New uncertainty modelling for cargo stowage plans of general cargo ships

ABSTRACT
The current approach to the cargo stowage plans (CSP) of general cargo ships (GCS) is safety-driven, which means that any CSP satisfying minimum safety requirements can be used in practice. Such an approach taking into account no economic and environmental concerns cannot help sustain GCS growth in today's competitive freight transportation market. This paper introduces a revised evidential reasoning (ER) approach to cope with the complex decision-making problem associated with the CSP of GCS. The complexity mainly results from the dynamic interdependency between the decision criteria and alternatives. The revised ER can determine the functions of the safety-related criteria in the decision making process by considering the extent to which each decision alternative meets the minimum safety requirements. The model is tested in multiple forms by an empirical study using a national GSC loading laboratory, and a real-life application by a shipping company in practice. The results reveals that the new model can aid general ship owners to make sustainable CSPs from a multiple-dimensional perspective and select an optimal CSP based on specific voyage scenarios.

Keyword: Cargo stowage plan, evidential reasoning, general cargo ships, maritime safety, maritime transport, AHP

1. INTRODUCTION

The modern maritime transport industry has subsectors still experiencing deep rooted and age old problems. Despite the important role general cargo ships (GCS) play in freight transportation, these types of vessels have an opportunity to optimise their operational processes. GCSs can be described as multipurpose vessels, which carry roll-on roll-off (RORO), Load on Load Off (LO-LO) and general cargoes (UNCTAD, 2019). Due to the very nature of shipments they carry, GCSs offer a more bespoke carriage service, which makes manual human intervention from a planning and operation perspective more demanding. With the advent and ongoing development of container ships, the ability to aggregate shipments into standardised carriage grows fast. Nevertheless, some specialised or more general cargos are not suitable to be transported in a standardised box. Consequently, there has been a strong demand on the transportation of the general cargos in the past decade. The data form UNCTAD (2017) indicates that GCSs make up more than 4% of the dead weight tonnage in global shipping. However, fierce shipping competition has recently driven all freight rates down (Christensen and Pacino, 2017; UNCTAD, 2019). Thus, the issue on maintaining GCSs safety standards on the one hand, while increasing commercial competition on the other hand (Yang and Ha, 2017) essentially presents a challenge to stakeholders. In order to address some of the difficulties currently experienced in planning stowage of non-standardised or general cargoes, it is necessary to review and revise the current approach to the cargo stowage plans (CSP) of GCS. The incorporation of the economic and environmental factors into the current safety-driven CSP practice is of great significance.

Research into the cargo stowage problem can be observed back to the early 1990s, mainly in container shipping. Important and specific topics such as decision-support frameworks tackling maritime container stowage (Fazi and Stefano 2019), cargo mix problems (Christensen et al. 2017), algorithms to container ship reduction in re-handing (Ding et al. 2015), allocation of container slots (Parreño, et al. 2016), and pre-planning of container stowage (Wilson, I.D. et al. 2001) only evidence the significant contributions made to optimising container ship stowage operations. Contrastingly, this plethora or information reveals the distinct lack of general cargo stowage planning research conducted to date. Due to the fundamental different features between container and general cargos, the developed methods on container CPSs are not really applicable in GCSs. Here, the general cargo stowage planning refers to the general cargo ship pre-stowage plan (GCSPP) that is to guide the loading process before the ship is loaded. Whereas, the stowage plan, reflecting the actual cargo stowage onboard, is to guide the unloading process after the ship is loaded. The GCSPP plays a crucial role in ensuring the safety of navigation, affecting economic benefits and improving loading efficiency. The traditional evaluation method of GCSPP is qualitative in nature, only concerning the safety criteria set by the associated maritime authorities. When the safety performance of a GCSPP is assured, it becomes a valid plan. When multiple GCSPPs become available, no decision methods are currently available to quantitatively rank them and aid the selection of a rational plan.

This paper aims to develop a revised evidential reasoning (ER) approach to cope with a complex decision making problem reflecting the CSP of GCS, in which decision criteria and alternatives have strong interdependency, and high uncertain in data exist with regards to different GCS voyages. The rest of the paper is organized as follows. Section 2 presents the literature relating to cargo stowage planning onboard ships. Additionally, the ER algorithm and new features of a revised ER are introduced to demonstrate the contributions of this research. Discussions on how the analytic hierarchy process (AHP) and entropy are combined to evaluate the weights of the employed criteria, are undertaken in section 3. To test the validity of the new model, a multiple source approach has been adopted by means of an empirical study in a the national GSC loading laboratory and a real life application of the model in practice for general cargo stowage plan problems are explained in Section 4, with any limitations of potential developments in this research. Finally, this paper is concluded in Section 5.

2. Literature review

GCSs present a special challenge for optimising the loading and unloading of cargoes as depicted in Fig.1, general cargo ships may have multiple decks with different size cargo holds. Some may or may not have the capacity to load containers on deck. Within this research, we define the stowage-planning problem as assigning cargoes to certain vessels positions onboard GCSs. In the reality of placing cargo in a certain position, safety requirements must be met whilst minimising the resources used in loading and unloading of the cargo.

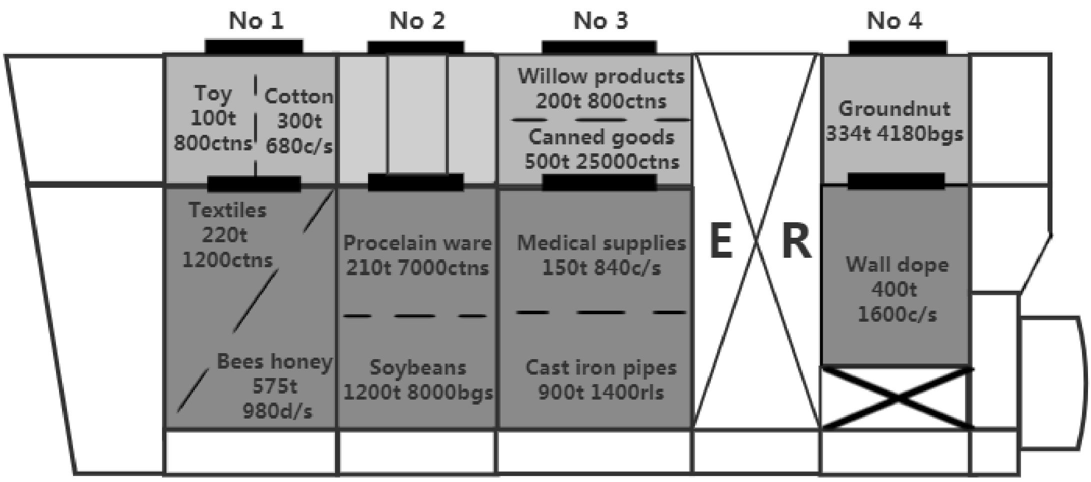

Fig. 1. Example of a general cargo ship stowage plan (Source: Authors)

2.1 The general cargo stowage process

The load planning process can be a shared responsibility between the shipping company planning department and onboard senior officers, depending on company practice. Often, the Chief Mate (Chief Officer) is responsible for preliminary-stowage plan (PRESTOW) verification, whether the plan has been made by a shore side or onboard planner. Pre-stowage planning is a basic plan based on the cargo manifest which accounts for basic characteristics such as weight, package form and special features. The shore side planners will ensure cargo manifests accurately classify the types and quantities of cargos and may prepare a tentative plan assigning cargo to available holds on the vessel based on the latest load plan. However, as the key cargo related decision maker onboard, the Chief has the full accountability for planning, loading (stowage), and securing of the cargo (House 2019) and so assumes full responsibility for the stowage planning to ensure the loading process is conducted in a safe and effective manner. Therefore, the Chief is likely to alter the plan based on their own current knowledge and preference or makes a new plan. When considering the different safety and efficiency factors, this presents a stowage puzzle depending on characteristics of the cargo, vessels safety and stability requirements, the port of loading (POL), Port of discharge or Port of Destination (POD) and behavior of cargo in relation to one another. Careful thought is also given to the unloading process upon arrival at the destination. This inevitably leads to conflicts between what is considered most safe and most efficient, and as these often differ, trade-offs need to be made.

Traditionally, evaluation and verification of the plan will ensure all relevant conventions, protocols, guidelines and regulations are met. Also, the loading operations will be planned and stowed in accordance with company policy. Once this basic legal requirement is satisfied, any optimisation considerations fall under personal experience and preference of the planner, chief officer and master. It means decision makers can create valid safety plans, which may not be very economical or even efficient. Without doubt, this can greatly reduce profitability and competitiveness. At present, economy and efficiency are becoming even more significant in the downturn of the shipping industry (Alexandridis al et., 2018). Hence, huge potential benefits exist in developing an advanced method that can improve the GCS stowage planning practice from the current safety-driven scheme, to a new regime in which more decision parameters such as economic and efficiency are taken into account in a consistent way. Compared to the intelligent cargo stowage plans of other standardized types of cargos (e.g. containers) (e.g. Wilson et al., 2001; Parreno et al., 2016), stowage planning process on general cargo vessels, which the authors hence refer to as GCSPP, is far more complex. Evaluation of the literature reveals the major challenges of GCSPP.

1) Unlike the standardization of containers, each type of general cargos (e.g. clean cargo, dusty and dirty cargo, smelly cargo etc.) has unique characteristics, resulting in diversified transport requirements (e.g. dunnage of cargo, cargo stowage and securing). As a result, the research findings from the mainstream ship CSP studies in the container shipping sector cannot be applied in GCS. Furthermore, the current GCSPP evaluation depends on subjective judgments and experience of decision makers, which often involves subjective bias.

2) Due to the complexity and subjectivity of GCS, the current GCSPP studies fail to present a comprehensive evaluation method involving all the key performance parameters. Instead, it only addresses some factors influencing its CSP, including free surface (Derrett et al., 2012), stowage properties of general cargos (House, 2015) and damaged ship stability (Vassalos et al., 2000). It also reflects the difficulty of collecting the experimental data relating to all the influencing factors for the overall evaluation of GCSPP.

3) In many cases, stowage information provided by cargo owners is incomplete or insufficient. During the process of GCSPP evaluation, the decision makers may encounter the following difficulties. i) The GCSPP evaluation process needs to take into account different factors (e.g. angle, area, moment, pressure, proportion, weight). Some of them are required for quantitative analysis, and the others can only be qualitatively analyzed and estimated. ii) Incomplete and imprecise information (e.g. dunnage of cargo, cargo nature) cannot be tackled by the decision makers without professional evaluation. iii) The decision makers need to predict and calculate the values of criteria (e.g. broken space of cargo) based on uncertain information. iv) There are various rules, conventions and regulations to obey, including Adoption of the International Code on Intact Stability, 2008 (IS CODE, 2008), International Maritime Dangerous Goods Code (IMDG, 2018), International Convention on Load Line (ILLC, 1996), Code of Safe Practice for Cargo Stowage and Securing (IMO, 2011), and Rules for Classification of Sea-going Steel Ships (RCS, 2013)) by the International Maritime Organization (IMO).

