A knowledge based hierarchical reliability allocation (HIRAL) approach for shipboard systems

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Abstract
Reliability has become a greater concern in shipboard systems due to increasing amount of technology level, system complexity, and multiple design demands. Enhancement of the shipboard system’s reliability ensures safe and continuous operation onboard a ship. To enhance the reliability of the shipboard system, it is essential to identify each individual component’s reliability. Within this scope, the onerous task of reliability allocation analysis enhances the reliability of shipboard systems through the optimization of component-based designs, construction, and operations. This study proposes a hybrid reliability allocation methodology based on a hierarchical structure with the integration of an analytic hierarchy process (AHP), data envelopment analysis (DEA), and feasibility of objectives (FOO) methods. The proposed methodology provides reliability allocation analyses for systems with any number of components. The study also examines the usefulness of the adaptation of AHP-DEA into reliability allocation analysis. To demonstrate the applicability of the proposed methodology, a case study on the steering gear system is presented.

Keywords
Shipboard systems, reliability allocation analysis, analytic hierarchy process, data envelopment analysis, feasibility of objectives

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Introduction
With the development of complex and technologically advanced large-scale systems, such as nuclear power plants, space systems, offshore platforms, and marine engineering systems on board ships, issues dealing with the reliability of complex systems have become an ever-greater concern in recent years. Especially, the increasing amount of technology, system complexity, and multiple design demands of shipboard systems and cost reduction in a highly competitive market highlight reliability as a substantial point for clients and operators. High-reliability shipboard systems neutralize deficits created by many non-safe elements and contribute to safe operation onboard ships. However, due to their specific characteristics and the harsh operating environment in which they operate, manufacturers still have difficulties in improving the reliability of shipboard systems.

The reliability of a system is affected by many factors such as system operating environment, condition indicating parameters, and human aspects: these can degrade or improve the reliability beyond what is expected under normal operating conditions or depending upon the amount of time that a system has been in use. Reliability practitioners are currently investing considerable research effort and expense to develop appropriate principles for ascertaining engineering systems’ reliability. Nowadays, the primary focus on the reliability of complex systems is to translate the reliability requirement of the systems into the individual components for the determination of overall system reliability. The fulfillment of component-based requirements increases the overall system reliability to meet overall requirements. It is thus necessary to implement an appropriate reliability allocation method proportionately, for the allocation of the required system
reliability into each individual component of the system. For the appropriate implementation of reliability allocation, a wide range of factors in the allocation of reliability requirements need to be taken into consideration. These include component criticality, complexity, operating environment, operating time, the extent to which systems are state-of-the-art, cost, and several other factors.5

Having a relevant and sufficient large set of qualitative or quantitative data on these factors related to the analyzed system is an important issue for appropriate reliability allocation. From the perspective of shipboard systems, however, reliability allocation analysis can be demanding due to the uncertainty and inadequacy of quantitative system data. To overcome these limitations, the study concentrates primarily on the adoption of expert judgments as a source of information in reliability allocation for shipboard systems. Additionally, in the study, reliability allocation analysis is accepted as a multi-criteria decision-making (MCDM) problem with its multiple factor structure. In this situation, a hybrid reliability allocation methodology integrating two different MCDM methods, the analytic hierarchy process (AHP) and data envelopment analysis (DEA) is introduced. Under limited system-based data circumstances, the proposed methodology allows us to utilize experts’ judgments as a source of information and also it provides an opportunity to handle multiple experts’ judgments. A growing number of researchers doing reliability allocation analysis increases consistency and the certainty of the elicited judgments.

The proposed methodology introduces a new understanding for reliability allocation analysis through providing analysis under uncertain and inadequate data for shipboard systems. The integration of AHP and DEA methods helps to retain the individual advantages and to overcome the shortcomings of these methods, as the proposed methodology has the ability to handle a system with any number of components. This study also extends the literature by weighting the reliability allocation factors in relation to each other. Furthermore, with its generic system analysis structure, the proposed methodology provides a comprehensive reliability allocation analysis solution not only for shipboard systems but also other complex and large-scale systems.

The paper is structured into five sections. Section 1 introduces the importance of reliability allocation analysis for complex systems and shipboard systems. Section 2 presents an overview of related literature. The formulation of the proposed hierarchical reliability allocation (HIRAL) methodology is explained in Section 3. The implementation of the HIRAL methodology is conducted on one of the critical ship-board systems onboard ship, steering gear systems, in Section 4 to test the applicability of the methodology. The paper is concluded in Section 5.

