the evaluation of maritime traffic safety influence factors.

5. ~~Discussions~~Discussion

Further discussions on the priority ranking results of traffic safety influence factors of autonomous ships maneuvering decisions under the specific navigational scenario are provided as below.

ships maneuvering decision-making is influenced by multi-source information, such as the information from the aspects of people, ships, environment, and it has an interaction with various influencing factors, and each factor plays a different role in the ships maneuvering decision-making process. At the same time, some factors interact with each other (e.g. when Y21(Heading) of the ship changed, then Y8 (relative wave direction) changed correspondingly; when the position changed, i.e. Y32 (Latitude) and Y33 (Longitude) changed, then Y11 (Water depth) changed correspondingly) to form a grey system with clear and partially unclear information, thus constitute a typical "grey system". In this paper, the maritime traffic safety influence factors of autonomous ships maneuvering decision-making are identified and classified into four aspects: “Draft & Position”, “Natural environment”, “Forces parameters”, “Ship motion”. Then the proposed grey and fuzzy algorithm are conducted and applied to prioritize these influence factors using the linguistic terms of the judgments of domain experts, among these procedures, the relative importance of the linguistic terms of experts judgments is also taken into consideration..

The results from the GRA showed that the values of grey grade for different influence factors are relatively large (the minimum value is over 0.95), moreover, the values of grey grade between the reference series TRO and comparative series of different influence factors are different, which indicates that the ships maneuvering decision-making is affected by different influence factors and each influencing factor plays different roles in ships maneuvering decision-making.

Furthermore, grey relational analysis combines with the fuzzy theory is a simple and practical method. The model elaborated in this innovative paper is utilized to prioritize the influence factors of autonomous ships maneuvering decision-making. The top ten most influential factors in the proposed method are Y15 (Summary force), Y19 (Summary force of mooring lines), Y8 (Relative wave direction), Y10 (Relative wind speed), Y17 (Lateral force of mooring lines), Y18 (Longitudinal force of mooring lines), Y13 (Lateral force), Y14 (Longitudinal force), Y9 (Relative wind direction), and Y7 (Relative current direction). In addition, among the four categories of influence factors, the most influential factor within each aspect are Y3 (Under keel clearance aft), Y8 (Relative wave direction), Y15 (Summary force), and Y26 (Pitch rate), respectively. The results are corresponding to the judgment/operation of experienced seafarers in the real word shipping. Likewise, they are reasonable and meaningful in the specific navigational scenarios under maritime traffic safety domain.

Therefore, in the process of ships maneuvering decision-making, as well as the programme design for the analysis system of the influence factors of autonomous ships maneuvering decision-making in specific scenarios, the above ten factors should be taken as the main influence factors considerations, at the same time, the most influential factor in each category also need to be paid particular attention, especially when the OOW/operators considering the impact of a certain type of influencing factors on ships maneuvering decision-making or the engineers design the maneuvering decisions programs for autonomous ships in specific maritime traffic scenarios. Furthermore, the degree of influence of various factors and the actual economic cost of ships operation should be further considered, thus to promote the development of autonomous merchant shipping reduce transportation costs and improve transportation efficiency and maritime traffic safety.

Though the proposed grey and fuzzy model is a promising model, this paper still has some shortcomings as follows, which should be solved in future research. In the specific experimental navigation scenario, as the above description and analysis for Fig. 9 and Fig. 10(c) in section 4, our proposed model is rational and widely applicable to the analysis of the maritime traffic safety influencing factors for the ships maneuvering decisions. However, when in a specific navigational scenario, for instance, the influence factors of longitude and latitude do not change correspondingly, there still has some shortcomings when add the general expert knowledge using general common sense, the accuracy of our proposed model for analyzing these influence factors is affected. Therefore, although the traditional grey theory has been largely criticized for the reason that it treats different indexes (influence factors) equally and takes no account of the relative importance of them, and does not fit with people's preference for specific index, it still has the accuracy and sensitivity in specific experimental scenario for specific factors, so it is better to combine with the results from traditional grey method when we apply the proposed model. Hence, further research is needed to find out more influence factors and navigational scenarios that can conduct a more comprehensive analysis of traffic safety influence factors which affecting autonomous ships maneuvering decision-making.

6. Conclusions

With the development of modern science and technology, the improvement of autonomous ships has been technically feasible. However, autonomous ships maneuvering decisions are influenced by several influence factors. The main propose of our study is to select/prioritize the main influence factors from all the decision-making influence factors, thereby establishing the decision-making model efficiently for our subsequent autonomous ships human-like decision-making algorithm studies.

