A Decision Support System for Mission-Based Ship Routing Considering Multiple Performance Criteria

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ABSTRACT

It is crucial to evaluate the structural risk associated with marine vessels subjected to inclement weather and sea conditions when developing a decision support system for ship routing. The generalized decision making framework developed in this paper performs a variety of tasks, including, but not limited to quantifying the flexural and fatigue performance of ship structures and employing multi-attribute utility theory to evaluate ship mission performance. A structural reliability approach is utilized to compute the probability of failure considering the uncertainty in structural capacity and load effects; specifically, effects of flexural and fatigue damage are investigated. The expected repair cost, cumulative fatigue damage, total travel time, and carbon dioxide emissions associated with ship routing are considered as consequences within the risk assessment procedure adopted in this paper. Additionally, the decision maker's risk attitude is integrated into the presented approach by employing utility theory. The presented methodology can assist decision makers in making informed decisions concerning ship routing. In order to illustrate its capabilities the approach is applied to the Joint High-speed Sealift Ship (JHSS).

Key words: Ship reliability; Risk assessment; Spectral fatigue analysis; Operational conditions; Multi-attribute utility theory; Decision making.

1. Introduction

When a ship is deployed on a given mission, the route the vessel traverses is typically a predetermined path with known potential sea conditions (e.g., sea states). Thus, a decision maker must determine, before the mission, which route a ship may take. It is crucial to evaluate the structural risk associated with marine vessels subjected to inclement weather and sea conditions when developing a decision management system for ship routing. Ship mission routing can be established considering the strength of the hull, accounting for both flexural and fatigue damage. Additionally, a multi-attribute decision making process may be incorporated to form a robust framework for ship routing that accounts for a wide range of consequences (e.g., total travel time and repair loss). The uncertainties associated with the risk evaluation process must also be included within a generalized ship routing decision making framework. During a mission, a ship must always satisfy safety and serviceability requirements. In some cases, marine vessels are forced to follow certain routes while simultaneously handling time and distance constraints; this combination of dire conditions puts ships in danger of accruing damage that may negatively impact society and the surrounding environment. Ultimately, ship mission performance assessment is of vital importance for ship managers since it provides them guidance for the real-time decision making.

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Often, marine vessels are used beyond their intended design life and are, therefore, found under-performing in terms of mission reliability. Consequently, it is of the utmost importance to assess the safety of ship structures by employing a holistic management program to ensure their functionality considering both flexural failure and fatigue damage. Ship performance associated with ultimate flexural failure of the hull's mid-ship section is considered as one of the most critical criteria regarding mission safety assessment [8]. Although the reliability of ship structures considering flexural failure has been previously studied [2, 4, 9, 46, 53], fatigue failure has yet to be comprehensively examined in a marine vessel routing context. Moreover, since ship structures are continuously subjected to oscillatory environmental loads, the risk associated with fatigue-damage under the loading cases must be carefully considered [24, 36]. The evaluation of fatigue damage associated with a ship's midsection is integral to ship routing performance assessment [40]. Overall, the failure associated with both hull girder collapse and fatigue damage must be considered simultaneously in order to capture the true performance of a marine vessel.

The spectral-based fatigue method is widely used in the fatigue damage evaluation of marine structures. In practice, the fatigue damage analysis of ship structures is often treated as a linear process and assessed using the spectral method [1, 12, 30]. Fatigue damage assessment may be implemented by utilizing a linear model to compute the response of a ship under wave loading [42]. The linear assumption ultimately allows for the solution of the hydrodynamic problem to be represented in the frequency domain. Several previous research efforts have investigated the role of the wave-induced vertical bending moment in the spectral fatigue analysis of marine vessels [35, 40, 42]. Furthermore, the combined effects of both the vertical and horizontal hull girder bending moments were considered in the fatigue damage assessment by Wang [58] and Xue et al. [59]. Additionally, the cumulative fatigue damage associated with a ship structure prior to and during a mission should be considered within the proposed framework. Since existing ship structures already have accumulated some fatigue damage, they may not be able to handle additional damage, especially if they are at late stages within their lifetimes. Accordingly, it is the decision maker's responsibility to determine whether a ship can still embark on a mission considering the cumulative fatigue damage.

The emissions associated with an operating marine vessel are regulated by the International Maritime Organization (IMO); the IMO states that it is essential to restrict the amount of carbon dioxide emissions and other greenhouse gases produced by a ship route [31]. Since air pollutants are amongst the most common forms of emissions from ship structures and there is a propensity for atmospheric levels of greenhouse gases to increase significantly in the next 20 years, the environmental consequences must be investigated for the ship mission decision making process. Within the proposed multi-attribute risk assessment of marine vessels, the repair loss, fatigue damage, total travel time, and CO₂ emissions are considered as consequences. Since there have been no significant research efforts regarding risk-based, multi-attribute shipping route decision making, it is necessary to develop sound approaches to effectively assess the risk associated with marine vessels.

The ship routing decision making procedure also greatly depends upon the risk attitude of the decision maker toward the consequences associated with structural performance. Utility theory is incorporated within the decision making framework to account for the attitudes of decision maker. A utility function that measures the value of a particular alternative to the decision maker is established for each attribute. In order to account for various sets of units corresponding to each type of consequence, Multi-Attribute Utility Theory (MAUT) is employed to convert each attribute (i.e., repair loss, fatigue damage, travel time, and carbon dioxide emissions) to a consistent unit. A balanced combination of various attributes comprising structural risk can be determined by employing MAUT [33]. The goal of MAUT, within this context, is to transfer the criteria under investigation into one combined value; this multi-attribute performance metric is representative of ship performance during a particular mission. Risk assessment has not been widely incorporated within previous decision support systems, except for a few studies [6, 7, 10, 43]. Additionally, to the best knowledge of the authors, multi-attribute utility theory has not been adopted in the ship routing decision making process. By employing utility theory, the decision maker's attitude can be incorporated into the decision making process.

Furthermore, attributes with various units can be all converted into a singular utility value that is always bounded by 0 and 1.

Overall, the approach adopted within this paper focuses on the estimation of ship safety considering flexural and fatigue damage and provides a sound ship routing risk assessment procedure. Additionally, the generalized framework developed herein performs a variety of tasks, including, but not limited to quantifying the flexural and fatigue performance of the ship structure and employing MAUT to evaluate ship mission performance. A structural reliability approach is utilized to compute the probability of failure considering the uncertainty in structural capacity and load effects. The attitudes of the decision maker are also considered herein using utility theory. The proposed multi-criteria based decision making management approach for ship structures has the ability to determine mission performance considering repair loss, fatigue damage, total travel time, and carbon dioxide emissions. Ultimately, the presented methodology can assist decision makers in making informed decisions concerning ship routing. The approach is applied to the Joint High-speed Sealift Ship (JHSS) [11] in order to illustrate the capabilities of the proposed methodology.