Literature review: Methodological perspective

Since the middle of the 20th century, there have been tremendous research efforts and progress on reliability allocation analysis. Within those studies which examine its methodological development, the characteristics of the systems are seen to substantially influence the structures of the methodologies. In the literature, it is possible to find various types and numbers of methodologies on reliability allocation analysis. One of the earliest methodologies in literature is the Advisory Group on Reliability of Electronic Equipment (AGREE) method.4 In the AGREE method, complexity and criticality factors are considered reliability allocations. In 1964 Aeronautical Radio Incorporated proposed the ARINC apportionment technique. The ARINC technique is structured based on the estimation of the failure rates of units or subsystems.5 Within the same year, Brach6 presented an allocated reliability method using four factors: state-of-the-art, subsystem complexity, environmental conditions, and relative operating time. In the following year, Karmiol7 introduced the reliability allocation method using four different factors: complexity, state-of-the-art, operational profile, and criticality of the system. In 1976, the feasibility-of-objectives (FOO) method was presented by Anderson8 in the Reliability Design Handbook. Performance time, system intricacy, environmental conditions, and the state-of-the-art are considered as allocation factors in the FOO method. In 1992, Boyd developed the Boyd9 method by incorporating the Equal and ARINC methods. In 1999, Balaban and Jeffers10 proposed the Base method. The base method considers the units of the investigated system in series. Also, in the same year, Kuo11 introduced an average weighting allocation method as a guide for commercial reliability allocation analysis in his book. These methodologies are accepted as traditional methodologies and they have wide applicability in reliability allocation analysis across many industries. However, the traditional methodologies have two important shortcomings: the first one is not considering the ordered weight of the reliability allocation factors and the second one is not being able to manage fuzzy or ambiguous information in reliability allocation.

To minimize the shortcomings of traditional methods, intensive research efforts have been carried out on methodological aspects in the literature. MCDM methods are frequently preferred in allocation processes to consider the ordered weight of reliability allocation factors. In the literature review, it is found that AHP mostly utilized MCDM method. The studies of the authors Zahedi and Ashrafi,12 Zhang and Liao,13 Cheng et al.,14 Chatterjee et al.,15 Li et al.,16 Ma et al.,17 Subhashis et al.,15 Chen et al.,18 Di Bona et al.,19 Di Bona and Forcina,20 and Di Bona et al.21 can be given
as example studies of using AHP in the reliability allocation process. The decision-making trial and evaluation laboratory (DEMATEL) method, as well as the AHP, is another preferred MCDM method in the literature. Liaw et al.22 and Chang et al.23 adopt the DEMATEL method to consider indirect relations between subsystems or components in reliability allocation. Also, Li et al.24 proposed a reliability allocation model based on another popular MCDM method: Grey System Theory, considering six affecting factors which are the importance, complexity, technology development level, manufacturing level, working time, and environmental conditions.

Apart from the MCDM methods aforementioned, multi-objective optimization methods,25–38 the integrated factors method,39 the genetic algorithm method,40–47 Markov Chain,48 Bayesian network,17,49 FMEA,23,50,51 Monte Carlo54 and the critical flow method,54 and the data envelopment analysis method55 are other important methods used in the literature to minimize the shortcomings of traditional reliability allocation methods.

It is clear from the literature review that most of the contemporary methodologies need a vast amount of system data for appropriate reliability allocation analysis. However, from the shipboard systems perspective, it is not possible to find sufficient, relevant and consistent data on system performance. That makes experts’ judgments an essential source of data on system reliability allocation analysis for shipboard systems. On the other hand, the methodologies in the literature could not guarantee efficient access and constant exchange of large amounts of expert measurement information on reliability allocation analysis.56 Additionally, existing reliability allocation methods can meet the requirements of reliability allocation for simple or specific systems.57