In this paper, the standardization principle of ships maneuvering is introduced and a innovative grey and fuzzy theories based inference model combined with the expert linguistic terms with different weights is proposed. This model can recognize the main decision-making factors of ships maneuvering from multi-source influence factors, so as to study the decision-making prioritization for maritime traffic safety in specific ships maneuvering scenarios accurately and efficiently, and provide the theoretical basis for decision-making of OOW and improve the maritime traffic safety as well as the programme design for the analysis system of the influence factors of autonomous ships maneuvering decisions in specific scenarios.

In this study, the overall influence factors and ~~the~~ four categories of influence factors are analyzed and prioritized separately. ~~, to recognize the main influence factors and the factors that should be noted in different perspectives of four categories.~~ The result provides ~~the~~ guidance for the OOW's attention to different navigational information ~~in the~~for ships maneuvering decision-making under specific maritime traffic scenarios. It not only emphasizes the main influence factors in the overall attributes but also pays attention to the maritime traffic safety influencing factors and their dynamic change features in each category. The results of the proposed model are more related to real world shipping scenarios~~. Meanwhile, the results~~ and are found to be satisfactory.

In addition, the fuzzy number functions are utilized to apply expert knowledge to the process of the main influence factors selecting/prioritizing of autonomous ships maneuvering decisions, which realizes the identification of the main influence factors. Furthermore, through using the fuzzy theory with expert knowledge, the order of the ranking results of various influence factors ~~got~~ obtained from traditional GRA is changed. The results show that the proposed model improves the ranking results of the influence factors, it is more rational and applicable. Likewise, it provides ~~the~~ guidance for autonomous ships maneuvering decisions. Moreover, with computer assistance, the model proposed in this paper permits an automatic conversion from the comparative series of maritime traffic safety influence factors and the corresponding maneuvering decisions (the combination of ship telegraph and rudder order) reference series to autonomous ships maneuvering influence factors analysis system. The proposed algorithm solves the computational problem of complex fuzzy systems under big data by computer programming (computing advantage), which is of great significance to the development of autonomous ships maneuvering decisions analysis system.

Overall, this paper proposes a prioritizing model for the influence factors of autonomous ships maneuvering decision-making using grey and fuzzy theories. Based on the actual operation data of the experienced seafarers collected from the simulator, a reference series is established by using the combination of ship telegraph and rudder orders which directly corresponding to the control of a ship. Likewise, establish the comparative series for various influencing factors of ship motion, natural and traffic environment which affect ships maneuvering decision-making. Moreover, combined with the expert knowledge, the proposed model is further optimized to ensure the rationality, accuracy, and generalizability of it, to select/prioritize the main maritime traffic safety influence factors of the autonomous ships maneuvering decisions in the specific navigational scenario. The proposed model has the following threefold advantages:

(i) Applying the expert knowledge to the process of autonomous ships maneuvering decisions influence factors prioritizing, furthermore, by establishing fuzzy linguistic terms sets and the corresponding fuzzy numbers, the basis for qualitative evaluation of the influence factors of the autonomous ships maneuvering decision-making is provided. Moreover, through the procedure of defuzzification, the fuzzy numbers are transformed into crisp numbers for priority ranking and comparison purpose. Therefore the analysis of maritime traffic safety influence factors for ~~of~~ autonomous ships maneuvering decision-making can be conducted. Thereby improving the accuracy and rationality as well as expanding the ~~of~~ application scope of the proposed model.

(ii) The weight of each expert and the weight of each influence factor in the whole grey system is introduced to rank and compare the order of various influence factors more reasonable and more accurately. Hence, the importance degree of each influence factor and the preference of decision makers are comprehensively considered according to the actual situation

(iii) The simulator used in this research can simulate various actual navigational scenarios in different ports all over the world, combining with the actual operation data of ~~the~~ experienced seafarers, thus, it can provide a meaningful guidance for the selection/prioritization of the maritime traffic safety influence factors of the autonomous ships maneuvering decisions and promote the development of autonomous ships.

In addition, the innovative and practical model represented in this paper can be utilized and tailored to achieve maritime traffic safety influence factors of autonomous ships maneuvering prioritization in the specific navigational scenario presented in this paper and other modes/scenarios of maritime transportation to improve the traffic safety and efficiency. The results of this research also provide theoretical and practical insights for prioritizing/evaluating the influence factors in the autonomous ships maneuvering and safety management of shipping industry, which can be further applied ~~in~~ to the more general widespread way of the analysis system for autonomous ships human-like decision-making in specific scenarios. In further research, we will explore more about the optimization method for the selection/prioritization of influence factors and use different datasets to further compare the research findings. Moreover, we need to illustrate and combine the expert knowledge in various specific navigational scenarios when we apply our proposed model.

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