4) GCSPP represents an under-research decision problem of which decision criteria and alternatives have strong functional interdependency. The functions of the decisive (i.e. safety-related) depend on the extent to which each GCSPP meets the minimal requirements of each safety related criterion. The extent is defined as a safety margin in GCSPP, and the definitions of a large and small safety margin with reference to the related safety criteria are dynamic, influenced by the navigation risk of a specific voyage.

2.2 Evidential reasoning

D-S evidence theory was first put forward by Dempster in 1960s and further developed and improved by Shafer in 1976. (Shafer, 2016). The ER approach is based on the D-S theory in which a belief function is employed to measure the uncertain and unknown issue. The ER algorithms have been continuously developed and improved, the one by Yang and Singh (1994) can effectively deal with both qualitative and quantitative information under uncertainty and hence has been widely applied to solve multiple criteria decision making (MCDM) problems, such as navigational risk assessment (Zhang *et al*., 2016); financial investment (Gao and Xu, 2018); identification of accident-prone sections (Sadeghi *et al.*, 2018); human reliability (Xi et al., 2018) and handling ships (Wu *et al*., 2018). Furthermore, the ER algorithm has been improved by Yang and Xu (2002) to aggregate all output from grades of each criteria to generate a rational conclusion. The latest ER algorithm is described as follows, while a numerical illustration of its calculation is provided in Appendix A.

To capture the non-linear relationship between different sets R_k (k = 1, 2, …, L), the *ER* approach (Yang and Singh, 1994; Yang and Xu, 2002) is used to combine all belief degrees β_j^k (j = 1, 2, …N) assigned to the j^{th} grades in R_k and generate a final conclusion. Having represented belief degree distributions β_j^k, the *ER* approach can be implemented as follows. First, it is required to transform the degrees of belief β_j^k for all j = 1, 2, …N, k = 1, 2, …, L into basic probability masses using the following equations (Yang and Xu, 2002; Liu *et al.*, 2005):

$$m_j^k = \theta_k \beta_j^k \tag{1}$$

$$m_D^k = 1 - \sum_{j=1}^{N} m_j^k = 1 - \theta_k \sum_{j=1}^{N} \beta_j^k \tag{2}$$

$$\overline{m}_D^k = 1 - \theta_k , \tag{3}$$

$$\tilde{m}_D^k = \theta_k \left(1 - \sum_{j=1}^{N} \beta_j^k\right) \tag{4}$$

where m_j^k are individual degrees to which each R_k supports the final synthesised conclusion D; θ_k represents the relevant importance of R_k and thus, $\sum_{k=1}^{L} \theta_k = 1$; and $m_D^k = \bar{m}_D^k + \tilde{m}_D^k$ for all $k = 1, 2, \ldots, L$.

The probability mass of R_k (m_D^k) unassigned to the final synthesised conclusion D, which is unassigned to any individual output variables D_j, is split into two parts, one caused by the relative importance of the k^{th} rule ($\bar{m}_D^k$), and the other due to the incompleteness of the belief degree assessment β_j^k ($\tilde{m}_D^k$).

Then, it is possible to aggregate all the output from R_k ($k = 1, 2, \ldots, L$) to generate the combined degree of belief (β_j) in each possible D_j of D. Suppose $m_j^{I(k)}$ is the combined belief degree in D_j by aggregating all the output from the k rules and $m_D^{I(k)}$ is the remaining belief degree unassigned to any D_j. Let $m_j^{I(1)} = m_j^1$ and $m_D^{I(1)} = m_D^1$. Then the overall combined belief degree in D_j is generated as follows (Liu *et al.*, 2005).

$$\{D_j\}: \; m_j^{I(k+1)} = K_{I(k+1)}[m_j^{I(k)} m_j^{k+1} + m_j^{I(k)} m_D^{k+1} + m_D^{I(k)} m_j^{k+1}] \tag{5}$$

$$m_D^{I(k)} = \tilde{m}_D^{I(k)} + \bar{m}_D^{I(k)} \qquad k = 1, 2, \ldots\ldots, L-1 \tag{6}$$

$$\{D\}: \; \tilde{m}_D^{I(k+1)} = K_{I(k+1)}[\tilde{m}_D^{I(k)} \tilde{m}_D^{k+1} + \tilde{m}_D^{I(k)} \bar{m}_D^{k+1} + \bar{m}_D^{I(k)} \tilde{m}_D^{k+1}] \tag{7}$$

$$\bar{m}_D^{I(k+1)} = K_{I(k+1)}[\bar{m}_D^{I(k)} \bar{m}_D^{k+1}] \tag{8}$$

$$K_{I(k+1)} = \left[1 - \sum_{j=1}^{N} \sum_{\substack{t=1 \\ t \neq j}}^{N} m_j^{I(k)} m_t^{k+1}\right]^{-1}, \; k = 1, 2, \ldots, L-1 \tag{9}$$

$$\{D_j\}: \beta_j = \frac{m_j^{I(L)}}{1 - \bar{m}_D^{I(L)}} \; (j = 1, 2, \ldots, N) \tag{10}$$

$$\{D_j\}: \beta_D = \frac{\tilde{m}_D^{I(L)}}{1 - \bar{m}_D^{I(L)}} \tag{11}$$

where β_j indicates the normalised belief degree assigned to D_j in the final synthesised conclusion D and β_D represents the normalised remaining belief degree unassigned to any D_j.

ER can accommodate both qualitative and quantitative information under uncertainty in a decision-making problem (Zhang al et. 2017). It therefore shows potential of addressing some aforementioned research challenges in GCSPP evaluation. However, in GCSPP the traditional ER cannot be used to cope with the functional interdependency between the decisive criteria and alternative. In this paper, a new feature is added to revise ER in Section 2.3.

2.3 A revised ER with a new feature

In the traditional ER algorithm, all the criteria have an impact on the synthetic result. This feature constrains the application of the ER algorithm in the situations where the functions/weights of decisive criteria vary, depending on how much they can meet the minimal requirements in a particular case. In this study, the minimal requirements of the safety related criteria are changeable depending on various factors influencing the safety at sea. In this study, when an alternative (i.e. a stowage plan) performance against a decisive criterion (e.g. safety) does not meet the mandatory requirement of relevant rules, conventions, and regulations, it fails. If all the CSPs meet the minimal requirements of all the safety related criteria with a large margin[1], then they will be evaluated by all non-decisive criteria (e.g. cost and efficiency) only. If the CSPs meet the minimal requirements of some safety criteria marginally, the weights of such safety criteria will be thoroughly calculated and rationalized accordingly in the decision-making process. The smaller the safety margins are, the higher the associated criterion weights.

The complicated relationship between the dynamic interdependency between the decision criteria and alternatives in CSPs stimulates the study on a revised ER. The revised ER can determine the functions of the decisive criteria in the decision making process by considering the extent to which each decision alternative meets the minimum safety requirements. The core of the revised ER method is to ensure the rationality of the ER algorithm by coordinating the functional relationship between decision criteria (i.e. decisive and non-decisive) and alternatives. The decisive criteria have mandatory requirements from relevant rules, conventions and regulations. It will therefore provide a solution to a particular type of MCDM problems in which the criterion weights/functions are affected by the alternative performance. For example, in this study if the loading weight causes the waterline to exceed the approved load line, this means that the information ‘Ship overload’ does not meet the mandatory requirements of the ILLC. It will result in the risk of navigation. Hence, ‘Ship overload’ is a decisive criterion.

In the revised ER approach, the first step is to identify decisive criteria based on the mandatory requirements of the relevant rules, conventions and regulations, such as 2008 IS CODE, IMDG, CCS, and so on. For example, the segregation of dangerous cargos has the mandatory requirement according to the IMDG and hence it is decisive criterion. In addition, some shipping companies have special requirements for certain criteria in GCSPP. For instance, a ship trim must range between -1.6 m and -1.2 m. This type of the information also makes ship trim a decisive criterion.

The second step is to set the thresholds according to the mandatory requirements of the relevant rules, conventions and regulations and then use them to screen all decisive criteria. For different types of decisive criteria, thresholds can be set either quantitative or qualitative. For example, 0.15 meters can be

[1] The large margin is defined against the industrial practice by shipping companies with reference to the navigational risk of a particular voyage, taking into account various factors such as the shipping routes, season, and the accidents occurred in the same/similar voyages.

set as a quantitative threshold of initial metacentric height (GM) based on the 2008 IS CODE, and 'Segregated from' can be set as the qualitative threshold of the cargos 'Calcium carbide' (CaC_2) and 'Sodium nitrate' ($NaNO_3$) based on the IMDG. It should be particularly noted that, due to the safety considerations, most shipping companies have higher margins on the decisive criteria than the ones from the relative rules, conventions and regulations in GCSPP practice.

The third step is to use the hybrid of entropy and AHP to quantify the weights of the retained decisive and non-decisive criteria. In the revised ER method, the combined entropy and AHP is used in a complementary way, in which entropy is used to measure the difference of all the target alternatives in terms of their values against the decisive criteria (to generate weight w_E), while the AHP is applied to reflect the margins of the values away from the minimal requirements of the criteria (to estimate w_A)[2].

3. A HYBRID METHODOLOGY FOR GCSPP SELECTION

After the identification of all the criteria influencing GCSPP, the revised ER approach is applied for GCSPP evaluation. A hierarchical decision table is established by the selected domain experts based on the relationship between different criteria, and the relative weights of the criteria are obtained by a combined entropy and AHP approach. When the performance of all the available GCSPP against the lowest level criteria are transformed and expressed by the top level criterion with a belief degree structure, they can be ranked using the utility theory for selecting the best GCSPP. The framework of the proposed hybrid model for GCSPP evaluation is shown in Fig.2 and detailed in the following sections.

[2] The detailed weight calculation is presented by Equation 11 in Section 4.4. For the development of a generic GCSPP model, CSPs are evaluated against the minimum safety requirements by the international regulations. Their weights are calculated by AHP in real case studies, while the analysis of the entropy weights are added in the sensitivity analysis in which we adjust the weights by taking into account the high safety margins from shipping companies at different levels. For not losing the generality of the model, the combined weights are presented in Section 4 (comparative analysis).