Apart from methodological studies, studies on reliability analysis for merchant shipping can be categorized under three main groups: structural reliability analysis, system reliability analysis, and human reliability analysis. As an example, for structural reliability analysis, Downes and Pu58 proposed a methodology for assessment of ship hull girder ultimate strength reliability to improve the ship design from the perspective of safety. Additionally, the study conducted by Parunov et al.,59 on a hull girder reliability assessment of the MSC Napoli at the time of its accident can be given as another example. To calculate the probability of failure, a first-order reliability method was used in the study. From the perspective of ship system reliability analysis, as one of the examples studies, Ruede et al.60 conducted a reliability and availability analysis using the semi-automatic fault tree synthesis method and Hierarchically Performed Hazard Origin and Propagation Studies (HiP-HOPS) tool together with the simulation platform SimulationX. Additionally, Zymaris et al.61 presented a system engineering methodology using the DNVGL COSSMOS (Complex Ship System Modelling and Simulation) for the analysis and condition assessment of complex marine machinery systems. Also, to assess the reliability of mooring systems of floating structure systems, Zhao et al.,62 developed a methodology based on artificial neural network–Bayesian network inference. To improve system reliability of marine mechanical systems, Kimera and Nangolo63 created a stochastic technique based on reliability data for determining the optimal maintenance policy. Dionysiou et al.64 proposed a functional model-based approach for ship systems safety and reliability analysis using the Maintenance Aware Design (MADe) software. In the study, a Failure Modes, Effects and Criticality Analysis (FMECA) and a Fault Tree Analysis (FTA) are integrated to implement safety analysis. Subsequently, Reliability Block Diagrams (RBDs) are used to estimate the system reliability and availability metrics. On the human reliability analysis, Bicen et al.,65 conducted a shipboard operation human reliability analysis (SOHRA) for a crankshaft overhauling operation of a general cargo ship during its dry-docking period. Also, Soner and Celik66 investigated the human element role during an enclosed space entry operation using the enhanced SOHRA method.

The findings gathered from the literature review reveal that methodological improvements in reliability allocation analysis still can be considered a crucial issue to research. Additionally, an allocation analysis under circumstances of limited information, evaluation of expert judgments as system reliability information, and aggregation of multiple expert judgments can be listed as potential methodological improvement points. Reliability allocation analysis for shipboard systems also needs to be focused on from the perspective of system reliability analysis. To provide solutions to the aforementioned gaps in the literature, this paper recommends a hybrid reliability allocation analysis method to implement reliability allocation in shipboard systems.

**Proposed methodology**

In this section, the theoretical background of the methods used in the proposed reliability allocation approach is described. In the proposed approach, to determine the importance of each reliability allocation factor (RAF), the AHP method is used. Calculation of the degrees of importance of RAFs provides the inclusion of system features and characteristics into the allocation process. In parallel with the calculation of the degrees of importance of RAFs, DEA is used to empirically measure the reliability rating of each component for each RAF with the help of multiple experts’ judgments. The motivation behind using multiple experts in allocation analysis is to obtain more comprehensive information that can lead to more accurate forecasts or estimates and, ultimately, to better reliability allocation. As inputs for FOO in its mathematical structure
the following are used: the outputs generated by AHP; weights of RAFs; weights of DEA; and individual reliability ratings. The framework of the proposed method is graphically illustrated in Figure 1.

The detailed information on AHP, DEA, and FOO methods are presented in the following sections respectively.

**Analytic hierarchy process (AHP)**

Analytic Hierarchy Process (AHP) is one of the most commonly preferred multi-criteria decision-making (MCDM) methods in the literature, introduced by Thomas Saaty. AHP mainly incorporates decomposing the decision problem into a hierarchical structure, collection of data and measurement through pairwise comparisons and calculation of the weights, and the degree of importance of attributes in each level. Saaty’s relative importance scale presented in Table 1 is used for the quantification of pairwise comparisons. The pairwise comparisons are then adopted in a square pairwise comparison matrix to obtain the relative importance degrees of attributes at a particular level of the AHP.

The process of applying AHP is starting with the construction of the pairwise comparison matrix by asking the expert questions to indicate the relative importance of allocation factors. From the pairwise comparison matrix $A$, the priority weights of factors are determined by solving the following equation:

$$Aw = \lambda_{\text{max}} w, \quad w = (w_1, w_2, \ldots, w_n)^T$$  \hspace{1cm} (1)

$\lambda_{\text{max}}$ represents the maximum eigenvalue of $A$. After carrying out pairwise comparisons, to verify whether the pairwise comparison matrix consistency is acceptable or not, the consistency ratio (CR) of the matrix is calculated using the following equation:

$$CR = \frac{(\lambda_{\text{max}} - n)(n - 1)}{RI}$$ \hspace{1cm} (2)

$RI$ states a random consistency index and the values of $RI$ with respect to the order of the pairwise matrices from 1 to 10 are presented in Table 2. If the consistency ratio is smaller than or equal to 0.10, the consistency of comparison matrix $A$ is acceptable; otherwise the
consistency of the comparison matrix is unacceptable and it is required to be reviewed and improved.