2. Framework for the Multi-Criteria Decision Making

The first step of the ship routing management procedure is to define the structural information and route alternatives corresponding to the ship under investigation. Next, the limit state and loading cases associated with ship structures should be determined. A flowchart outlining the proposed framework is shown in Figure 1. The environmental conditions (e.g., sea states) must be identified in order to determine the loading scenarios. Each sea state is regarded as the general condition of the free surface on a large body of water and may be characterized by certain significant wave heights and frequencies of these waves. The limit state corresponding to flexural failure is incorporated within this approach. Additionally, the uncertainties involved with this limit state are considered within the risk assessment procedure. Risk is defined as the product of adverse consequences and probability of occurrence associated with a given limit state. In order to quantify the risk performance indicator, the probability of failure associated with a given limit state should be determined first by using simulation and/or first/second order reliability analysis. Then, given the specific consequences of structural failure, the risk can be assessed accordingly. Finally, each decision should be made on basis of risk, which associates the probability of occurrence of specific event with the consequences. The spectral-based fatigue damage is also included as a performance criterion regarding ship routing decision making. The next step includes determining the consequences associated with the ship routing process. Furthermore, the attitude of the decision maker is also considered herein; the attitude of the decision maker can significantly affect the results of the consequence evaluation, risk assessment, and, ultimately, decision making regarding ship routing. The consequences under investigation are multiplied by the probabilities of occurrence in order to calculate the risk performance metric. There are several types of attributes (i.e., repair loss, fatigue damage, travel time, and carbon dioxide emissions) considered within this analysis, all with differing units.

2.1 Single Attribute Utility Function

A utility function that measures the value of a particular alternative to the decision maker is established for each attribute. Generally, the utility function contains information about the decision maker's attitude toward risk [34, 48]. Within the presented methodology, the desirability of each alternative depends on the values of four attributes (i.e., repair loss, cumulative fatigue damage, total travel time, and CO₂ emissions), all of which are measured with different units. Thus, there is a need to establish a consistent range of values that each attribute may take so that all attributes are directly comparable to each other. First, a utility function that measures the value of a particular alternative to the decision maker must be defined for each attribute. The formulation of the utility function corresponding to each attribute greatly depends on the knowledge and preferential characteristics of the decision maker.

Considering an exponential formulation, the utility associated with a single attribute (e.g., repair loss and total travel time) can be expressed as [3]

$$u(x) = \frac{1}{1 - \exp(-\rho)} \left[1 - \exp\left(-\rho \frac{x_{max} - x}{x_{max}}\right) \right] \quad (1)$$

where x is the attribute value under investigation; ρ indicates the attitude of the decision maker; and x_{max} denotes the maximum value of the attribute. x_{max} is included within this formulation in order to normalize the utility function so that it always takes values between 0 and 1. An illustrative example of a utility function associated with a general loss is shown in Figure 2(a). The risk attitude of the decision maker is reflected within the parameter ρ ; a positive value of ρ indicates a risk averse attitude while a negative value indicates a risk taking attitude. Additionally, the absolute value of ρ represents the severity of the risk attitude.

2.2 Multi-Attribute Utility Theory

In order to account for various sets of units corresponding to each type of consequence, MAUT is employed to convert each attribute to consistent units. A multi-attribute utility function is formed as a combination of each attribute multiplied by weighting factors. The alternative that provides the highest multi-attribute utility value is the preferred solution [25]. MAUT is commonly used in the field of decision making and allows for the incorporation of multiple criteria into a decision. Decision making regarding mission routing depends on the encountered sea states, ship capacity (e.g., flexural and fatigue strength), and prescribed constraints associated with all attributes. The ideal combination of the different attributes comprising risk can be determined by employing MAUT. The goal of MAUT, within this context, is to transfer these four metrics (i.e., repair loss, fatigue damage accumulation, total travel time, and CO₂ emissions) into one combined value. Once the utility function associated with each attribute is appropriately established, they may be combined into one multi-attribute utility that effectively represents all aspects under investigation. Within the additive formulation for the multi-attribute utility function, marginal utility values associated with each attribute are multiplied by weighting factors and summed over all attributes involved [56]. The flowchart regarding MAUT in the context of this paper is indicated in Figure 2(b). Considering an additive formulation, the multi-attribute utility function utilized within the presented decision making framework can be computed as [34]

$$u(x_1, x_2, x_3, x_4) = k_1 u_1(x_1) + k_2 u_2(x_2) + k_3 u_3(x_3) + k_4 u_4(x_4) \quad (2)$$

where $u(x_1, x_2, x_3, x_4)$ is the multi-attribute utility function and k_i is the scaling factor corresponding to the i th attribute. The weighting factor associated with each attribute is calculated considering information obtained from the decision maker. The alternative that provides the highest multi-attribute utility value is the preferred solution. Overall, the consequences considered in this paper may be evaluated based on professional judgment and existing information while utility theory can be used to quantify the decision maker's preference. Considering the multi-attribute utility value corresponding to each possible shipping route, the decision maker can identify the best route.

3. Ship Performance Associated with Flexural Failure and Fatigue Damage

3.1 Load Effects

The effects induced by the sea on the hull are due to two separate events: still water and waves. Safety evaluation of ship structures operating in different sea conditions requires an accurate estimation of the load effects due to still water and waves [19]. As recognized by previous study [23], the primary load effects within the hull are the sagging and hogging vertical bending moments (VBMs). According to the International Association of Classification Societies [29], the VBMs $M_{sw,sag}$ and $M_{sw,hog}$ (associated with sagging and hogging, respectively) for a specific ship cross-section (CS) under still water can be expressed as

$$M_{sw,sag} = 0.05185 f_{sw,CS} C_{wv} L^2 B (C_b + 0.7) \quad (3)$$

$$M_{sw,hog} = 0.01 f_{sw,CS} C_{wv} L^2 B (11.97 - 1.9 C_b) \quad (4)$$

where $f_{sw,CS}$ is a factor accounting for the variation of VBMs along the vessel length (equal to 1.0 at mid-ship); C_b is the ship block coefficient; L is the ship length (m); B is the ship breadth (m); and C_{wv} is the wave coefficient. Based on [20] and [22], the values of the still water bending moment can be well approximated by a normal distribution. Later, Hørte *et al.* [28] proposed a stochastic model for tankers in full load condition that describes the still water vertical bending moment by a normal distribution with mean value and standard deviation of 70% and 20% of the maximum value in the loading manual, respectively.

The load effects on ship structures associated with waves are related to many factors, including ship geometry, heading angle, speed, and encountered sea state. The linear response theory is commonly employed to compute structural performance of marine vessels [26, 53]; a widely used approach for ship performance evaluation based on linear response theory is the strip method [16]. The relationship between input and output, which is described by a spectral density function, may be established from the results of applying the strip method. In addition to the strip method, other methods have been established to account for the non-linear effects [21, 32].

The main goal of the load assessment procedure is to obtain response amplitude operators (RAOs) corresponding to a particular cross-section of a marine vessel. The RAOs can be determined by converting the time domain response of a ship to the frequency domain. Based on the RAOs, a ship's response to a particular sea state can be computed. Using the linear superposition theory, a ship's response in a given sea state can be obtained. Moreover, the RAOs are calculated as a vessel's response considering excitation waves with unitary amplitude. The response spectrum can be computed as [26]

$$S_Y(\omega) = |RAO(\omega)|^2 S_X(\omega) \quad (5)$$

where $S_Y(\omega)$ and $S_X(\omega)$ are the spectral density functions of the output and input, respectively and ω is the circular frequency of excitation waves (rad/s).