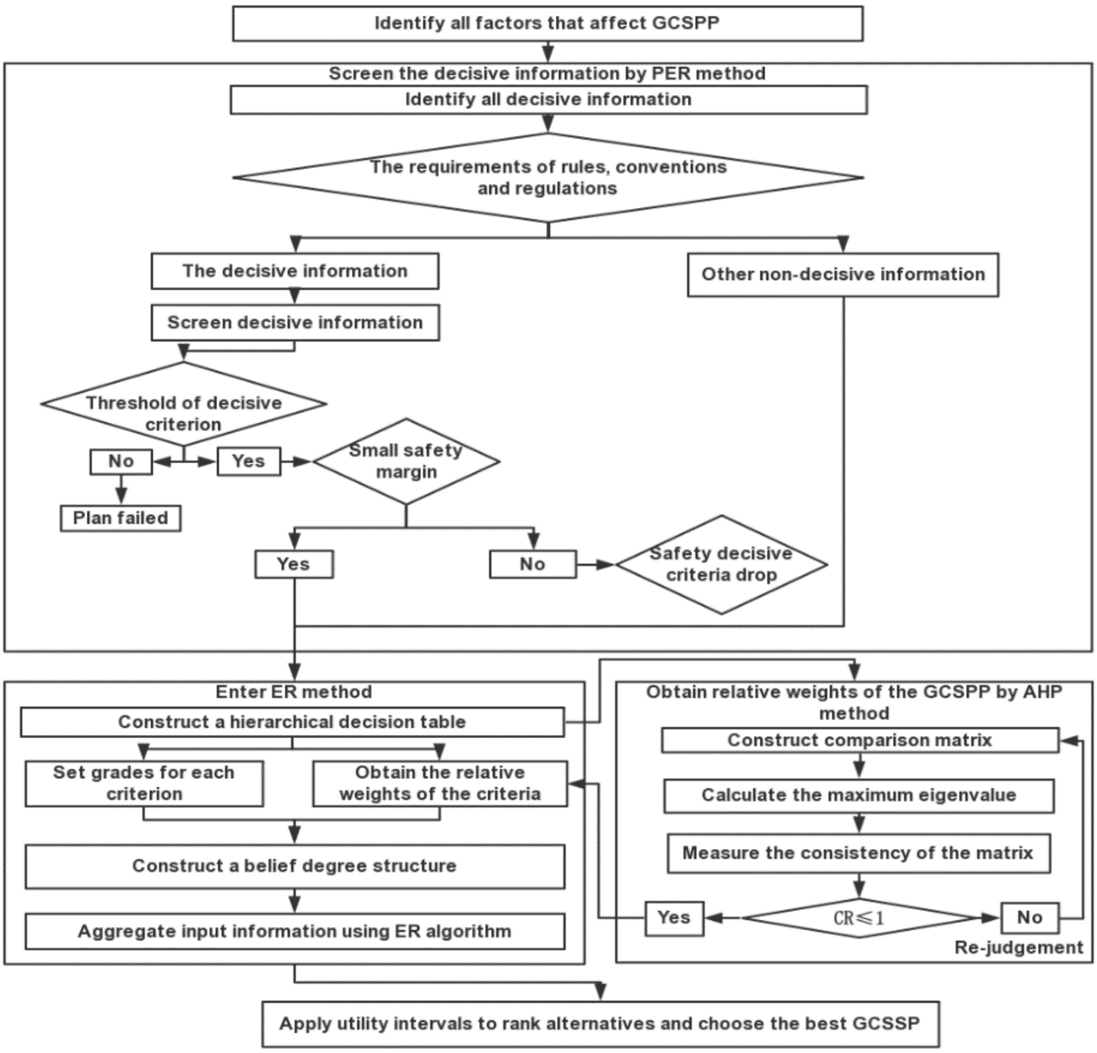

Fig.2. The framework of hybrid model for GCSPP evaluation

3.1 Identify all criteria influencing GCSPP

The appropriate decision criteria have been obtained from multiple sources to ensure validity and robustness. Survey by questionnaire and follow up pilot studies with domain experts have been carried out and are described in the remainder of this section.

3.1.1 Questionnaire design

Based on knowledge from relevant literature, criteria influencing GCSPP have been evaluated by domain experts through a structured semi-structured questionnaire. The content of the questionnaire is presented in three parts. The first part screens the participants background to ensure they have sufficient experience, knowledge, skills and overall expertise in the subject matter. Within the second part a list of influential criteria is included. This has been designed for domain experts to choose the most relevant. These factors are initially selected from the literature, including the rules, conventions and regulations related to GCSPP that are then further verified in a pilot study. The final part requires participants to prioritise and modify, where appropriate, the criteria. Allowing for the removal of irrelevant criteria, merging the seemingly synonymous criteria, include additional unaccounted for (in the literature) criteria. The pilot study was carried out with two domain experts (i.e. 2 professors with more than 10 years research and teaching experience in marine cargo operations, and both have captain certificates).

3.1.2 Select the appropriate respondents

Using the purposive sampling (Topp et al., 2004), respondents were targeted if they had the sufficient comprehension of the complexity of the problem and were able to give appropriately reflective opinion for their field and roles held. Despite this requirement, experts who have similar knowledge and working backgrounds may still have different judgments about the contents and number of criteria. Hence the robustness provided by the follow up study. The selected experts must have good understanding of GCSPP as well as rich practical work experience in the industry. Consequently, participant selection was based on the following features:

- All the experts are working on general cargo stowage planning problems in practice.
- Experts where sourced from different shipping companies in different countries.
- All experts have an extensive work experience and held senior posts for general cargo ship operations.

Aided by Jiangyin pilot station and Jinzhou maritime bureau in China, 18 domain experts were successfully recruited. Participants were from 15 different shipping companies in six different countries (China, Korea, Philippines, Vietnam, Turkey, Greece), including 13 captains and 5 first mates (chief officers). Four of them have been working on general cargo ships for more than 30 years, and the average working time of all experts is more than 18 years.

3.1.3 Results of the questionnaire

The questionnaire was conducted from the beginning of April to the end of May 2018. After summarizing the result of the questionnaire based on the Delphi technique, through multiple iterative feedback discussions, the experts suggested that some criteria were deleted, segmented or merged into new criteria. For example, the sub criterion of the 'Ship stability' was originally segmented as 'Static stability', 'Dynamic stability', 'Damaged stability', and 'Torsional stability' but 9 experts emphasized that only on container ships and very large bulk carriers (VLBC) 'Torsional stability' needs to be considered. Therefore, 'Torsional stability' was removed from this study. Moreover, to distinguish between the different natures of cargos, the 'Nature of the cargos' was segmented into 'Mechanical properties' and 'Biological characteristics'. Furthermore, 'Stowage factor' and 'Ratio of broken space' were considered to be overlapping terms. Hence, 'Broken space of cargo' was used to represent the combination of 'Stowage factor' and 'Ratio of broken space'.

Finally, the 13 criteria and sub-criteria were identified and verified. They included 'Ship stability', 'Ship strength', 'Segregation of dangerous cargo', 'Healing angle[3]', 'Ship overload', 'Cargo stowage and securing', 'Damage of cargo', 'Broken space of cargo', 'Ship trim[4]', 'Locations of the optional cargos'(LOC), 'Locations of cargos in the first arrival port'(LCF), 'Locations of cargos in the intermediate arrival port'(LCI), and 'Location of cargos in the final arrival port'(LCFP). It is noteworthy that such factors are generic, and they can be amended to fit specific scenarios. For example, when there is no optional cargo in the loading list, there is no need to consider the 'Locations of the optional cargos'.

3.2 Screen the decisive safety criteria

[3] Heeling angel is defined as the amount a vessel is heeled from the upright due to waves and/or winds

[4] Ship trim is defined as the difference between the draft forward and the draft aft.

Firstly, the mandatory requirements in the relevant safety rules, conventions and regulations (e.g. 2008 IS CODE, IMDG, ILLC, CSS, and RCS, etc.,) are used to determine that 5 out of 13 criteria are decisive, including 'Ship stability', 'Ship strength', 'Segregation of dangerous cargo', 'Ship overload', 'Cargo stowage and securing'. Secondly, the actual values used to set the thresholds are obtained from the loading instrument of general cargo ships with reference to the safety rules, conventions and regulations.

3.3 Construct a hierarchical decision table

A hierarchy decision table helps clarify the relationship between different level criteria and visualize the process of GCSPP evaluation. For example, 'AGZ' means the area under a righting lever curve, 'GZ30°' is the value of the righting lever GZ when the heeling angle is equal to 30°, and 'θGZ_{MAX}' is the heeling angle corresponding to the maximum righting lever. After the initial analysis, five experts were employed to classify all criteria with respect to the three dimensions 'Safety', 'Economy' and 'Efficiency', and then determine relationship between criteria (e.g. 'Damage of cargo' contains 3 sub-criteria 'Avoidance of mixed cargo', 'Nature of cargo' and 'Dunnage of cargo'). As a result, 13 third-level criteria, 9 fourth-level criteria, and 7 fifth-level criteria under the three first-level dimensions (i.e. 'Safety', 'Economy' and 'Efficiency') are presented in Fig. 3.