Data envelopment analysis (DEA)

Data envelopment analysis (DEA) was introduced by Charnes et al., and is one of the most widely-used and well-known methods for measuring efficiency between Decision-Making Units (DMUs). It helps to classify all system units under assessment into two groups: efficient and inefficient. However, nowadays decision-makers (DMs) are not only interested in classifying system units into efficient and inefficient: they are also interested in ranking all system units. By reason of the fact that various modified approaches on DEA were introduced to rank all system units under assessment. DEA approaches that have applied multiple criteria decision making (MCDM) concepts to rank system units are mostly preferred in literature. For this reason, this paper uses the advantages of the DEA ranking model introduced by Wang et al. to rank system units dealing with ordinal data. The approach of Wang et al. is constituted to analyze complex multi-component systems and structures. It provides a reasonable compromise between accuracy and simplicity in the aggregation of multiple experts’ judgments. The general definitions and steps of this methodology can be explained as follows:

For each RAF: \( G = \{ H_{j1}, H_{j2}, \cdots, H_{jK} \} \) a set of assessment grades are defined to clarify the relative importance of each system component with respect to each RAF. \( H_{j1}, H_{j2}, \cdots, H_{jK} \) implies that the degrees of importance from the most to least where \( K \) is the number of assessment grades for RAF \( j \). With the help of these sets of assessment grades, it is possible to assess different RAFs using different numbers of assessment grades. Within this direction, the linguistic assessment grade for each RAF in the study is presented in Table 3. The linguistic assessment grades provide a more meaningful and manageable assessment. Additionally, they help to handle the complexity and uncertainty of objective things and the fuzziness of human thought.

The reliability allocation is structured on four factors which are described in the FOO method: state-of-the-art, operating time, intricacy, and environmental conditions. The Intricacy factor, \( RAF_1 \), represents how intricate the component is. The least intricate element is rated as very simple (VS), and the most intricate component is rated as very complex (VC). The state-of-the-art factor, \( RAF_2 \), represents how technologically up-to-date the component is. The least developed component is assigned a value of very low (VL), and the most developed is assigned a value of very high (VH) relative to the other components. The operating time factor, \( RAF_3 \), represents how continuously the components are in operation. The component that operates from beginning to end of the operation is rated very high (VH), and the component that operates for the least operation time is rated as very low (VL). The Environment factor, \( RAF_4 \), represents how harsh the component’s environment is. The components that operate under harsh environments are rated as very severe (VS), and those operating under least severe environments are rated as least severe (LS).

The experts assess the system components with respect to the four RAFs using the linguistic assessment scale presented in Table 2. The assessment results of system components assessed by experts are defined as the following distribution assessment vectors:

### Table 2: Random consistency index R.I.

| n   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| R.I.| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|     |

### Table 3: Linguistic assessment scale of RAFs.

| Intricacy \((RAF_1)\) | Very simple | Simple | Complex | Very complex |
|------------------------|-------------|--------|---------|--------------|
| State of the art \((RAF_2)\) | Very Low | Low | High | Very high |
| Operating time \((RAF_3)\) | Very low | Low | High | Very high |
| Environmental conditions \((RAF_4)\) | Least severe | Moderately severe | Severe | Very severe |

### Table 1: The relative importance scale of Saaty.

| Strength of importance | Description |
|------------------------|-------------|
| 1                      | Equally preferred |
| 2                      | Between equal and moderate |
| 3                      | Moderately preferred |
| 4                      | Between moderate and strong |
| 5                      | Strongly preferred |
| 6                      | Between strong and very strong |
| 7                      | Very strongly preferred |
| 8                      | Between very strong and extreme |
| 9                      | Extremely preferred |
| Reciprocals            | Reciprocals for inverse comparison |
The Feasibility of objectives (FOO)

The Feasibility of objectives (FOO) method was first introduced in 1963. The method was developed primarily for allocating reliability in repairable electromechanical systems. Nowadays, commercial and military-based applications are quite popular. The main philosophy of FOO in determination of component allocation scores is based on achieving high reliability of the component under relative difficulty. The difficulty for component is described by four different factors: intricacy (RAF1), operating time (RAF2), and environmental conditions (RAF3). With its simple mathematical structure, the reliability allocation factors are constructed.