In reality, the sea's surface is highly irregular under dynamic conditions. The spectrum for a fully developed sea may be computed using the guidelines established by the International Ship and Offshore Structures Congress (ISSC). A modified version of the Pierson-Moskowitz sea spectrum is used to formulate the following expression describing the sea spectrum [15]

$$S_\omega(\omega) = \frac{0.11 H_s^2 T_1}{2\pi} \left(\frac{\omega T_1}{2\pi} \right)^{-5} \exp \left[-0.44 \left(\frac{\omega T_1}{2\pi} \right)^{-4} \right] \quad (6)$$

where $S_\omega(\omega)$ is the sea spectrum for a given sea state; T_1 is the wave mean period (s); and H_s is the significant wave height corresponding to the mean of the one third highest waves (m). The values of the mean period and significant height associated with excitation waves depend upon the intensity of the sea states encountered. For a particular operational condition, the wave spectrum is usually expressed in terms of the encountered frequency ω_e , instead of the circular frequency ω , accounting for a ship's speed and heading angle. The encountered wave frequency ω_e is defined as follows [1]

$$\omega_e = \left| \omega - U \frac{\omega^2}{g} \cos \theta \right| \quad (7)$$

where g is gravitational acceleration (m/s^2); U is the forward ship speed (m/s); and θ is the heading angle (e.g., 0° , 90° , 180° for following, beam, and head seas, respectively). Although the Pierson-Moskowitz sea spectrum is utilized herein for load analyses, other sea spectrums (e.g., JONSWAP) could also be used.

For the spectral-based fatigue analysis, a linear model assumption of loading is generally adequate and the non-linear effects can be neglected [42]. FREE!ship [17], an open source surface-modeling program based on subdivision surfaces, can be used to model a ship's body and estimate its hydrodynamic parameters. Based on the given sea spectrum, load descriptors due to wave effects are evaluated using a developed MATLAB [38] code linked with PDSTRIP [49], a program that performs strip analysis. As an example, a qualitative representation of the VBM RAOs associated with a ship's cross section considering certain operational cases is shown in Figure 3. The vertical bending stress $RAO_{\sigma,ver}$ at the structural component associated with a particular cross section is given as [51]

$$RAO_{\sigma,ver} = \frac{z - z_0}{I_{yy}} RAO_{M,ver} \quad (8)$$

where z is the vertical distance from the structural detail to the baseline (m); z_0 is the vertical distance from the neutral axis to the baseline (m), and I_{yy} is the moment of inertia with respect to the horizontal axis of the section (m^4).

The evaluation of probabilistic hull strength with respect to ultimate flexural failure can be carried out utilizing a classical incremental curvature method [29]. In order to significantly reduce the total computational time, [44] developed an optimization-based approach that yields results that are as accurate as those obtained from the incremental curvature method. The safety evaluation of ship structures operating in different sea and cargo conditions requires a probabilistic estimation of various parameters. The uncertainties associated with vessel dimensions, material properties, and applied loads should be treated as random variables [9]. Furthermore, the load effects due to still water and waves must be probabilistically simulated to account for uncertainties in loading conditions [19].

Based on the short-term statistics and the assumption that the instantaneous value of ocean elevation follows a Gaussian distribution [15], the probability density function (PDF) of the peak response under given operational conditions can be estimated using a Rayleigh distribution as follows [18]

$$f(M_w) = \frac{M_w}{m_{o,M}} \exp\left(-\frac{M_w^2}{2m_{o,M}}\right) \quad (9)$$

where M_w is the wave-induced VBM response and $m_{o,M}$ is the zeroth moment of the VBM response spectrum. Accordingly, the mean μ_M and standard deviation σ_M associated with the random variable M_w can be obtained as

$$\mu_M = \sqrt{\frac{\pi \cdot m_{o,M}}{2}} \quad (10)$$

$$\sigma_M = \sqrt{\frac{(4 - \pi) \cdot m_{o,M}}{2}} \quad (11)$$

The zeroth moment of the wave spectrum regarding the VBM spectrum can be computed as

$$m_{o,M} = \int_0^\infty \omega_e^0 S_w(\omega_e) d\omega_e \quad (12)$$

Furthermore, the response spectrum for the wave-induced VBMs is

$$S_M(\omega_e) = |H_M(\omega_e|U, \theta)|^2 S_w(\omega_e) \quad (13)$$

where $H_M(w_e | U, \theta)$ is the RAO for the VBMs under given ship speed U and heading angle θ .

3.2 Reliability Analysis Associated with Flexural Failure

Reliability assessment of ship structures is performed based on knowledge of the probability distributions associated with hull structural resistance and statistical descriptors of load effects. The sources of uncertainties associated with the random variables can be classified as follows: inherent, measurement, statistical, model, and other (e.g., due to human errors) uncertainties [47]. The first step within the reliability analysis involves determining the probability of flexural failure based on the ultimate failure limit state. Considering modeling uncertainties associated with resistance and load effects, the limit state equation for the ultimate failure of a particular ship cross section can be expressed as [47]

$$x_R M_{UR} - x_{SW} M_{SW} - x_W M_W \leq 0 \quad (14)$$

where M_{UR} is the resisting bending moment associated with ultimate failure; M_{SW} is the still water bending moment; M_W is the wave-induced bending moment; x_{SW} and x_W are the model uncertainties associated with still water and wave-induced bending moment prediction, respectively; and x_R is the model uncertainty associated with hull resistance determination. The geometric parameters and material properties, such as plating thickness, elastic modulus, plating yielding stress, and stiffener yielding stress, are treated as random variables. Additionally, the model uncertainty is considered by using coefficients x_R , x_{SW} , and x_W , which are assumed normally distributed with mean values of 1.0, 1.0, and 0.9, respectively, and coefficients of variation equal to 0.10, 0.05, and 0.15, respectively [47]. More probabilistic models associated with ship structure safety assessment have been reviewed by Teixeira et al. [57]. The probability of failure p_f corresponding to the flexural limit state may be obtained using simulation techniques. Additionally, the reliability index β is

$$\beta = \Phi^{-1}(1 - p_f) \quad (15)$$

where Φ^{-1} denotes the inverse standard normal cumulative distribution function. The probability of failure associated with a given limit state can be determined by using simulation (e.g., Monte Carlo simulation) and/or first/second order reliability analysis.

3.3 Spectral-Based Fatigue Damage Assessment

In order to avoid structural failure and adverse consequences, it is essential to assess and predict the fatigue performance and safety of marine vessels. A ship may be subjected to a variety of load effects, including vertical and horizontal bending moments, in addition to torsional moments. Typically, wave-induced loads are the main source of fatigue damage to ship structures. In this paper, the vertical bending moments induced from encountered waves are emphasized for the fatigue assessment. The linear model assumption is generally adequate for fatigue analysis of marine vessels [42].

Within the context of this study, the spectral-based fatigue analysis involves a method for the direct calculation of fatigue damage [5, 58]. The whole history of stress associated with the ship's operating condition is considered in the cumulative fatigue damage assessment. Based on the spectral approach, the Rayleigh PDF associated with the short-term stress range distribution, zero-up crossing frequency, and spectral bandwidth parameters for the wide band random process can be obtained [55]. Additionally, considering the short-term stress range distribution, the fatigue damage accumulation associated with a structural element with a linear S-N curve in a specific sea state can be expressed as [1]

$$D_i = \frac{T}{A} (2\sqrt{2})^m \Gamma(1 + \frac{m}{2}) \lambda(m, \nu_i) f_{oi} p_i(\sigma_i)^m \quad (16)$$

where T represents the service time of a ship structure; A is fatigue strength coefficient; m is the fatigue strength exponent; λ is the cycle counting correction factor; f_{0i} is the zero-up crossing frequency of the stress response; p_i is the probability of occurrence of sea state i ; σ_i is the standard deviation of the stress process associated with sea state i ; ν_i is spectral width parameter; and Γ is the gamma function.