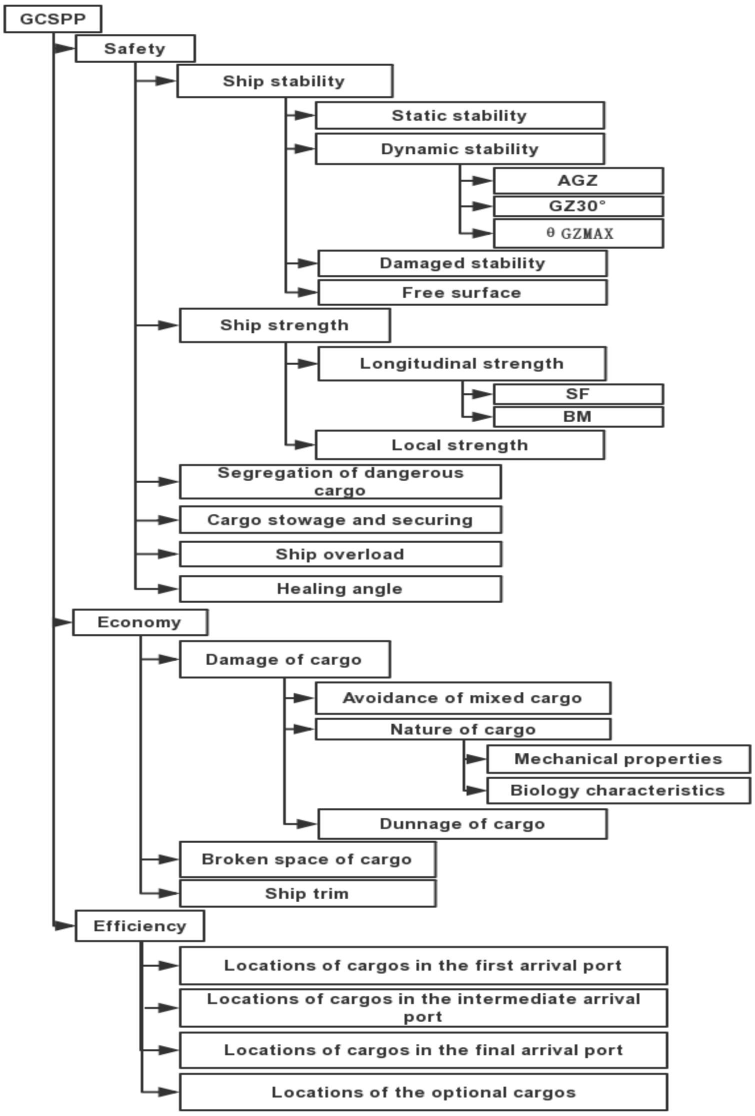

Fig.3 Hierarchical decision table of candidate GCSPPs

Safety. It is the most important dimension in GCSPP evaluation. Its six sub-criteria include the 'Ship stability', 'Ship strength', 'Segregation of dangerous cargo', 'Ship overload', 'Heeling angle', and 'Cargo stowage and securing'. 'Ship stability' is the ability of a ship to return to a balanced location without capsizing when the ship is subjected to external forces or external moments (Francescutto, 2016). It is concerned with 'Static stability', 'Dynamic stability', 'Damaged stability' and 'Free surface' (Vassalos et al., 2000). The 'Dynamic stability' is determined by 'AGZ', 'GZ30°' and 'θGZ_{MAX}'. 'Ship strength' refers to the ability of a ship's hull structure to resist various external forces under specified conditions without causing serious deformation or damage (Tekgoz et al., 2018), which contains 'Longitudinal strength' and 'Local strength'. The 'Longitudinal strength' can be measured using the 'Shear force' (SF) and 'Bending moment' (BM). 'Segregation of dangerous cargos' is the process of separating two or more incompatible substances or items. If they are packed or stowed together, there will be a danger in the event of leakage or other accidents (Barbucha and Filipowicz, 1997). 'Ship overload' means that the loading weight causes the waterline to exceed the approved load line. It can result in insufficient of reserved buoyancy of a ship (ILLC, 1996). 'Heeling angle' is the angle of the transverse inclination caused by the difference in weights between port and starboard after loading (Woodward *et al.*, 2016). The greater of a heeling angle, the worse the ship's ability to resist wind and waves. 'Cargo stowage and securing' refers to how the cargo is arranged on a ship, stacking, and effective securing. It also contains the analysis and method of the force calculation of the cargo unit (CSS, 2011).

Economy. It is related to three third-level criteria 'Damage of cargo', 'Broken space of cargo', and 'Ship trim'. 'Damage of cargo' is the loss of quantity or quality in the process of transportation, loading, unloading and maintenance of cargos. It is crucial for reducing transportation cost of the cargos (Xu et al., 2010), caused by 'Avoidance of mixed cargo', 'Dunnage of cargo' and 'Nature of cargo'. 'Broken space of cargo' is defined as the difference between the volume occupied by the cargo in the hold and the measured volume of the cargo. For the cargo in the same loading list, the lower the ratio of broken space of cargo, the more economic the pre-stowage plan is. 'Ship trim' is the difference between the draft forward and the draft afterward. The moderate 'Ship trim' can reduce the ship voyage resistance and fuel consumption, and hence the transportation cost (Perera et al., 2015).

Efficiency. Efficiency of GCSPP is mainly evaluated by the speed of loading and unloading operations in port. It is affected by the locations of the cargos. When the locations of the cargos to be unloaded later blocks those to be discharged earlier, it requires cargo shift, and seriously reduce the efficiency of loading/unloading operations. Therefore, all the locations of cargos should be considered in a sequence of their loading/unloading order, including such influencing factors as 'Locations of optional cargos', 'Location of cargos in the first arrival port', 'Location of cargos in the intermediate arrival ports', and 'Location of cargos in the final arrival port'.

3.4 Set grades for each criterion

All the decision criteria need to be properly graded to help decision makers assess GCSPPs when using ER (Xu et al., 2008). The setting mainly depends on the type of criterion and the expert's experience. For the criterion of quantitative input information, the quantitative grades will be set. For example, the grades of 'Healing angle' is set by quantitative grades ('0.3°', '0.1°', '0°'). These quantitative grades are derived from industrial norms and relevant rules (e.g. Derrett et al., 2012). For the criterion of qualitative input information, the subjective linguistic grades are appropriately used. For example, the grades of 'Cargo stowage and securing' can be denoted by qualitative linguistic terms (Loose, Common, Firm). These linguistic grades are derived from the relevant literature (e.g. House, 2015) or the experience of domain experts when the previous studies are not available. All the criteria grades are given their specific definitions to aid decision makers to make the evaluation with confidence. The questionnaires were distributed to two groups of experts, deck officer group (e.g. 5 captains) and academic group (e.g. 3 professors). The five captains are from the selected respondents in Section 3.1, and the three professors with each of more than 15 years research and teaching experience in the cargo stowage-planning field are from two world leading maritime universities. After completing the questionnaire, the two groups of questionnaires were interchanged to find the differences and give explanations and corrections until two group members had a consensus on the final results. Due to the diversity of cargos involved in the GCSPP, it is difficult to provide a uniformed grade setting for all the criteria. The specific grades are given to the specific criteria for further illustration in the case study in Section 4.

3.5 Transform the input data at the lowest level to the output at the highest level of the hierarchy

After obtaining the relative weights of all criteria by a combined entropy and AHP method (Chen et al., 2018), the GCSPP belief degree structure is established by using a fuzzy mapping technique. The fuzzy mapping technique is used to express the correlation and similarity between two fuzzy sets (Liu and Noor, 2012). The utility theory is used to establish belief degree distribution channels and obtain a uniform dimension for different criteria grades (Dragan and Ivana, 2015). A part of GCSPP belief degree structure is shown in Fig.4, while the detailed belief degree transformation method is seen in Yang et al., (2009b).

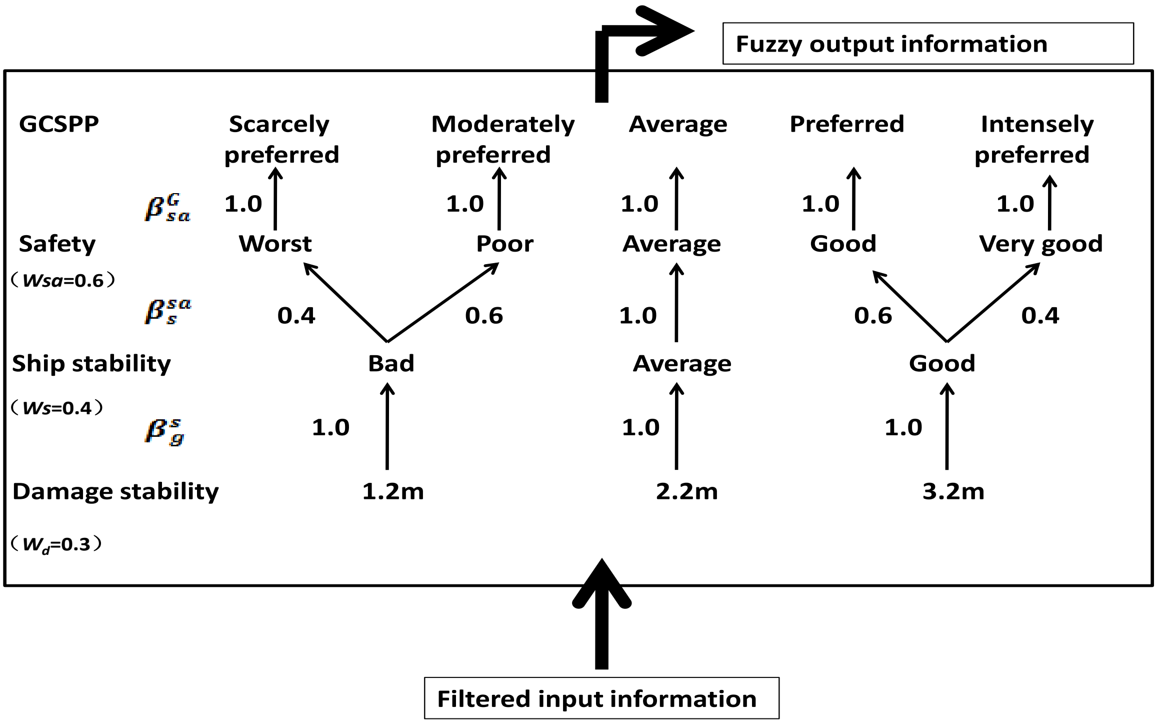

Fig.4. An example of GCSPP belief degree structure

The synthesis of information begins with the input information from the lowest level criteria. Qualitative criteria are directly judged by domain experts based on the definitions of the grades. For quantitative criteria, the specific location measurement method is used (Yang et al., 2009b). For instance, a 0.3m value of 'GZ30° is calculated to have 50 per cent degrees of belief belonging to 0.2 m and 50 per cent belonging to 0.4 m. Then, with the help of the ER algorithm (see Section 2.1) and its associated intelligent decision software called Intelligent Decision System (IDS) (Yang and Xu 2000), the output expressed by the degrees of belief of the criterion grades can be obtained at the highest level.

3.6 Apply utility intervals to rank alternatives and choose the best GCSPP

It is difficult for decision makers to accurately compare different GSCPPs based on the linguistic terms. Therefore, the utility interval technique is applied to rank all the alternatives (Yeo et al., 2014). β_j is the belief degree of grades of output, U_j is the utility value of the j^{th} linguistics grade, R_C represents the possible average preferred synthesized result by the possible most preferred R_B and the possible worst preferred R_W. Therefore, the larger R_C , the more preferred the associated GCSPP is.

$$R_C = \sum_{j=1}^{N} \beta_j U_j, when \sum_{j=1}^{N} \beta_j = 1 \; or \tag{12}$$

$$R_B = \sum_{j=2}^{N} \beta_j U_j + (\beta_1 + \beta_D)U_1$$

$$R_W = \sum_{j=1}^{N-1} \beta_j U_j + (\beta_N + \beta_D)U_N \tag{13}$$

$$R_C = \frac{R_B + R_W}{2}, when \sum_{j=1}^{N} \beta_j < 1$$

Here β_D means the unassigned synthesized degree of belief. It should be noted that to choose the best GCSPP, the stakeholders can adjust the relative weights of criteria in the GCSPP based on the specific transportation conditions. For example, when many dangerous goods cargoes are to be loaded or the ship will pass through a high-risk area, the weight of the criterion 'Safety' is increased. When there is already ample voyage or loading time compared to shipping schedule, the relative weight of the criterion 'Efficiency' can be appropriately decreased. As a result, the ranking of the alternatives will change, reflecting the dynamics and diversity of general cargo shipping.