To determine the individual reliability rating of each component, a decision-making unit (DMU) and $s(H_{jk})$ states the relative importance weight attached to the NEijk, and the following DEA model developed for preference voting and aggregation is constructed.

Maximize $\alpha$

Subject to

$s(H_{1j}) \geq 2s(H_{2j}) \geq \cdots \geq K_{i}(H_{K_{i}j}) \geq 0,$

The obtained overall reliability ratings of the components used as inputs of FOO method.

Table 4. Distribution assessment matrix for system components.

| Components | Reliability allocation factors |
|------------|--------------------------------|
|            | $H_{1i}$ | $H_{2i}$ | $H_{3i}$ | $H_{4i}$ | $H_{5i}$ | $H_{6i}$ | $H_{7i}$ | $H_{8i}$ | $H_{9i}$ | $H_{10i}$ |
| $C_{i}$    | NE_{1i1} | NE_{1i2} | NE_{1i3} | NE_{1i4} | NE_{1i5} | NE_{1i6} | NE_{1i7} | NE_{1i8} | NE_{1i9} | NE_{1i10} |
| $C_{j}$    | NE_{j11} | NE_{j12} | NE_{j13} | NE_{j14} | NE_{j15} | NE_{j16} | NE_{j17} | NE_{j18} | NE_{j19} | NE_{j110} |
| $C_{n}$    | NE_{n11} | NE_{n12} | NE_{n13} | NE_{n14} | NE_{n15} | NE_{n16} | NE_{n17} | NE_{n18} | NE_{n19} | NE_{n110} |

$R(C(A_i)) = \{(H_{1j}, NE_{i1j}), \ldots, (H_{K_{i}j}, NE_{iK_{i}j})\},$

where $NE_{ijk}$ ($k = 1, \ldots, K_{i}$) represent the numbers of experts who assess system component $C_{i}$ to grade $H_{jk}$ under the RAF $j$. Then, the obtained distribution assessment vectors are transformed into the belief structure as below:

$B(C(A_i)) = \{(H_{1j}, b_{ij}), \ldots, (H_{K_{i}j}, b_{ij})\},$

where $b_{ij} = NE_{ijk}/N_{j}$ with $0 \leq b_{ij} \leq 1$ for $i = 1, \ldots, n$, $k = 1, \ldots, K_{i}$ and $j = 1, \ldots, m$.

Following the obtained distribution assessment vectors, a distribution assessment matrix is generated:

$W(C_i) = \sum_{j=1}^{m} w_{ij} s \left( \sum_{k=1}^{K_{i}} s(H_{jk}) NE_{ijk} \right), i = 1, \ldots, n$

The obtained overall reliability ratings of the components used as inputs of FOO method.
multiplying system failure rate ($\lambda_s$) and component complexity factor ($C_i^*$) defined as in equation (9):

$$
\lambda_k = \lambda_s \cdot C_i^*, \quad i = 1, \ldots, k.
$$

(9)

After the calculation of the failure rate of the $i$th component, the allocated reliability of $i$th component ($R_i$) is obtained using the following equation:

$$
R_i = e^{-\lambda_i t}.
$$

(10)

**Demonstration: Steering gear system reliability allocation analysis**

**Description of the steering gear system**

The demonstration of the proposed methodology is presented with a case study on a steering gear system, which is one of the most critical systems on board ship. The reliability of the steering gear system plays a significant role in the safe handling of ships. To produce highly reliable and durable ship-board systems will substantially contribute not only to the safe handling of the ships but also will be a next step toward unmanned shipping. From the design to operation stages of ship-board systems, a reliability allocation analysis provides valuable information specific to each component of the system and provides a concrete determination of the factors affecting the system reliability.

In the study, an electro-hydraulic steering gear system which can be used in tankers of 10,000 gross tones (GT) or less, or any other ships of 70,000 GT and upwards, is selected for the demonstration of the proposed methodology. The selected electro-hydraulic steering gear system is a ram-type and equipped with a main and an auxiliary steering gear. The auxiliary steering gear is activated automatically when the main steering gear fails, which is considered an emergency condition on board ships. Under such emergency conditions, it is not possible to navigate safely with an auxiliary steering gear so the ship is navigated to the nearest and safest anchorage area. Within the scope of this study, I focus on the main steering gear system without considering the auxiliary steering gear system.

The main steering gear system consists of three major subsystems; telemotor, control unit, and power unit. The complete subsystems and components list of the ram-type steering gear system is presented in Table 5.