The standard deviation σ and zero crossing frequency f_0 associated with the stress response can be expressed as

$$\sigma = \sqrt{m_0} \quad (17)$$

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}} \quad (18)$$

where m_0 and m_2 are the spectral moments of the stress process. Accordingly, these two parameters can be computed as [1]

$$m_n = \int_0^\infty w_e^n S_\sigma(w_e) dw_e \quad (19)$$

$$S_\sigma(w_e) = |H_\sigma(w_e|\theta, U)|^2 S_w(w_e) \quad (20)$$

where $H_\sigma(w_e|\theta, H)$ is the stress transfer function obtained by the linear hydrodynamic analysis.

The total fatigue damage of a structural element is computed by summing the fatigue damage over all the k possible sea states. The closed form expression of the total fatigue damage can be computed as [1]

$$D = \frac{T}{A} (2\sqrt{2})^m \Gamma(1 + \frac{m}{2}) \sum_{i=1}^k \lambda(m, \nu_i) f_{0i} p_i (\sigma_i)^m \quad (21)$$

4. Multi-Attribute Risk Assessment

This section presents the risk assessment regarding ship routing considering multiple performance criteria. Risk, which combines the probability of occurrence of a specific event with the consequence associated with the event, is regarded as an important performance indicator. The evaluation of the consequences plays a fundamental role in the decision making process. The following consequences are considered within the approach: repair loss (economic impact), fatigue damage accumulation, travel time (social impact), and carbon dioxide emissions (environmental impact).

4.1 Repair Loss Associated with Flexural Failure

The first attribute investigated in detail is the repair loss which describes the direct monetary loss associated with structural failure. In order to calculate the economic risk, the construction cost of a ship must be computed considering its preliminary design and work breakdown system [10]. The costs associated with the ship work breakdown system (SWBS) are subdivided into several categories, including propulsion, structural, and electrical systems. The construction cost C_{Cons} is the sum of all the labor and material costs involved in the construction process and is computed as follows [41]

$$C_{Cons} = 5747.19 \times STF \times DISP^{-0.3792} \times WGT_{100}^{0.862} + 800 \times WGT_{100} \quad (22)$$

where WGT_{100} is the weight of SWBS 100 (long tons); STF is the ship type factor; and $DISP$ is the ship full load displacement (long tons).

In this paper, the repair loss is associated with the ultimate flexural failure; the probabilities of ultimate flexural failure under different sea states are first calculated and then the repair loss is computed by multiplying these probabilities by the associated repair costs and summing over all sea state and operational conditions. The repair loss of a ship structure considering the contribution of all sea states and ship operational cases can be computed as

$$RL = \sum_{SS} \sum_{U, \theta} P(SS) \cdot P(U, \theta | SS) \cdot P(f | SS, U, \theta) \cdot C_{Cons} \quad (23)$$

where $P(SS)$ is the probability of occurrence of sea state (SS) during a ship route; $P(U, \theta | SS)$ is the probability of ship operation cases (i.e., speed U and heading angle θ) given the sea state; $P(f | SS, U, \theta)$ is the conditional probability of ship section failure given the occurrence of a specific set of SS , U , and θ .

4.2 Fatigue Damage Accumulation

The second attribute considered herein is the fatigue damage accumulation. Fatigue damage associated with ship structures is a continuous process that should be taken into account in the design and performance assessment procedure. In practice, the fatigue damage accumulation associated with ship structures is often treated as a linear process and evaluated using the spectral method [1, 11, 30]. In order to ensure structural safety, when conducting a fatigue analysis on a marine vessel, it is necessary to identify fatigue-critical structural details (e.g., the connections of the deck longitudinal to transverse web) associated with stress analysis under wave-induced loading. In this paper, the spectral-based fatigue damage method is employed. For a given ship mission process, the fatigue damage associated with specific sea state conditions can be computed by considering the total time a ship encounters the prescribed sea states [40]. The total fatigue damage associated with a ship detail is computed by summing the fatigue damage over all encountered sea states. The closed form expression corresponding to the total fatigue damage can be computed using Eq. (21). Within this formulation, the total fatigue damage is calculated using strip theory considering the total time of travel, ship speed, wave spectrum, and scatter diagrams [1].

4.3 Total Travel Time

The third attribute considered in the risk analysis is the total travel time associated with a ship mission. The ship route planning relies on decision making tools that estimate the time of arrival for a ship mission. The expected speed loss experienced by a ship structure during a route is influenced by the significant wave height of the surrounding water and heading angle of the ship. Determining a ship's operational speed within different sea states is of vital importance for the economic and environmental risk assessment. Ultimately, severe sea states yield relatively high reductions of ship speed [50]. The percentage of time spent in each possible sea state may be estimated based on the fraction of the route distance corresponding to each possible sea state [39]. The total travel time required for a ship to complete a particular route may be considered as a social impact of ship routing. The total travel time is computed as

$$TT = \sum_{SS} \sum_{U, \theta} P(SS) \cdot P(U, \theta | SS) \cdot \frac{l}{U(SS)} \quad (24)$$

where U is the speed of the ship at a given sea state and l is the length of the route.

4.4 Carbon Dioxide Emissions

The fourth and final attribute is the total carbon dioxide emissions produced during a ship mission. The speed of a ship is dynamic and may change based on current sea state conditions. In general, the speed loss associated with each possible sea state is related to the greenhouse gas emissions produced by a ship. Severe sea states can yield a large increase in CO₂ emissions [50]. Consequently, the CO₂ emissions of a ship operating in different sea states and operational conditions must be considered when calculating the environmental

attribute within the proposed multi-attribute risk assessment procedure. The carbon dioxide emissions can be expressed as [50]

$$CDE = \sum_{SS} \sum_{U, \theta} P(SS) \cdot P(U, \theta | SS) \cdot l \cdot cde(U) \quad (25)$$

where cde is the carbon dioxide emission per unit distance (i.e., kg/km) for a ship structure associated with specific sea states and ship operational conditions.

5. Illustrative Example

The proposed approach is applied to the Joint High-Speed Sealift (JHSS) provided by Devine [11] to illustrate ship routing decision making using MAUT. This particular marine vessel measures 290 m in length, 22.3 m in height, and 32 m in breadth. The block coefficient is taken as 0.4835. The ship's body and a representative transverse cross-section at mid-ship are shown in Figure 4(a) and (b), respectively. The ship performance under different operational and sea states is depicted using a polar representation, which presents the ship's response as a function of wave direction under given conditions. The reliability analysis is performed using the computer program RELSYS [13], based on the First-Order Reliability Method (FORM). Within this illustrative application, the ship's reliability is calculated considering ultimate flexural failure while its four separate attributes are included within the comprehensive risk analysis. The sea conditions adopted in Decò and Frangopol [10] are utilized herein; a stationary storm system that yields severe sea states is considered to occur at a location along the straight-line path between the origin and destination points. The straight-line route that takes the ship directly through the storm is considered as Route 3. The possible shipping courses considered in this paper are Routes 1, 2, and 3 (see Figure 4(c)). Route 1 is associated with the longest travel time and largest CO₂ emissions; it is considered to be the safest shipping course. Conversely, Route 3 is regarded as the most dangerous route, but results in the lowest travel time and CO₂ emissions. Route 2 may be considered as another alternative. Additionally, the effects of the decision maker's risk attitude (i.e., ρ in Eq. (1)) and the weighting factors (i.e., k_1, k_2, k_3 , and k_4 in Eq. (2)) on the multi-attribute utility value corresponding to each route are investigated. A decision about ship routing using the approach outlined by [10] is based only on direct losses related to rehabilitation of a damaged ship. However, within this paper, the decision maker ultimately chooses which shipping path is best by considering the proposed multi-attribute risk performance associated with each route. Thus, the approach adopted in this paper effectively includes a broad range of consequences within a risk assessment. Moreover, the attitudes of the decision maker are incorporated within this approach. The ultimate aim of this illustrative example is to demonstrate the capabilities of the proposed MAUT-based decision making framework by applying it to a ship. The hull section is investigated herein as an illustrative example. The proposed decision support system could also be applied to other types of ship structures.