4 APPLICATION OF THE REVISED ER TO GCSPP EVALUATION

4.1 Background information

To test and verify the revised ER model, the ship pre-stowage system in a national-level cargo loading laboratory is used for the experiment of GCSPP evaluation. One of the functions of the system is to offer specific simulation assessment questions based on the experimenter's requirements such as the type and dimension of the ship, the quantity and type of cargos in the loading list, port of loading (POL), port of discharge (POD), the navigational zones, and so on. Meanwhile, the corresponding contextual requirements are set for the criteria of GCSPP (i.e. the range of ship trim). Another function is to collect the experimental result from the GCSPP. The representative GCS type and loading list are selected to simulate GCSPP. The main parameters of the selected GCS and loading list are shown in Tables 1 and 2, respectively.

Table 1. Main parameters of the selected general cargo ship

Main parameter	Parameter values	Main parameter	Parameter values
Δ_L	5565.01t	L_{BP}	148.0m
B	21.2m	D	12.5m
Δ_T	20205.0t	d_T	9.392m
Δ_S	19710.0t	d_S	9.200m
Δ_W	19215.0t	d_W	9.008m
C	220t	$\sum G_l$	18t

Table 2. Selected loading list of simulation assessment question

S/0 NO.	Name of cargos	POD	Weight (tons)	Volume （m3）	Package	Nature of cargos
1	Bitter almond	B	825	1650	Bags	Smelling cargo
2	Camphor	B	300	600	Cases	
3	Milk powder	B	600	1272	Cases	
4	Willow products	B	200	1760	Cartons	Fragile cargo
5	Tungsten iron	B	1100	1243	Drums	
6	Chloropicrin	C	300	438	Drums	Dangerous cargo
7	Lithopone	C	700	882	Bags	
8	Magnesia dead-burned	C	3200	2624	In bulk	
9	Honey	C	540	756	Drums	
10	Cotton fabric	C	300	1140	Cases	

The simulation assessment question is that ship X loaded at port A, and the POD is port B. It is required that the fuel oil and fresh water tanks are full at port A, the range of ship trim must be between -1.6m to 0.0m, and the summer load line is used for this voyage. Five captains carried out the experimenters to complete five candidate GCSPPs for evaluation.

4.2 Case analysis

4.2.1 Identify the active criteria in the case

From the simulation experiment, irrelevant factors such as ‘Locations of the optional cargos’, ‘Locations of cargos in the intermediate arrival port’, ‘Segregation of dangerous cargo’ and ‘Cargo stowage and securing’ that fit in general CSP are removed from this specific case GCSPP.

4.2.2 Determine the decisive criteria

Among the retained 9 factors, 4 (i.e. ‘Ship stability’, ‘Ship strength’, ‘Ship overload’, and ‘Ship trim range’) are decisive based on the relative rules, conventions, rules and simulation assessment questions. The 4 decisive criteria contain 10 sub criteria in total, and their thresholds are shown in Table 3.

Table 3. The thresholds of the decisive criterion

Criterion	Threshold	Relative rules, convention
GM	0.15 m	2008 IS CODE
AGZ	0.055meter-radians (angle of heel range between 0 ° and 30°） 0.09 meter-radians (angle of heel range between 0 ° and 40° or the angle of down-flooding φ_f if this angle is less than 40^0） 0.03 meter-radians (angle of heel range between 30 ° and 40° or the angle of down-flooding φ_f if this angle is less than 40^0）	2008 IS CODE
$GZ30^0$	0.2 m	2008 IS CODE
θGM_{MAX}	25 °	2008 IS CODE
GM_d	1.2 m	RCS
SF	Maximum allowable value	RCS
BM	Maximum allowable value	RCS
Local strength	Maximum allowable value	RCS
Overload	19710.0t	ILLC

Trim range	-1.6m~0.0m	Assessment question

All the decisive information in five candidate GCSPPs must be screened in order to meet the above thresholds. Take the 5th GSCPP as an example, since the decisive information GM=0.11m is smaller than the threshold GM=0.15m, it is eliminated given it does not satisfy the minimal requirements of 2008 IS CODE. The other 4 GCSPPs meet the thresholds and will be evaluated by the revised ER approach. However all the plans have small safety margins to pass some decisive criteria (e.g. GM≥0.15m). As a result, all the criteria are taken into account in the final decision process.

4.2.3 Set the grades for all the hired criteria

The grades of each criterion and sub-criterion need specific definitions based on its own characteristics to aid rational decision making. For example, the grades of first level criteria and the definition of grades of 'Safety' are shown in Tables 4 and 5, respectively.

Table 4. Grades defined for the second level criteria

Criteria	Grades				
Safety	Worst	Poor	Average	Good	Very good
Economy	Very bad	Bad	Average	Good	Very good
Efficiency	Low		Average		High

Table 5. The definitions of the grades defined for the 'Safety'

Grades of 'Safety'	Definitions
Worst	Most criteria of the relevant conventions, rules and shipping company requirements have just reached the minimum standards. However, there are obvious security risks. Navigation is at risk when weather conditions in the shipping route become critical or accidents occur during the voyage.
Poor	A few criteria of the relevant conventions, rules and shipping company requirements exceed the minimum standards. However, there is not enough capacity for the ship to be risk-free.
Average	Most criteria of the relevant conventions and rules have reached an acceptable level. However, there is still a potential safety hazard.
Good	Most criteria of the relevant conventions and rules have been satisfied with a high safety margin, although there is still safety room for improvement.
Very good	All criteria of the relevant conventions and rules have been met with the highest safety margin. When the weather conditions in the navigational zone deteriorate or accidents occur during navigation, the ship safety is still guaranteed.

4.2.4 Assign the weights of active criteria

Five experienced captains of GCS from three countries (China, Hungary, and Greece) evaluated the relative weights of the criteria by an AHP method. The results of the criterion weights are shown in Table 6.

Table 6. The relative weights of criteria in GCSPP

2nd level	3rd level	4th level	5th level
Safety 0.67	Ship stability 0.43	Static stability 0.36	
		Dynamic stability 0.36	AGZ 0.36
			GZ30° 0.32
			θGZ_{MAX} 0.32
		Damaged stability 0.24	
		Free surface	

		0.04	
	Ship strength 0.43	Longitudinal Strength 0.59	SF 0.5
			BM 0.5
		Local strength 0.41	
	Ship overload 0.03		
	Healing angle 0.11		
Economy 0.22	Damage of cargo 0.55	Avoidance of mixed cargo 0.62	
		Nature of cargo 0.27	Mechanical Properties 0.72
			Biology Characteristics 0.28
		Dunnage of cargo 0.11	
	Broken space of cargo 0.16		
	Ship trim 0.29		
Efficiency 0.11	LCF 0.69		
	LCFP 0.31		

4.2.5 Transform the input data from the lowest level criteria to GCSPP

With the establishment of the belief degree structure of GCSPP (e.g. Fig 3), input information will be transformed in the form of degrees of belief from the lowest level criteria. For instance, the assessment of the 1st GCSPP against the 19 lowest level criteria is shown in Table 7.

Table 7. The transformation of the assessment of the 1st GCSPP against the lowest level criteria

The lowest level criteria	The evaluation of the 1st GCSPP	Transformed output data in GCSPP
Static stability	0% bad, 0% average, 100% good	0% scarcely preferred, 0% moderately preferred, 0% average, 60% preferred, 40% intensely preferred
AGZ	0% bad, 70% average, 30% good	0% scarcely preferred, 0% moderately preferred, 30% average, 42% preferred, 28% intensely preferred
GZ30°	0% 0.2m, 60% 0.4m, 40% 0.6m	0% scarcely preferred, 0% moderately preferred, 60% average, 24% preferred, 16% intensely preferred
θGZ_{MAX}	0% 25°，80% 35°，20% 45°	0% scarcely preferred, 0% moderately preferred, 80% average, 12% preferred, 8% intensely preferred
Damaged stability	0% 1.2m, 40% 2.2m, 60% 3.2m	0% scarcely preferred, 0% moderately preferred, 40% average, 36% preferred, 24% intensely preferred
Free surface	0% 1.1m, 52% 0.6m, 48% 0.1m	0% scarcely preferred, 0% moderately preferred, 48% average, 31.2%preferred, 20.8% intensely preferred
Shear force	25% very big, 35% big, 40% moderate, 0% small, 0% very small	25% scarcely preferred, 35% moderately preferred, 40% average, 0% preferred, 0% intensely preferred
Bend moment	10% very big, 20% big, 70% moderate, 0% small, 0% very small	10% scarcely preferred, 20% moderately preferred, 70% average, 60% preferred, 40% intensely preferred
Local strength	0% very weak, 0%weak,40%moderate, 50% strong, 0% very strong, 10% unknown	0% scarcely preferred, 0% moderately preferred, 40% average, 50% preferred, 0% intensely preferred, 10% unknown
Ship overload	0% bad, 0% average, 100% good	0% scarcely preferred, 0% moderately preferred, 0% average, 60% preferred, 40% intensely preferred

Healing angle	0% 0.3°，0% 0.1°，100% 0°	0% scarcely preferred, 0% moderately preferred, 0% average, 0% preferred, 100% intensely preferred
Avoidance of mixed cargo	0% very bad, 0% bad,10%average,10% good, 60% very good, 20% unknown	0% scarcely preferred, 0% moderately preferred, 10% average, 10% preferred, 60% intensely preferred, 20% unknown
Mechanical properties	10% fragile, 25%firm, 30% very strong, 35% unknown	4% scarcely preferred, 6% moderately preferred, 25% average, 18% preferred, 12% intensely preferred, 35% unknown
Biology characteristics	15% lively, 20% common, 25% inactive, 40% unknown	6% scarcely preferred, 9% moderately preferred, 20% average, 15% preferred, 10% intensely preferred, 40% unknown
Dunnage of cargo	10% bad, 25% average, 20% good, 45% unknown	4% scarcely preferred, 6% moderately preferred, 25% average, 12% preferred, 8% intensely preferred, 45% unknown
Broken space of cargo	0% very big, 20% big, 35% average, 15% small, 0% very small, 30% unknown	0% scarcely preferred, 20% moderately preferred, 35%average, 15% preferred, 0% intensely preferred, 30% unknown
Ship trim	0% 0m, 0% -0.4m, 0% -0.8m, 62.5% -1.2m, 37.5% -1.6m	0% scarcely preferred, 0% moderately preferred, 0% average, 62.5% preferred, 37.5% intensely preferred
Locations of cargos in the first arrival port	0% bad, 20% average, 80% good	0% scarcely preferred, 0% moderately preferred, 20% average, 48% preferred, 32% intensely preferred
Locations of cargos in the final arrival port	0% bad, 20% average, 80% good	0% scarcely preferred, 0% moderately preferred, 20% average, 48% preferred, 32% intensely preferred

4.2.6 Synthesis of the transformed data for GCSPP

Using the ER algorithm and its software IDS, the overall evaluation results of the four candidate GCSPPs are presented by linguistics grades with degrees of belief in Table 8. Their crispy numerical values are obtained using the utility interval by Eq. (13) and presented in Table 9. It is noteworthy, when one GCSPP is superior to another with certainty, the worst possible value of the preferred GCSPP must be greater than the best possible value of the compared one. Consequently, the 1st GCSPP and 4th GCSPP are superior to the 2nd GCSPP and 3rd GCSPP, whereas the 1st GCSPP has a higher average utility than the 4th plan.