**Demonstration of the reliability allocation analysis**

Following the determination of the components of the ram-type steering gear system, the hierarchical structure of the reliability allocation created for the system is presented in Figure 2.

With respect to the hierarchical structure illustrated in Figure 2, as a first step, the importance degrees of RAFs were determined by AHP. The pairwise comparison matrix was obtained through the expert judgments using Saaty’s scale of relative importance presented in Table 1 as follows:

$$
A = 
\begin{bmatrix}
    \text{RAF}_1 & \text{RAF}_2 & \text{RAF}_3 & \text{RAF}_4 \\
    1 & 3 & 5 & 7 \\
    1/3 & 1 & 3 & 5 \\
    1/5 & 1/3 & 1 & 3 \\
    1/7 & 1/5 & 1/3 & 1 
\end{bmatrix}
$$

![Figure 2. Hierarchical structure.](image-url)
With the help of pairwise comparison matrix $A$, the importance degrees were obtained. The results the degrees of importance were obtained as; $W = (0.56, 0.26, 0.12, 0.06)^T$. The consistency ratio of the matrix was found to be $CR = 0.044$. With the fact that $CR < 0.1$, it can be said that the matrix was consistent and the obtained importance degrees of RAFs were acceptable.

Following the determination of the importance degrees of RAFs, the components were then assessed one by one against the RAFs. The assessment was done by experts in the maritime industry. Experts from ship machinery manufacturers were invited to evaluate the components of the steering gear system against the intricacy and state-of-the-art factors and marine engineers took part in the assessment of the components against operating time and environment factors. The proposed approach provides great flexibility in the number of experts invited to assess the components with respect to each RAF. In the study, 15 experts from ship machinery manufacturers and 15 marine engineers who are operators of the steering gear system took part in the evaluation. The judgments of experts formed a distribution assessment matrix which is illustrated in Table 6.

Using the obtained optimal solutions for each RAF, the individual reliability ratings of steering gear components were calculated using equation (5) and the results obtained are presented in Table 7.

After the calculation of the individual reliability ratings ($v_{ij}$) of steering gear components, they were aggregated into overall reliability ratings ($W(C_i)$) using equation (7). The overall reliability ratings were presented in column 2 of Table 8. With the help of these overall reliability ratings, the complexity factor ($C_i$) of each component was calculated by equation (8) and illustrated in column 3 of Table 8.

In the MSc. thesis of Brocken,\(^7\) it was found that steering gear system failure behavior is directly connected to the exponential failure distribution and, for the reliability requirement ($R_s$), 0.90 for 1000 h operation time was judged acceptable.\(^7\) In the light of this information, the system failure rate of steering gear system ($\lambda_s$) was found to be 105.361 per 106 h. Following with the system failure rate, as a final step, the allocated failure rate ($\lambda_i$) and allocated reliability rate ($R_i$) of each component was calculated using equation (9).
The obtained results were presented in columns 4 and 5, respectively in Table 8.

### Results and discussions

Following the obtained results, C_{12}, safety valve, was found to be the most reliable component of the steering gear system. On the other hand, C_{5}, pump, and C_{16}, electric motor, were found to be the least reliable components of the steering gear system. To maintain the steering gear system reliability at 0.90, it is essential to sustain the components’ allocated reliability at the degrees thus calculated. Also, to improve the reliability of the steering gear system, it is necessary to provide attention to increase the reliability of the components with lower reliability values. For example, by developing a more effective maintenance approach and also a more detailed control system, it can be possible to improve the reliabilities of the components with lower reliability values. Additionally, investment in system redundancy, installation condition monitoring to provide early warning of failures and appointment of highly qualified marine engineers on board ships can be given as other examples to improve the reliability of the components with lower reliability values.

The results obtained through the reliability allocation analysis clearly recommend the possible points of improvement to steering gear systems in order to enhance the system reliability from the perspective of ship machinery manufacturers. The results also highlight the potential error-prone components of steering gear systems: it is necessary to devote more attention to these during the operation of the system.

As can be seen from the results, the proposed methodology helps to calculate the allocated reliabilities of system components with respect to the overall system reliability goal. However, in order to calculate the allocated reliability rate of the system components that is aimed to be obtained in the study, the desired reliability goal of the system must be known and/or calculated precisely. Therefore, it is possible to state as the first limitation of the study that the desired reliability level of the system to be analyzed have to be known and/or calculated prior to start the analysis. Additionally, the proposed methodology is developed without considering any redundancy between the system components, and this may be considered as a second limitation of the study.