5.1 Performance Associated with Ultimate Flexural Failure and Fatigue Damage

The load effects associated with still water and wave loads in terms of the VBM's corresponding to sagging and hogging are investigated herein. Based on Hussein and Guedes Soares [27], the VBM associated with still water is assumed to follow the normal distribution with a mean and standard deviation equal to 70% and 20% of the maximum still water bending moment, respectively. The optimization-based method is adopted herein to compute the probabilistic hull strength [43]. The elastic modulus E , the yielding stresses of plating and stiffener s_{Yp} and s_{Ys} , respectively, and the plating thickness t_p are considered to be lognormal random variables with the coefficients of variation of 0.03, 0.1, 0.1, and 0.05, respectively [8, 47]. The mean values of the variates E , s_{Yp} , and s_{Ys} are assumed to be 2.1×10^5 , 351.6, and 351.6 MPa, respectively [8]. Additionally, the model uncertainty is considered by using the coefficients x_R , x_{SW} , and x_W , which are assumed normally distributed with mean values of 1.0, 1.0, and 0.9, respectively, and the coefficients of variation equal to 0.10, 0.05, and 0.15, respectively [47]. Within this paper, Latin-Hypercube sampling techniques are utilized with

5,000 samples to compute the moment capacity of the mid-section of the JHSS under wave loading in a probabilistic manner. The generated samples of flexural capacities are fitted to a lognormal distribution with mean values equal to 99.83×10^8 Nm and 95.05×10^8 Nm for hogging and sagging, respectively. The COV (coefficient of variation) corresponding to the hogging and sagging bending moment capacity are 8.9% and 8.3%, respectively. Furthermore, the bending moment associated with still water can be computed using Eq. (3) and (4). The expected value for the hogging and sagging under still water conditions are 20.1×10^8 Nm and 11.15×10^8 Nm, respectively. The RAO curves are formulated considering the VBM load effects under given operation conditions. Additionally, the Pierson-Moskowitz spectrum is applied in this paper to describe irregular wave patterns. Heading angles between 0° (following sea) and 180° (head sea), in increments of 15° , are accounted for within the RAO curves. Using PDSTRIP [49], the linear response of the ship structure under regular wave loading is obtained. Due to the implementation of linear theory, the resulting bending moments are the same for both sagging and hogging [26, 37]. More detailed information regarding the VBM evaluation using linear strip theory can be found in [9]. Within this paper, the mean and standard deviation of the JHSS's VBM response distribution are computed using Eqs. (10) and (11).

The reliability index associated with sagging and hogging for the mid-ship section is determined given the sea state, ship speed, and heading as shown in Eq. (14). The reliability analysis is performed using the computer program RELSYS [13], based on the First-Order Reliability Method (FORM). The intensity of the sea may be expressed in terms of significant wave height. Within the illustrative example, the intensity of the sea in terms of significant wave height ranges from 1.07 and 7.10 m. Given the weather conditions outlined in [10], it is determined that sea states 4, 5, 6, and 7 may be used to represent the possible sea conditions. The significant wave height, period, and length associated with each sea state are shown in Table 1. Herein, the ocean conditions are based on a hypothetical sea map [8]. With new measurement techniques and if more data associated with wind and waves becomes available, the uncertainties related to ocean condition could be well developed and incorporated within the decision making process [6, 7]. Overall, sea state 7 yields relatively low reliability, which indicates poor operational conditions for each considered heading angle. Figure 5 shows the reliability index associated with the load effects under still water and waves. It is evident from this figure that as the ship's speed increases, the VBM typically increases considering head sea, whereas for following sea, relatively larger VBM responses are obtained for lower speeds. The lowest reliability index with respect to heading angle is obtained when the heading angle equals to 180° . Furthermore, the reliability index associated with sagging is overall larger than the reliability index calculated with respect to hogging. Similar results associated with reliability index corresponding to the mid-ship cross-section under different sea states have been obtained by Decò et al. [9] and Zhu and Frangopol [60].

A spectral-based method is used in this paper for the fatigue damage assessment of the JHSS. The structural detail considered within the fatigue analysis is a connection that joins the main deck longitudinally to a transverse web at the mid-ship section. The linear model assumption is adopted herein since the nonlinear effects are considered negligible. In this paper the wave-induced VBMs are considered as the main source of fatigue damage. For illustrative purposes, the cumulative service time under investigation (T in Eq. (16)) is taken as 20 years and the fraction of time that this vessel is out at sea is assumed to be 85%. The RAOs associated with the VBM stress at a fatigue-critical structural component are obtained considering given operational cases by using Eq. (8). The probabilities of encountering certain sea states during a ship's service life are obtained from a wave scatter diagram associated with unrestricted service classification provided by the ABS [1]. Considering these wave scatter diagrams, the annual largest significant wave height investigated within this illustrative example is assumed to be 3.5 m for the fatigue damage accumulation of the JHSS during its service time. Additionally, the average service speed of the JHSS is assumed to be 15 m/s for calm seas. Based on Prpić-Oršić and Faltinsen [50], the ship's speed as a function of significant wave height is shown in Figure 6. As indicated, there is a significant reduction of the ship's speed in severe sea states. The fatigue damage accumulation for the structural component is computed using Eq. (21); the correction factor to account

for the wide band process is considered in this equation. The linear S-N approach is also applied in this paper, with curve slope parameters defined as $m = 3$ and $A = 4.31 \times 10^{11}$. Note that the fatigue damage accumulation associated with ship structures increases with time if no repair or maintenance actions are applied. The fatigue damage accumulated by the JHSS's fatigue critical component is 0.6238 after the assumed 20 year service time.

5.2 Risk Assessment Considering Multiple Performance Criteria

The consequences associated with a ship's mission are outlined within this section; impacts to the surrounding social setting, environment, and economy are accounted for in the presented approach. The first step within the attribute evaluation procedure is to calculate the direct monetary loss corresponding to ship routing. This attribute, measured in monetary terms, is computed utilizing Eq. (23) for Routes 1, 2, and 3. The ship type *STF* and *WGT*₁₀₀ associated with the JHSS regarding its construction costs are 7 and 10,300, respectively [10]. The second detrimental attribute included within this risk analysis is the fatigue damage accrued by a marine vessel. The fatigue damage is represented by the fatigue damage accumulation calculated using Eq. (21). In this illustrative example, the fatigue damage prior to the mission is significantly larger than that during the ship mission process. Overall, the fatigue damage is highly dependent upon sea and ship operational states.