Table 8. The overall evaluation results of the four candidate GCSPPs

	Scarcely preferred	Moderately preferred	Average	preferred	Intensely preferred	Unknown
1stGCSPP	3.18%	5.53%	34.48%	29.31%	25.09%	2.41%
2ndGCSPP	11.24%	25.75%	38.66%	13.29%	9.07%	1.99%
3rdGCSPP	3.98%	11.17%	41.39%	26.19%	14.4%	2.34%
4thGCSPP	2.37%	4.42%	38.97%	33.92%	17.96%	2.36%

Table 9. Quantitative assessment of the four candidate GCSPPs

Alternatives	Worst possible	Average	Bes possible
1stGCSPP	0.6569	0.6690	0.6811
2ndGCSPP	0.4480	0.4580	0.4680
3rdGCSPP	0.5767	0.5883	0.6000
4thGCSPP	0.6399	0.6517	0.6635

Comparatively, the traditional GCSPP method can only obtain qualitative results according to the safety criteria in GCSPP assessment in Table 10. For example, GM=0.11m in 5th GCSPP is smaller than the safety criteria GM=0.15m, so the evaluation result of the ship stability is unqualified. The other four GCSPP met the safety criteria, and any of them can be used in practice. For other influencing factors without safety criteria (e.g. economy, efficiency) in GCSPP, traditional methods do not evaluate them. The new approach is able to obtain a quantitative assessment by combining economy and efficiency criteria.

Table 10. The evaluation results of the five candidate GCSPPs by traditional method

Alternatives	Ship stability	Ship strength	Ship overload	Healing angle
1stGCSPP	Qualified	Qualified	Qualified	Qualified
2ndGCSPP	Qualified	Qualified	Qualified	Qualified
3rdGCSPP	Qualified	Qualified	Qualified	Qualified
4thGCSPP	Qualified	Qualified	Qualified	Qualified
5thGCSPP	Unqualified	Qualified	Qualified	Qualified

4.3 Sensitive analysis

Selecting GCSPPs is a dynamic process which needs to fit specific transportation conditions with different load lists, sailing conditions and ship structures. For example, if the transportation schedule is tight, then the requirement for fast loading and unloading will be considered relatively high and, thus, the weight of efficiency will increase accordingly. Such a sensitivity analysis is shown in Fig. 5, where the Y-axis represent the average score of 4 candidate GCSPPs, the weight of efficiency increase at a step of 0.1 for a range of [0-1] while the weights of other criteria (safety and economy) are fixed at the given weights (normalized weights will decreased accordingly). When the efficiency becomes more significant, the average score of GCSPP 4 is larger than GCSPP 1. This will lead to the new ranking of 4 candidate GCSPPs. In reality, GCSPP4 is the best solution in terms of efficiency, and the sensitivity analysis results (new ranking of the four candidate plans) well reflect the reality. This process partially helps validate the model.

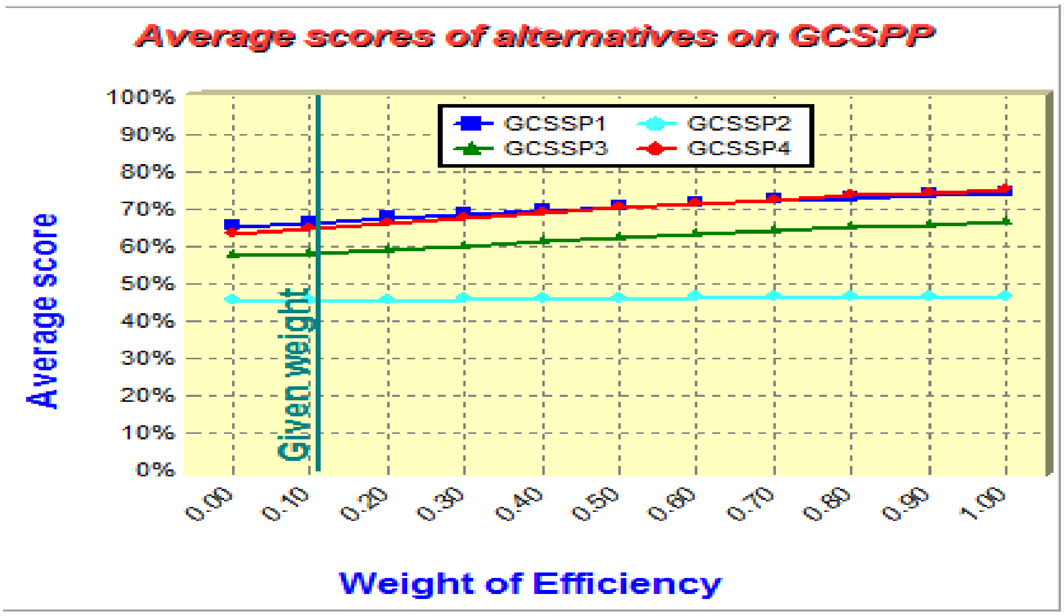

Fig 5. Sensitivity of preference to weights of the efficiency

For a specific shipping activity, it is valuable for decision makers to know the performance of each candidate GCSPP against different criteria. Using the revised ER method, we can obtain the ranking of the alternatives against the dimensions and main criteria in Tables 11 and 12, respectively. The 4th GCSPP is better than other alternatives in terms of 'Efficiency' dimension, 'Ship stability', 'Broken space of cargo', 'LCF' and 'LCFP.', while the 1st solution shows clear advantages for 'Ship stability', 'Damage of cargo', and 'Ship trim'. Such findings reveal that new method can aid the dynamic selection of the best GCSPP based on the specification of a GCS voyage. For instance, if it is predicted to have a rough weather on a routes associated with high incident rates, the weighting of the safety criteria should be increased and the 1st solution will become preferable.

Table 11. GCSPP evaluation with respect to three dimensions

Dimension	GCSPP1	GCSPP2	GCSPP3	GCSPP4	Ranking order
Safety	0.6376	0.4587	0.6066	0.6339	1>4>3>2
Economy	0.7627	0.4508	0.4041	0.6647	1>4>2>3
Efficiency	0.7899	0.4722	0.7349	0.8222	4>1>3>2

Table 12. GCSPP evaluation with respect to main criteria

Main criteria	GCSPP1	GCSPP2	GCSPP3	GCSPP4	Ranking order
Ship stability	0.7547	0.3425	0.6099	0.6212	1>4>3>2
Ship strength	0.4449	0.4784	0.5241	0.5722	4>3>2>1
Damage of cargo	0.7627	0.5181	0.5116	0.6983	1>4>2>3
Broken space of cargo	0.4875	0.3500	0.2875	0.6375	4>1>2>3
Ship trim	-1.35m	-0.56m	-0.36m	-0.96m	1>4>2>3
LCF	0.7800	0.4650	0.7275	0.8150	4>1>3>2
LCFP	0.7800	0.4650	0.7275	0.8150	4>1>3>2

4.4 Comparative analysis with TOPSIS for implications

Based on the original assessment of GCSPP against the lowest level criteria from Table 7, an entropy method and technique for order performance by similarity to ideal applications (TOPSIS) are applied in the same case study to compare and verify the result and the model through a comparative analysis. If the results from the proposed ER-AHP and the established TOPSIS methods are kept consistent, the robustness of the ER-AHP method is partially validated (Yan et al., 2018). As aforementioned, entropy is used to measure the difference of all the target alternatives in terms of their values against the decisive criteria (to generate weight w_E), while the TOPSIS is used to verify the results. In this subsection, we also carry out a sensitivity analysis by investigating the influence of the change of the criteria weights on the ranking order of the plans to reinforce the comparative analysis and to further verify the robustness of the model in dealing with uncertainty data. In this process, the details of steps of the entropy and TOPSIS methods can refer to (Yang et al., 2009b) and are not described here. The combined weight w_C consisting of the weight w_A from AHP and weight w_E from the entropy method is shown in Table 13.

$$w_C = \lambda w_A + (1 - \lambda) w_E \qquad (11)$$

where $0 \leq \lambda \leq 1$. A higher λ value means there are small margins for all the pre-stowage plans to satisfy the minimal requirements of the decisive criteria (e.g. the case in Section 4.2). Domain experts have a key role in evaluating the importance of the decisive criteria with respect to the specific voyage requirements. Subjective weights are important. A small λ value indicates the pre-stowage plans meet the minimal requirements of the decisive criteria with high margins, and the stowage plan requires less subjective input in terms of non-decisive criteria too.

Table 13. The combined weight of each method

w_C	λ	method	Safety	Economy	Efficiency
w_{C1}	1	AHP	0.67	0.22	0.11
w_{C2}	0	Entropy	0.13	0.54	0.33
w_{C3}	0.5	Combined	0.4	0.38	0.22

Use the w_C in Table 13, we obtain the new utility values and ranking order of the four GCSPP, as shown in the Table 14.