Following the reliability allocation analysis, to demonstrate the sensitivity of the proposed methodology depending upon the variation of the importance degrees and to discover the influence of the importance degrees on the reliability allocation analysis, a sensitivity analysis is carried out. In the sensitivity analysis, four different scenarios were developed and, in the scenarios, four different importance degree sets were assigned to RAFs. In Scenario 1 the importance degrees of RAFs were accepted as follows: RAF1: 0.56, RAF2: 0.26, RAF3: 0.12, RAF4: 0.06; in Scenario 2: RAF1: 0.3, RAF2: 0.3, RAF3: 0.2, RAF4: 0.2; in Scenario 3: RAF1: 0.25, RAF2: 0.25, RAF3: 0.25, RAF4: 0.25 and in Scenario 4: RAF1: 0.1, RAF2: 0.2, RAF3: 0.30, RAF4: 0.40 were accepted. The results of the scenarios, in terms of failure rates and allocated reliabilities of components are tabulated in Table 9. Figure 3 represents the variations in the failure rates of the components and Figure 4 shows the components’ reliabilities.

The results demonstrated that the variation in the RAFs’ importance degrees influences allocated reliability ratings. For example, while transmitter (C_{13}) is the second most reliable component in Scenario 1, it became the sixth most reliable component in Scenario 4. Additionally, tiller (C_{15}) became the third most reliable component in Scenario 1, the fourth most reliable component in Scenario 2 and Scenerario3, and the seventh most reliable component in Scenario4. However, the safety valve (C_{12}) maintained its position as the most reliable component in all the scenarios.

| Table 7. Individual reliability ratings of steering gear components. |
|----------------------|------------------|------------------|------------------|------------------|
| Component | RAF1 (0.56) | RAF2 (0.26) | RAF3 (0.12) | RAF4 (0.02) |
| C_1 | 0.736 | 0.920 | 0.736 | 0.370 |
| C_2 | 0.736 | 0.787 | 0.736 | 0.423 |
| C_3 | 0.747 | 0.867 | 0.747 | 0.375 |
| C_4 | 0.793 | 1.000 | 0.793 | 0.500 |
| C_5 | 1.000 | 0.733 | 1.000 | 0.620 |
| C_6 | 1.000 | 0.720 | 1.000 | 0.769 |
| C_7 | 0.626 | 0.613 | 0.626 | 0.923 |
| C_8 | 0.626 | 0.680 | 0.626 | 0.981 |
| C_9 | 0.759 | 0.693 | 0.759 | 1.000 |
| C_10 | 0.603 | 0.747 | 0.603 | 0.813 |
| C_11 | 0.621 | 0.733 | 0.621 | 0.447 |
| C_12 | 0.293 | 0.747 | 0.293 | 0.519 |
| C_13 | 0.569 | 0.647 | 0.569 | 0.702 |
| C_14 | 0.569 | 0.753 | 0.569 | 0.736 |
| C_15 | 0.569 | 0.653 | 0.569 | 0.755 |

| Table 8. Allocated reliability of steering gear components. |
|----------------------|------------------|------------------|------------------|------------------|
| Component | W (C_i) | C_i | λ_i | R_i |
| C_1 | 0.7616 | 0.0725 | 7.6424 (per 10^6 h) | 0.9924 |
| C_2 | 0.7201 | 0.0695 | 7.3264 (per 10^6 h) | 0.9927 |
| C_3 | 0.7559 | 0.0720 | 7.5845 (per 10^6 h) | 0.9924 |
| C_4 | 0.8293 | 0.0790 | 8.3214 (per 10^6 h) | 0.9917 |
| C_5 | 0.9079 | 0.0865 | 9.1097 (per 10^6 h) | 0.9909 |
| C_6 | 0.9134 | 0.0870 | 9.1647 (per 10^6 h) | 0.9909 |
| C_7 | 0.6408 | 0.0610 | 6.4301 (per 10^6 h) | 0.9936 |
| C_8 | 0.6616 | 0.0630 | 6.6388 (per 10^6 h) | 0.9934 |
| C_9 | 0.7561 | 0.0720 | 7.5871 (per 10^6 h) | 0.9924 |
| C_10 | 0.6532 | 0.0622 | 6.5545 (per 10^6 h) | 0.9935 |
| C_11 | 0.6396 | 0.0609 | 6.4174 (per 10^6 h) | 0.9936 |
| C_12 | 0.4246 | 0.0404 | 4.2604 (per 10^6 h) | 0.9957 |
| C_13 | 0.5971 | 0.0569 | 5.9918 (per 10^6 h) | 0.9940 |
| C_14 | 0.6269 | 0.0597 | 6.2903 (per 10^6 h) | 0.9937 |
| C_15 | 0.6021 | 0.0573 | 6.0410 (per 10^6 h) | 0.9940 |
while electric motor \( C_6 \) was consistently the least reliable.