The third attribute considered within this analysis is the travel time experienced by a ship. The total travel time is considered as a social impact herein and is calculated using Eq. (24). The factors that affect this social risk metric include the sea conditions and vessel velocity. The fourth and final consequence examined in detail within this paper is the total amount of carbon dioxide emissions associated with a specific route. Environmental impacts of a marine vessel's mission may be represented by the greenhouse gas emissions associated with a specific route in addition to ship speed and heading angle. The carbon dioxide emissions associated with ship routing is calculated with Eq. (25). The expected CO₂ emissions from the JHSS are assumed to be 355 kg/km considering calm sea conditions [50]. Additionally, significant wave heights are associated with specific reductions of ship speed as shown in Figure 6. The mean values of the risk metrics calculated with Eqs. (21) and (23) - (25) are then utilized as attribute values within the single attribute utility assignment. For instance, as indicated in Table 2, the expected value of the repair loss and total travel time corresponding to Route 1 are 2.0385×10^5 USD and 9.7841×10^4 seconds, respectively. The expected repair losses associated with Route 2 and 3 are 3.1595×10^5 and 4.1754×10^5 USD, respectively.

5.3 Decision Making Using Multi-Attribute Utility Theory

MUAT is utilized within the route decision making framework presented herein. The expected values of the attributes (i.e., repair loss, fatigue damage, travel delay, and carbon dioxide emissions), all of which are represented in different units, are transferred to a uniform scale ranging from 0 to 1 by employing separate single attribute utility functions. The utility assignment for each attribute is facilitated by Eq. (1) with varying x_{max} values as outlined in Table 3. This formulation for single-attribute utility accounts for the risk attitude of the decision maker. Figure 7 depicts the utility values associated with the expected values of each attribute considering two different risk averse attitudes ($\rho = 2$ and $\rho = 4$). The effect of the decision maker's risk attitude on the utility function associated each attribute of risk is investigated herein. Figure 7 shows the resulting marginal utility functions corresponding to each attribute considering two different risk taking attitudes ($\rho = -2$ and $\rho = -4$). Comparing Figures 7 and 8 reveals that utility functions associated with attributes follow the general trends shown in Figure 2(a); a concave utility function corresponds to a risk averse attitude, while a convex utility function indicates a risk taking attitude.

Once the single attribute utility functions are formulated, the marginal utility values are then combined into one multi-attribute utility value utilizing Eq. (2). Note that subscripts 1, 2, 3, and 4 on u and k in Eq. (2) correspond to the repair loss, cumulative fatigue damage, total travel time, and carbon dioxide emissions,

respectively. For Route 1, the multi-attribute utility values associated with a risk averse decision maker are shown in Table 2 considering weighting factors $(k_1, k_2, k_3, \text{ and } k_4) = (0.25, 0.25, 0.25, 0.25)$. This combination of weighting factors indicates equal contributions of all four attributes within the multi-attribute utility assessment.

In order to determine which route the ship should take, the multi-attribute utility values associated with Routes 1, 2, and 3 must be compared; the Route that corresponds to the largest multi-attribute utility value is the one that should be chosen. Table 4 shows the result of applying the proposed methodology to all three Routes considering different risk attitudes and weighting factor combinations. Within Table 4, each column represents a decision maker that has a certain risk attitude ρ and assigns particular weighting factors to the consequences investigated (e.g., $k_1, k_2, k_3, \text{ and } k_4$). Additionally, within each column, the largest multi-attribute utility value is bolded; this value corresponds to the best route for the ship. For instance, considering a risk taking attitude with weighting factors $(0.3, 0.3, 0.2, 0.2)$, the decision maker will always choose Route 1 since it corresponds to the largest utility value. However, if the same risk taking decision maker weighs the consequences slightly differently with weighting factors equal to $(0.2, 0.2, 0.3, 0.3)$, then Route 3 is determined as the best shipping route. Furthermore, a risk averse decision maker with attribute weighting $(0.2, 0.2, 0.3, 0.3)$ will always choose Route 1.

As an extension of the results obtained in Table 4, Figure 9 depicts the effects of the severity of the decision maker's risk averse attitude on the ship routing. This figure presents the multi-attribute utility value as a function of the decision maker's risk averse attitude ρ . Figure 9(a) considers a risk averse decision maker with consequences weighting $(0.2, 0.2, 0.3, 0.3)$. As evidenced by Figure 9(a), as a decision maker becomes more risk averse (increasing values of ρ), the multi-attribute utility value corresponding to each Route increases. Additionally, the difference between the multi-attribute utility values corresponding to Route 1 and Route 3 increases as the decision maker becomes more risk averse. For the scenario presented in Figure 9(a), Route 1 is always chosen as the best route. When the consequence weighting is changed to $(0.1, 0.1, 0.4, 0.4)$, the effect on the resulting multi-attribute utility values associated with Routes 1 and 3, is investigated in Figure 9(b). For this combination of consequence contributions, a decision maker with a relatively small risk averse attitude (i.e., $0 \leq \rho \leq 4$) will choose Route 3, while a decision maker with a relatively severe risk averse attitude (i.e., $\rho > 4$) will choose Route 1 as the best shipping course. Overall, the decision maker's risk attitude, in addition to the weighting factors involved in the multi-attribute utility assessment, have great effects on the final ship route decision.

6. Conclusions

This paper presents an efficient approach for ship routing decision support by using MAUT. The strip theory is used for the assessment of the RAOs associated with VBMs and stresses at the mid-ship cross section. The repair loss, fatigue damage accumulation, total travel time, and CO₂ emissions are considered as performance criteria for ship routing decision making. Overall, a holistic and quantitative approach for ship routing decision making considering the utility associated with different attributes is reported. The proposed framework effectively includes state-of-the-art ship performance assessment techniques while simultaneously considering the decision maker's preferences to facilitate ship routing decision making.

The following conclusions are obtained:

1. Ship structures are sometimes forced to follow certain routes with severe sea states while simultaneously handling time and distance constraints; this combination of dire conditions puts ships in danger of accruing damage that may negatively impact society and the surrounding environment. Ultimately, ship mission performance assessment is of vital importance for ship managers since it provides them guidance for the decision making of marine vessels under uncertainty.

2. The generalized decision making framework developed in this paper effectively incorporates the effects of both flexural and fatigue damage within a risk assessment for ship structures. Overall, it is crucial to consider both types of damage and their associated detrimental consequences.
3. The performance of a ship during routing may be represented by the four metrics considered herein. MAUT is utilized to combine all single-attribute utilities into a uniform metric that reflects the overall utility associated with a specific ship route. Overall, the consequences of decision making regarding ship routing may be evaluated based on professional judgment and existing information while utility theory can be employed to quantify the decision maker's preference.
4. Both the attitude of the decision maker and weighting factors employed in the multi-attribute utility assessment have significant effects on the multi-attribute utility value obtained for a route. The proposed methodology may be used to assist decision making regarding traffic control and risk mitigation activities, and to ultimately improve the traffic safety of maritime transportation.
5. The linear approach is adopted herein to compute the load effects and improved results can be obtained by using methods that account for non-linearity in wave-induced loading. Other risk attributes (e.g., risk associated with environmental pollution or being lost at sea) are not considered in this paper; however, with more available data, other adverse attributes can be incorporated within the ship mission risk assessment process.
6. The proposed framework could be enhanced by including structural health monitoring (SHM) technologies. This framework can accommodate SHM data by means of updating the prior information with newly recorded data sets [14, 45, 60].