Table 14. The utility value and ranking order of four candidate GCSPPs

Method	GCSPP1	GCSPP2	GCSPP3	GCSPP4	Ranking order
AHP	0.6690	0.4580	0.5883	0.6517	1>4>3>2
Entropy	0.7665	0.4607	0.5244	0.7143	1>4>3>2
Combined	0.7217	0.4588	0.5558	0.6850	1>4>3>2

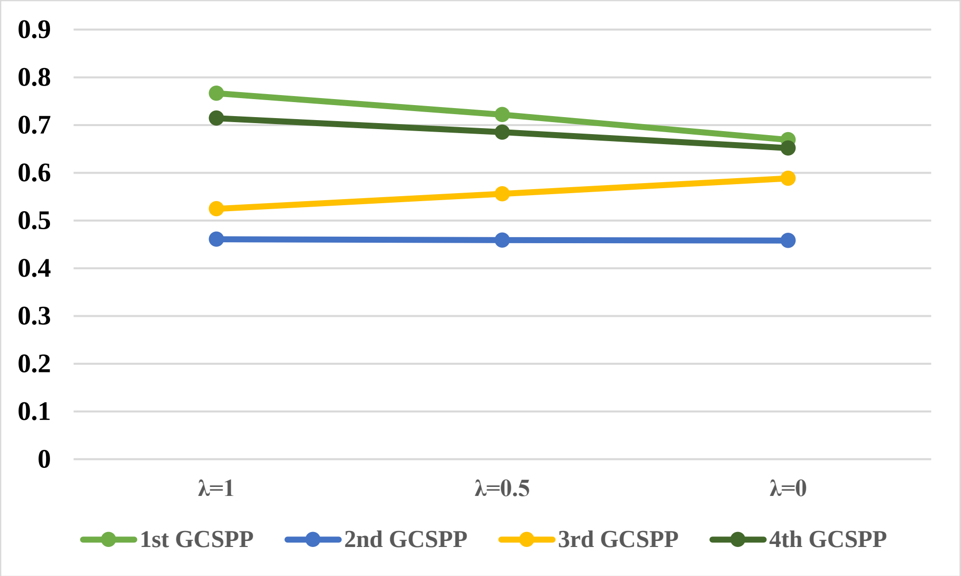

Fig 6. Variation of utility values of 4 candidate GCSPPs in different weights

It can be seen from Fig. 6 that as λ decrease (from 1 to 0), the utility value from 1st GCSPP, 2nd GCSPP, and 4th GCSPP show a continuous downward trend, while that of 3rd GCSPP increases. It means that the combined effect of economy and efficiency on GCSPP 3 is larger than that of safety, compared to the other plans. However, the ranking order of the 4 candidate GCSPPs does not change. This means that no matter how the weight changes, the 1st GCSPP is always the best solution, while the 2nd GCSPP ranked the lowest. The results from TOPSIS and the revised ER keep consistent, revealing the robustness of the new method. In the meantime, the revised ER shows superiority in terms of the ability of dealing with incomplete data and comparing alternative at sub-criteria levels (e.g. Tables 11 and 12).

4.5 Model validation via real life applications

In order to test and verify the reliability of the model, with the help of China Ocean Shipping Company (COSCO), a representative multi-functional GCS was selected for the real life GCSPP evaluation experiment. This GCS also can carry containers on its main deck whilst having general cargo in the holds. The ship has 4 holds, each is divided into upper tween deck and lower tween deck. Therefor each cargo hold effectively is made up of multiple stowage sections, similarly to Fig.1. The specific route was to depart from Taicang port in China on April 21, 2020 and arrive at Geelong port in Australia on May 13, 2020. The main parameters of the real GCS and load list are shown in Tables 15 and 16, respectively.

Table 15. Main parameters of the selected real general cargo ship

Main parameter	Parameter values	Main parameter	Parameter values
Δ_L	10027.0t	L_{BP}	158.32m
B	27.40m	D	14.20m
DW	28000.0t	d	8.50m
MCC	1742TEU	Endurance	13000 nmile
C	220t	$\sum G_1$	18t

Table 16. Load list of the selected real general cargo ship

S/0 NO.	Name of cargos	POL	POD	Weight (tons)	Volume （m3）	Unit
1	Blade	Taicang	Geelong	25.657	1123	27
2	Generator	Taicang	Geelong	8.6300	87	7
3	Nacelle	Taicang	Geelong	4.2200	217	4
4	Wind turbine generator accessory	Taicang	Geelong	0.072	0.19	50
5	Transformer	Taicang	Geelong	10.500	29.20	9
6	Hub	Taicang	Geelong	45.433	104.80	4
7	Tower top section	Taicang	Geelong	51.046	380.49	4
8	Tower mid-lower section	Taicang	Geelong	96.650	445.10	9
9	Tower bottom section	Taicang	Geelong	108.953	351.02	9

The purpose of using the revised ER is to select the best plan from two candidate GCSPPs. The 1st GCSPP was made by the first mate of the ship, and the 2nd GCSPP was from the loading master of the port. The biggest difference between the two GCSPPs was the location of the cargos numbered 7, 8 and 9 in Table 16. The cargos were located on the main deck in the 1st GCSPP, while on the upper tween deck in the 2nd GCSPP. The reason for the 1st GCSPP was that it was more conducive to improving the efficiency of cargo handling and saving money. The loading master believed that the 2nd GCSPP was more conducive to the stability and strength of the ship, making navigation safer.

Using the revised ER approach, the results were obtained and shown in Table 17 in terms of each dimension and Table 18 concerning the overall ranking, respectively.

Table 17. Real GCSPPs evaluation with respect to three dimensions

Dimension	6thGCSPP	7thGCSPP	Ranking order
Safety	0.7143	0.7742	2>1
Economy	0.6332	0.5534	1>2
Efficiency	0.7963	0.4955	1>2

Table 18. Quantitative assessment of the two real candidate GCSPPs

Alternatives	Worst possible	Average	Best possible
6thGCSPP	0.6843	0.7143	0.7457
7thGCSPP	0.6661	0.6955	0.7322

The 2nd GCSPP is superior to the 1st GCSPP in terms of safety dimension, and both GCSPPs have a high score in terms of safety dimension. It means that they both could be applied in practice, however the 2nd GCSPP is more desirable given it has a better performance in terms of safety criterion when using the traditional GCSPP method. When other criteria are taken into account, the 1st GCSPP is better than the 2nd GCSPP in terms of economy and efficiency criteria using the newly proposed PER method, and overall, it has a higher average utility score than the 2nd GCSPP. Consequently, the captain of the ship decided to choose the 1st GCSPP to run the ship in the abovementioned voyage in practice. The new model is being used in a wide range of GCSs owned by COSCO to improve their GCSPP efficiency.

5. CONCLUSION

Presented in this paper is the theoretical development in using ER with revised decisive criteria into a functioning assessment model. In practice, the model is being used to evaluate the efficiency and economy trade-offs of a GCSPP by a leading freight shipping line. The model facilitates evidence led decision making and allows for quantifiable assessment of combinations of cargos in certain port rotations. This can then enable better resource planning, scheduling and estimation of associated costs when considering carriage of different cargos. The model allows for tangible information in both qualitative and quantitative way to ensure vessels remain safe but can also feel secure in choosing to increase efficiency and economy in the GSCPP process.

Practically, CSP of general cargo ships has attracted little research compared to that of container ships. General cargo ships play an important role in the established routes between coastal ports in many countries of long coastal lines. The current best practice for the CSP is simply based on the relevant safety criteria, which makes general cargo shipping less competitive. In this paper, we propose a revised ER method to incorporate multiple criteria from economic and efficiency perspectives to optimize the GCSPP. From a methodological perspective, in the revised ER approach, the weights of the criteria change depending on the performance of the alternative CSP against each of the decisive criteria. For instance, if all the qualified CSPs meet the minimal requirements of all the decisive criteria with a high margin (to be defined by the industrial practice depending on specific criterion), they will be evaluated based on their performance against all the non-decisive criteria solely (i.e. economy and efficiency) and the decisive criteria will not be incorporated into the final decision. If all the remained qualified CSPs meet the minimal requirements of all the decisive criteria with a small margin, they will be evaluated based on their performance against all the decisive and non-decisive criteria. The weights of the decisive criteria will be evaluated based on the navigational environments of a particular voyage using AHP and entropy. This weight adjustment approach can significantly reduce calculation cost, while improving the accuracy of selecting the best GCSPP.

The research findings have the following scientific and practical contributions. First, the criteria influencing GCSPP, especially those related to economy and efficiency, are identified in the form of questionnaire by the purposive sampling. It triggers new research on GCSPP in the future to meet the need of a high competitive shipping market. Secondly, the revised ER method is pioneered to make the overall evaluation result rational by identifying and screening the decisive criteria. This method is also applicable to solve other MCDM problems with decisive criteria in a dynamic environment. Thirdly, the relative weights of criteria are determined by a hybrid AHP and entropy method, and the belief degree structure of GCSPP is established by a fuzzy mapping technique and the utility theory. The hybrid model is proven by real experiments to be useful in processing quantitative and qualitative information simultaneously. Fourthly, the new hybrid model, with the aid of the utility intervals in IDS, enables maritime stakeholders to evaluate and select the best GCSPP in a dynamic environment. Moreover, the results of real-time overall evaluation can also enable the first mate and professional pre-stowage staff to recognize current strengths and the defects in any proposed GCSPP, then get more rational GCSPP through re-stowage. It will significantly improve the overall selection of GCSPP.

Currently the risk levels of the navigational environments and their impact to the safety margins have not been studied. The application of the revised ER in GCSPP can be improved by the development of an advanced Bayesian network/Artificial Neural Network (ANN) based risk forecasting model to foreseen the risk level(s) of a particular voyage. The combination of the risk forecasting method and the revised ER method will better rationalize GCSPP in future.

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Appendix A. Illustration of the ER algorithm

To calculate the basic conditional probability masses M_j^n as defined by Eq. 3.

$M_1^1 = 0.6 \times 0 = 0$; $M_2^1 = 0.6 \times 0.6 = 0.36$; $M_3^1 = 0.6 \times 0.2 = 0.12$;.
$M_1^2 = 0.4 \times 0.4 = 0.16$; $M_2^2 = 0.4 \times 0.5 = 0.20$; $M_3^2 = 0.4 \times 0 = 0$;
Next the remaining relative importance $\overline{H}_n$ for all $i = (1, 2, 3)$ is obtained as follows using Eq. 5
$\overline{H}_1 = 1 - w_1 = 1 - 0.6 = 0.4$; $\overline{H}_2 = 1 - w_2 = 1 - 0.4 = 0.6$

The remaining probability mass $\widetilde{H}_n$ due to the possible incompleteness of any individual grade β_j^n is defined by Eq. 5.