According to the sensitivity analysis, this research reveals that one of the most essential points in reliability allocation analysis is the appropriate estimation of the degrees of importance for RAFs with respect to the characteristics of the analyzed system. It is furthermore understood that the proposed approach provides a sensitive and robust reliability allocation analysis, the obtained results help reliability practitioners to identify the core component/components in the system which require extra attention, and to increase the consistency of the decision-making processes.

**Conclusion**

The reliability of shipboard systems is always accepted as one of the most critical issues for reliability practitioners and researchers since potential failures of shipboard systems often lead to catastrophic consequences. Therefore, reliability researchers focus on enhancing the system reliability through implementing proactive solutions to minimize critical system failures to prevent unexpected consequences related to critical system failures. With this insight, we propose a new reliability allocation approach for shipboard systems structured on the knowledge-based system to transform...
theoretical information into a practical solution. The
proposed approach combines AHP and DEA by
adopting the FOO approach. Whilst the AHP method
provides a hierarchal conceptual framework to ana-
lyze the system, the DEA method quantifies the local
reliability rates of each system component. Moreover,
the proposed approach offers an advantage on the
linguistic assessment scale to minimize the uncertainty
and ambiguity in allocation analysis. The demonstra-
tion of the proposed approach is illustrated on the
steering gear system as one of the critical shipboard
systems.

The important aspect of the approach is the ability
to assess different factors using numerous experts and
precise assessment grades. It integrates the importance
degrees of allocation factors into the assessment to con-
sider the analyzed system requirement. The generic and
simple structure of the approach has led to implemen-
tation not only for shipboard systems but also for other
made-to-order engineering systems.

With respect to the results obtained from the case
study in the paper, the main findings of the study can
be listed as follows:

- The proposed approach provides proactive solu-
tions and insights on enhancement the reliability of
shipboard systems.
- By analyzing the systems on the board-ship in a
similar way, it is possible to calculate the failure rate
and reliability degree of each system component.

With the identification of the components with
lower reliability values and higher failure rates.
- According to the identified reliability values of the
components, it turns into possible to switch from
the planned maintenance approach to the preven-
tive maintenance approach, which includes appro-
priate countermeasures to increase the reliability of
the systems on board ship.
- The proposed approach is expected to encourage
ship owners and ship management companies to
monitor and identify shipboard system failure rates
on-board ships.
- With the help of the allocated reliabilities, the nec-
ecessary preventive measures can be taken effectively
with the aim of minimizing the system failures and
also improving the system reliability.

As a consequence, the paper presents a theoretical con-
tribution on reliability allocation for shipboard systems
structured on a knowledge-based system. The proposed
approach is applicable not only for steering gear systems
but also other critical shipboard systems whose system
failure rates are relatively high. Also, the outcomes of
the paper contribute to research studies on reliability-
centered maintenance systems on shipboard systems.

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Appendix

List of notation

- $A$ Pairwise comparison matrix
- $\lambda_{\text{max}}$ Maximum eigenvalue of $A$
- $G$ A set of assessment grades
- $H_{jK_j}$ Importance degrees for RAFs
- $K_j$ Number of assessment grades for RAF $j$
- $N_{E_{ijk}}$ Numbers of experts ($k = 1, \ldots, K_j$)
- $C_i$ System component ($i = 1, 2, \ldots, n$)
- $s(H_{jk})$ Relative importance weight attached to the $N_{E_{ijk}}$, ($k = 1, \ldots, K_j$)
- $v_{ij}$ Individual reliability rating of each component ($i = 1, \ldots, n; j = 1, \ldots, m$)
- $W(C_i)$ Overall reliability rating ($i = 1, \ldots, n$)
- $C^*_i$ Component complexity factor
- $\lambda_k$ Failure rate of $i$th component
- $\lambda_s$ System failure rate
- $R_i$ Allocated reliability of $i$th component
- $t$ Operating time