The proposed multi-criteria based decision making management approach for ship structures has the ability to determine a ship's mission performance considering the response of the structure under probabilistic environmental scenarios. Ultimately, the presented methodology can aid in the decision making and ship management processes.

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7. References

- [1] ABS. *Guide for fatigue assessment of off shore structures*. American Bureau of Shipping, 2010; Houston.
- [2] Akpan UO, Koko TS, Ayyub B, Dunbar TE. Risk assessment of aging ship hull structures in the presence of corrosion and fatigue. *Marine Structures*, 2002; 15(3), 211-231.
- [3] Ang AH-S, Tang WH. Probability concepts in engineering planning and design. *Volume II: decision risk and reliability*. 1984; John Wiley & Sons, Inc.
- [4] Ayyub BM, Assakkaf IA, Atua KI. Reliability-based load and resistance factor design (LRFD) of hull girders for surface ships. *Naval Engineers Journal*, ASNE, 2002; 112(4), 279-96.
- [5] Bai Y. *Marine Structural Design*, Elsevier Science, 2003
- [6] Bitner-Gregersen EM, Skjong R. Concept for a risk based navigation decision assistant. *Marine Structures* 2009; 22, 275-286.
- [7] Bitner-Gregersen EM, Ewans KC, Skjong R. Some uncertainties associated with wind anwave description and their importance for engineering applications. *Ocean Engineering* 2014; 86, 11-25.
- [8] Decò A, Frangopol DM, Okasha NM. Time-variant redundancy of ship structures. *Journal of Ship Research*, SNAME, 2011; 55(3), 208 - 219.
- [9] Decò A, Frangopol DM, Zhu B. Reliability and redundancy assessment of ships under different operational conditions. *Engineering Structure*, 2012; 42, 457 - 471.

- [10] Decò A, Frangopol DM. Risk-informed optimal routing of ships considering different damage scenarios and operational conditions. *Reliability Engineering and System Safety*, 2013; 119, 126 - 140.
- [11] Devine EA. *An overview of the recently-completed JHSS monohull and trimaran structural seaways loads test program*. Naval Surface Warfare Center, Carderock Division (NSWCCD), 2009; PowerPoint Briefing, 30 October, 2009.
- [12] DNV. Classification Note No. 30.7: *Fatigue assessment of ship structure*, 2010; Det Norske Veritas, Oslo, Norway.
- [13] Estes AC, Frangopol DM. RELSYS: a computer program for structural system reliability analysis. *Structure Engineering and Mechanics*, Techno Press 1998; 6(8), 901–19.
- [14] Frangopol DM, Bocchini P, Decò A, Kim S, Kwon K, Okasha NM, Saydam D. Integrated life-cycle framework for maintenance, monitoring, and reliability of naval ship structures. *Naval Engineers Journal*, 2012; 124(1), 89-99.
- [15] Faltinsen OM. *Sea Loads on Ships and Offshore Structures*. Cambridge University Press, 1990; Cambridge, UK.
- [16] Fonseca N, Guedes Soares C. Time domain analysis of large-amplitude vertical ship motions and wave loads. *Journal of Ship Research*, 1998; 22, 139-153.
- [17] FREE!ship. *FREE!ship manual - Version 2.6*. 2006. Website: www.freeship.org.
- [18] Guedes Soares C, Moan T. Model uncertainty in the long term distribution of wave induced bending moments for fatigue design of ship structures. *Marine Structures*, 1991; 4(4), 295-315.
- [19] Guedes Soares C. Combination of primary load effects in ship structures. *Probabilistic Engineering Mechanics*, 1992; 7(2), 103-111.
- [20] Guedes Soares C, Moan T. Statistical analysis of still water load effects in ship structures. *Transactions of the Society of Naval Architects and Marine Engineers*. New York, NY, 1988; 96, 129-156.
- [21] Guedes Soares C, Schellin TE. Nonlinear effects on long-term distribution of wave-induced loads for tankers, *J Offshore Mech Arct Eng*, 1998; 120, 65 - 70.
- [22] Guedes Soares C, Dogliani M. Probabilistic modelling of time-varying still-water load effects in tankers. *Marine Structures*, 2000; 13(2). 129-143.
- [23] Guedes Soares C, Teixeira AP. Structural reliability of two bulk carrier designs. *Marine Structures*, 2000; 13(2), 107-128.
- [24] Guedes Soares C, Garbatov Y, von Selle H. Fatigue damage assessment of ship structural components based on the long-term distribution of local stresses, *Int Shipbuild Prog*, 2003; 50, 35–56.
- [25] Howard RA, Matheson JE. *Readings on the principles and applications of decision analysis*. 1989; Menlo Park, CA, Strategic Decisions Group.
- [26] Hughes OF. *Ship structural design: A rationally-based, computer-aided, optimization approach*. 1983; Wiley and Sons, New York.
- [27] Hussein AW, Guedes Soares C. Reliability and residual strength of double hull tankers designed according to the new IACS common structural rules. *Ocean Engineering*, Elsevier, 2009; 36(17-18), 1446-1459.
- [28] Hørte T, Wang G, White N. Calibration of the hull girder ultimate capacity criterion for double hull tankers. *10th International Symposium on Practical Design of Ships and Other Floating Structures*, Houston, TX, American Bureau of Shipping, 2007; 553-64.
- [29] IACS. *Common structural rules for double hull oil tankers*. International Association of Classification Societies (IACS), 2008; London, UK.
- [30] IACS. *Common structural rules for bulk carriers*. International Association of Classification Societies (IACS), 2009; London, UK.
- [31] IMO. *Prevention of air pollution from ship*. MEPC 57/4/10, 2008; London.
- [32] Jensen JJ, Pedersen, PT. Wave induced bending moment in ships - quadratic theory, *Trans Royal Inst Naval Architects (RINA)*, 1978; 120, 151-161.