$\widetilde{H}_1 = w_1(1 - \sum_{j=1}^{3} \beta_j^1) = w_1 \, [1 - (\beta_1^1 + \beta_2^1 + \beta_3^1)] = 0.6 \, [1 - (0 + 0.6 + 0.2)] = 0.12$

$\widetilde{H}_2 = w_2(1 - \sum_{j=1}^{3}\beta_j^2) = w_2\,[1 - (\beta_1^2 + \beta_2^2 + \beta_3^2)] = 0.4\,[1 - (0.4 + 0.5 + 0)] = 0.04$

The normalizing factor $k_{n(n+1)}$ for combining the two assessments form 'Mechanical properties' and 'Biology characteristics' is calculated using Eq. 6.

$$k_{n(n+1)} = \left[1 - \sum_{j=1}^{N}\sum_{\substack{t=1 \\ j\neq t}}^{N} M_j^n\, M_t^{n+1}\right]^{-1}$$

$$= [1 - (0 + 0 + 0.36 \times 0.16 + 0 + 0.12 \times 0.16 + 0.12 \times 0.2)]^{-1}$$

$$= 1.1121$$

The remaining combined probability mass $\widetilde{H'}_U$ due to the possible incomplete assessment of β_j^n by 'Mechanical properties' and 'Biology characteristics' is defined by Eq. 6.

$$\widetilde{H'}_U = K\left(\widetilde{H}_1\widetilde{H}_2 + \widetilde{H}_1\overline{H}_2 + \overline{H}_1\widetilde{H}_2\right) = 1.1121(0.12 \times 0.04 + 0.12 \times 0.6 + 0.4 \times 0.04) = 0.1032$$

The combined remaining relative importance $\overline{H'}_U$ from the two assessments conducted by 'Mechanical properties' and 'Biology characteristics' are obtained using Eq. 6.

$$\overline{H'}_U = K(\overline{H}_1\overline{H}_2) = 1.1121(0.6 \times 0.4) = 0.2669$$

To calculate the combined probability mass a_j, Eq. 7 is employed as follows.

$$a_1 = \frac{a'_1}{1-\overline{H'}_U} = \frac{0.0925}{1-0.2669} = 0.1262$$

$$a_2 = \frac{a'_2}{1-\overline{H'}_U} = \frac{0.4520}{1-0.2669} = 0.6166$$

$$a_3 = \frac{a'_3}{1-\overline{H'}_U} = \frac{0.0854}{1-0.2669} = 0.1165$$

Finally, the remaining combined probability mass H_U due to the possible incomplete assessment of 'Mechanical properties' and 'Biology characteristics' is calculated by Eq. 7.

$$H_D = \frac{\widetilde{H'}_U}{1-\overline{H'}_U} = \frac{0.1032}{1-0.2669} = 0.1407$$

Then the result can be described as follows

'Nature of cargo'= { 0.1262'Bad', 0.6166'Average', 0.1165 'Good'0.1407 'Unknown' }

Appendix B. The explanations of the assessment grades defined for the lowest level criteria

Grades of 'Static stability'	Definitions and explanations
Bad	T_θ<9s or T_θ>21 s. The small static stability of the ship makes the ship easy to capsize or the excessive static stability makes it shake violently, which is not conducive to the navigation of the ship.

Average	9s≤T_θ<13s or 17s<T_θ≤21s. The ship's static stability is within the proper range and the rolling period is at an acceptable level.
Good	13s≤T_θ≤17s. The static stability of the ship is very good, and the rolling period of the ship is in the range that is conducive to the safety of the ship.

T_θ in the Table stands for rolling period.

Grades of 'AGZ'	Definitions and explanations
Bad	0.055 ~0.065 meter-radians（angle of heel range between 0 ° and 30°） 0.09 ~0.10 meter-radians （angle of heel range between 0 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） 0.03 ~0.04 meter-radians（angle of heel range between 30 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） The ship's dynamic ability to resist external moments is weak and it is easy to capsize in heavy winds and waves.
Average	0.065 ~0.075 meter-radians（angle of heel range between 0 ° and 30°） 0.10 ~0.11 meter-radians （angle of heel range between 0 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） 0.04 ~0.05 meter-radians（angle of heel range between 30 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） The ship has enough dynamic stability to resist external moment and is not easy to capsize in heavy wind and waves.
Good	More than 0.075 meter-radians（angle of heel range between 0 ° and 30°） More than 0.11 meter-radians （angle of heel range between 0 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） More than 0.05 meter-radians（angle of heel range between 30 ° and 40°or the angle of down-flooding φf if this angle is less than 40°） The ship has great dynamic stability to resist external moment, and it is difficult to capsize in heavy wind and waves.

'AGZ' stands for the area under righting level curve.

Grades of 'GZ30°'	Definitions and explanations
0.2 m	When the ship's heel angle is 30°, the righting level is small, and the ship's ability to withstand wind and waves is poor.
0.4 m	When the ship's heel angle is 30°, the righting level is moderate, and the ship's ability to withstand wind and waves is general.
0.6 m	When the ship's heel angle is 30°, the righting level is enough, and the ship's ability to withstand wind and waves is strong.

'GZ30°' is the value of the righting lever GZ when the heeling angle is equal to 30°.

Grades of 'θGZ_{MAX}'	Definitions and explanations
25 °	This will cause the ship's rolling period to be too short, and the ship shakes too violently.
35 °	This will cause the ship's rolling period to be short, and the ship's shaking is acceptable.
45 °	This will cause the ship's rolling period to be appropriate, and the ship's shaking is suitable for navigation.

'θGZ_{MAX}' is the heeling angle corresponding to the maximum righting lever.

Grades of 'Damaged stability'	Definitions and explanations
1.2 m	GM_d has just met the minimum requirement and the ship's damaged stability is poor.
2.2 m	The ship's damaged stability is acceptable.
2.3 m	The ship's damaged stability is good.

'GMd' is limit Initial metacentric height of damage stability.

Grades of ‘Free surface’	Definitions and explanations
1.1 m	δGM =1.1 m. Some of the tanks are not filled, and the free surface has a great influence on stability.
0.6 m	δGM =0.6 m. The tank is mostly filled, and the free surface has a moderate impact on stability.
0.1 m	δGM =0.1 m. The tank is basically full and the free surface has little effect on stability.

δGM is the difference of the initial metacentric height reduced by free surface.

Grades of ‘Shear force’	Definitions and explanations
Very weak	The weight of the cargo and ballast water is too concentrated, and the distribution of gravity and buoyancy is very different along the length of the ship, and the value of the shear force reaches the maximum allowed.
Weak	The weight of the cargo and ballast water is relatively concentrated, and the distribution of gravity and buoyancy is different along the length of the ship, and the value of the shear force reaches 75% of the maximum allowed.
Average	The weight distribution of the cargo and ballast water is acceptable, and the distribution of gravity and buoyancy is roughly the same along the length of the ship, and the value of the shear force reaches 50% of the maximum allowed.
Strong	The weight distribution of the cargo and ballast water is rational, and the distribution of gravity and buoyancy is basically the same along the length of the ship, and the value of the shear force reaches 25% of the maximum allowable value.
Very strong	The weight distribution of the cargo and ballast water is perfect, the distribution of gravity and buoyancy in the direction of the length of the ship is the same, and the value of the shear force is zero.

Grades of ‘Bend moment’	Definitions and explanations
Very weak	The weight of the cargo and ballast water is too concentrated, and the distribution of gravity and buoyancy is very different along the length of the ship, and the value of the bend moment reaches the maximum allowed.
Weak	The weight of the cargo and ballast water is relatively concentrated, and the distribution of gravity and buoyancy is different along the length of the ship, and the value of the bend moment reaches 75% of the maximum allowed.
Average	The weight distribution of the cargo and ballast water is acceptable, and the distribution of gravity and buoyancy is roughly the same along the length of the ship, and the value of the bend moment reaches 50% of the maximum allowed.
Strong	The weight distribution of the cargo and ballast water is rational, and the distribution of gravity and buoyancy is basically the same along the length of the ship, and the value of the bend moment reaches 25% of the maximum allowable value.
Very strong	The weight distribution of the cargo and ballast water is perfect, the distribution of gravity and buoyancy in the direction of the length of the ship is the same, and the value of the bend moment is zero.

Grades of ‘Ship overload’	Definitions and explanations
Bad	The ship's draught reaches the upper edge of the load line, and the ship has a hidden danger.
Average	The ship's draught is lower than the load line, and the ship basically has no hidden danger
Good	The draught of the ship is far below the load line, and the ship is not overloaded.

Grades of ‘Healing angle’	Definitions and explanations
0.3°	The weight distribution of port and starboard side is different, which has a great influence on ship maneuver and navigation safety.
0.1°	The weight distribution of port and starboard side is slightly different, which has influence on ship maneuver and navigation safety
0°	The weight distribution on port side and starboard side is the same. There is no heel angle at all.

Grades of ‘Avoidance of	Definitions and explanations

mixed cargo'	
Very bad	A large quantity of incompatible cargos is stowed together, causing a large amount of damage of cargos.
Bad	Some incompatible cargos are stored together, causing damage to the cargos.
Average	A small quantity of incompatible cargoes is stored together, causing minor damage to the cargoes.
Good	Potential danger of damage of cargo.
Very good	No damage of cargo.

Grades of 'Mechanical properties'	Definitions and explanations
Bad	The stacking of the cargo makes the cargo and packaging vulnerable to damage, deformation, and leakage.
Average	Cargo stacking is acceptable and there may be little damage, deformation, leakage.
Good	The cargo is stowed properly and the mechanical properties of the cargo is basically unchanged.

Grades of 'Biology characteristics'	Definitions and explanations
Lively	Because of where the cargo is placed, the cargo is more susceptible to respiration, microbial action, and insect infestation, causing extensive damage to the cargo.
Common	Because of where the cargo is placed, the cargo maybe affected by respiration, microbial action, and insect infestation, causing minor damage to the cargo.
Inactive	Because of the location where the goods are placed, there is almost no damage of cargo.

Grades of 'Dunnage of cargo'	Definitions and explanations
Bad	Unreasonable selection of dunnage materials, dunnage methods, or lack of adequate dunnage of cargo.
Average	The selection of dunnage material and method of dunnage basically meets the requirements, and adequate dunnage is provided.
Good	The selection of the dunnage material and packing method is reasonable and adequate.

Grades of 'Broken space of cargo'	Definitions and explanations
Very big	The packaging form of many cargos is not compatible with the shape of most cargo hold.
Big	The shape of the ship's main cargo compartment (usually the cargo hold in the middle of the ship) does not correspond to the packing of the cargo
Average	The shape of the ship's non-key cargo hold (usually the cargo hold at the bow and stern of the ship) is not compatible with the form of packaging of the cargo.
Small	The location of a small number of different packaging forms is unreasonable.
Very small	The location of the cargos in different packaging forms is reasonable.

Grades of 'Ship trim'	Definitions and explanations
0 m	Propeller efficiency and ship maneuverability are very poor.
-0.4 m	Propeller efficiency and ship maneuverability are poor.
-0.8 m	Propeller efficiency and ship maneuverability are average.
-1.2 m	Propeller efficiency and ship maneuverability are good.
-1.5 m	Propeller efficiency and ship maneuverability are very good.

Grades of 'LCF'	Definitions and explanations
Bad	The locations of cargos in the final arrival port is above the cargos in the first arrival port,

	and it is impossible to unload the cargos in the first arrival port without cargo shift.
Average	The locations of cargos in the first arrival port is not convenient for unloading
Good	The locations of cargos in the first arrival port is convenient for unloading.

LCF is the location of the first arrival port cargo.

Grades of ‘LCFP’	Definitions and explanations
Bad	The locations of cargos in the final arrival port is above the cargos in the first arrival port, and it is impossible to unload the cargos in the first arrival port without cargo shift.
Average	The locations of cargos in the final arrival port is not very convenient for unloading
Good	The locations of cargos in the final arrival port is convenient for unloading.

LCFP is the location of the final arrival port cargo.