- [33] Jiménez A, Ríos-Insua S, Mateos A. A decision support system for multiattribute utility evaluation based on imprecise assignments. *Decision Support Systems*, 2003; 36(1), 65–79.
- [34] Keeney RL, Raiffa H. *Decisions with multiple objectives: preferences and value tradeoffs*. Cambridge University Press, 1993.
- [35] Kukkanen T, Mikkola TPJ. Fatigue assessment by spectral approach for the ISSC comparative study of the hatch cover bearing pad. *Marine Structures*, 2004; 17(1), 75-90.
- [36] Kwon K, Frangopol DM. System reliability of ship hull structures under corrosion and fatigue. *Journal of Ship Research*, 2012; SNAME, 56(4), 234-251.
- [37] Lua J, Hess PE. First-failure-based reliability assessment and sensitivity analysis of a naval vessel under hogging. *Journal of Ship Research*, SNAME, 2006; 50(2), 158-170.
- [38] MathWorks. Natick, MA: The Math Work, Inc.; 2013.
- [39] Mansour AE, Preston DB. Return periods and encounter probabilities, *Applied Ocean Research*, Elsevier Science Ltd, 1994; Oxford, United Kingdom.
- [40] Mao W, Li Z, Ringsberg JW, Rychlik I. Application of a ship-routing fatigue model to case studies of 2800 TEU container vessels. *Proceeding of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 2012; 222-234.
- [41] Miroyannis A. Estimation of ship construction costs. *Master thesis*. 2006; Department of Mechanical Engineering, Massachusetts Institute of Technology, Boston, MA.
- [42] Nguyen KT, Garbatov Y, Guedes Soares C. Spectral fatigue damage assessment of tanker deck structural detail subjected to time-dependent corrosion. *International Journal of Fatigue*, 2013; 48, 147-155.
- [43] Nielsen UD, Jensen JJ. A novel approach for navigational guidance of ship using onboard monitoring systems. *Ocean Engineering* 2011; 38, 444-455.
- [44] Okasha NM, Frangopol DM. (2010). Efficient method based on optimization and simulation for the probabilistic strength computation of the ship hull. *Journal of Ship Research*, 2010; 54(4), 1–13.
- [45] Okasha NM, Frangopol DM, Decò A. Integration of structural health monitoring in life-cycle performance assessment of ship structures under uncertainty. *Marine Structures*, 2010; 23(3), 303-321.
- [46] Paik JK, Thayamballi AK, Kim SK, Yang SH. Ship hull ultimate strength reliability considering corrosion. *Journal of Ship Research*, SNAME, 1998; 42(2), 154-165.
- [47] Paik, JK, Frieze, PA. Ship structural safety and reliability. *Progress in Structural Engineering and Materials*, Wiley and Sons, 2001; 3(2), 198-210.
- [48] Park J. Development and application of probabilistic decision support framework for seismic rehabilitation of structure systems. *Ph.D. Dissertation*, 2004; Civil and Environmental, Georgia Institute of Technology, Atlanta, GA.
- [49] PDSTRIP. Program PDSTRIP: Public domain strip method - User Manual. 2006. Website: <http://sourceforge.net/projects/pdstrip>.
- [50] Prpić-Oršić J, Faltinsen OM. Estimation of ship speed loss and associated CO₂ emissions in a seaway. *Ocean Engineering*, 2012; 44, 1-10.
- [51] Rasmus F. Spectral fatigue damage calculation in the side shells of ships, with due account taken of the effect of alternating wet and dry areas. *Marine Structures*, 1998; 11, 319–343.
- [52] Resolute Weather. Pierson–Moskowitz Sea Spectrum. (<http://www.eustis.army.mil/weather>) (accessed March 3, 2014), 2014.
- [53] Salvesen N, Tuck E, Faltisen O. Ship motions and sea loads. *Transactions the Society of Naval Architects and Marine Engineering* (SNAME), 1970; 78, 250-287.
- [54] Saydam D, Frangopol DM. (2013). Performance assessment of damaged ship hulls. *Ocean Engineering*, 2013; 68, 65-76.
- [55] Siddiqui NA, Ahmad S. Fatigue and fracture reliability of TLP tethers under random loading. *Marine Structures*, 2001; 14, 331-352.

- [56] Stewart TJ. Robustness of additive value function methods in MCDM. *Journal of Multi-Criteria Decision Analysis*, 1996; 5(4), 301-309.
- [57] Teixeira AP, Parunov J, Guedes Soares C. Assessment of ship structural safety. *In Marine Technology and Engineering 2011*; London, UK, 1377-94.
- [58] Wang Y. Spectral fatigue analysis of a ship structural detail – A practical case study. *International Journal of Fatigue*, 2010; 32, 310-317.
- [59] Xue J, Pittaluga A, Cervetto D. Fatigue damage calculation for oil tanker and container ship structure. *Marine Structures*, 1994; 7(6), 499-535.
- [60] Zhu B, Frangopol, DM. Reliability assessment of ship structures using Bayesian updating. *Engineering Structures*, 2013; 56, 1836-1847.

Figure Captions

Figure 1- Flowchart for the decision support system

Figure 2 – (a) Utility functions associated with different risk attitudes and (b) flowchart for the multi-attribute utility assessment

Figure 3 - The qualitative VBM RAOs associated with given cross section

Figure 4 - (a) The ship body under investigation; (b) mid-ship cross-section of the JHSS; and (c) alternative ship routes

Figure 5 – Figure 6. Polar representation of the reliability index corresponding to the mid-ship cross-section under sea state 5 considering different ship speeds and (b) profiles of the reliability index for different sea states considering a ship speed of 10 m/s. Associated Cartesian plots of the reliability indices for the ship with respect to different (c) ship speeds, and (d) sea states.

Figure 6 – Expected ship speed reduction as a function of significant wave height

Figure 7 - Utility functions for the four attributes considering a risk averse attitude

Figure 8 - Utility functions for the four attributes considering a risk taking attitude

Figure 9- Multi-attribute utility values as a function of risk averse attitude ρ considering weighting factors equal to (a) (0.2, 0.2, 0.3, 0.3) and (b) (0.1, 0.1, 0.4, 0.4)

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Table 1. Statistical information corresponding to sea states (based on information from [49])

Sea state	Significant wave height (m)	Average wave period (s)	Average wave length (m)
4	1.83	5	24.08
5	2.44	5.5	32
6	4.27	7.5	56.09
7	7.62	10	100.13

Table 2. Multi-attribute utility values associated with Route 1, 2, and 3 considering equal weighting factors (0.25, 0.25, 0.25, 0.25) under different risk attitudes

Alternative	Attribute	Expected value	$\rho = 2$		$\rho = -2$	
			Single attribute utility	$u(x_1, x_2, x_3, x_4)$	Single attribute utility	$u(x_1, x_2, x_3, x_4)$
Route 1	A_1 (10^5 USD)	2.0385	0.8028	0.7134	0.3552	0.2604
	A_2	0.6238	0.6116		0.1757	
	A_3 (10^4 second)	9.7841	0.7401		0.2782	
	A_4 (10^5 kg)	5.4058	0.6951		0.2358	
Route 2	A_1 (10^5 USD)	3.1595	0.6026	0.6961	0.1703	0.2470
	A_2	0.6238	0.6238		0.7570	
	A_3 (10^4 second)	8.8277	0.7781		0.3219	
	A_4 (10^5 kg)	4.9793	0.7328		0.2707	
Route 3	A_1 (10^5 USD)	4.1754	0.3249	0.6724	0.0612	0.2666
	A_2	0.6238	0.6116		0.1757	
	A_3 (10^4 second)	7.4117	0.8281		0.3946	
	A_4 (10^5 kg)	4.2679	0.7890		0.3360	

Note: A_1 : repair loss; A_2 : fatigue damage accumulation; A_3 : total travel time; A_4 : carbon dioxide emissions.

Table 3. Information regarding the single attribute utility functions

Attribute	Maximum Value	Minimum value
Repair loss (USD)	5.0×10^5	0
Fatigue damage accumulation	1	0
Total travel time (second)	2.0×10^5	0
Carbon dioxide emissions (kg)	1.0×10^6	0

Table 4. Multi-attribute utility values associated with Routes 1, 2, and 3 considering different risk attitudes ρ and various weighting factors

Alternative	Multi-attribute utility value					
	$\rho = -2$	$\rho = -4$	$\rho = -2$	$\rho = -4$	$\rho = 2$	$\rho = 4$
Weighting factor	(0.3, 0.3, 0.2, 0.2)	(0.2, 0.2, 0.3, 0.3)	(0.2, 0.2, 0.3, 0.3)		(0.2, 0.2, 0.3, 0.3)	
Route 1	0.2621	0.1186	0.2604	0.1164	0.7134	0.8661
Route 2	0.2223	0.0936	0.2471	0.1084	0.6961	0.8531
Route 3	0.2172	0.1006	0.2666	0.1302	0.6724	0.8126