Journal of Marine Science and Technology (2023) 28:288–313
https://doi.org/10.1007/s00773-022-00917-2

ORIGINAL ARTICLE

Techno-economic model-based design space exploration of ‘combined’ ship propulsion systems

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Received: 19 March 2022 / Accepted: 25 December 2022 / Published online: 8 February 2023

Abstract

The architecture of a ship propulsion system, developed during early stages of the overall ship design process, has a very large impact on the overall design and performance of the ship. The design space exploration to arrive at the final ship propulsion architecture can be a rather complex process for high-performance 'combined' ship propulsion systems designed to achieve multiple, often conflicting, design objectives. This paper proposes a novel process for the process of design space exploration based on a model-based ‘Techno-economic & Environmental Risk Assessment’ (TERA) approach, executed using a hybrid ‘Multiple-Criteria Decision-Making’ (MCDM) procedure, to select a compromise solution from competing propulsion system architectures populating the design space. The process utilizes a combination of performance data generated from performance simulation of developed models, as well as comparative expert opinions-based metrics for information not available early in the ship design process for selection of a 'compromise solution'. The paper includes an illustrative example of application of the proposed process for design space exploration for a combined propulsion system architecture for a notional destroyer.

Keywords Ship propulsion system design · Design space exploration · Model-based design · Techno-economic & Environmental Risk Assessment (TERA) · Multiple-Criteria Decision-Making (MCDM) · Analytic Hierarchy Process (AHP) · Analytic Network Process (ANP) · Decision-Making Trial and Evaluation Laboratory (DEMATEL) · DANP · VIKOR

Abbreviations

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CODAG	COmbined Diesel engine and Gas turbine
CODAG-E	COmbined Diesel engine and Gas turbine with Electric
CODELAG	COmbined Diesel ELectric and Gas turbine
COGAG	COmbined Gas turbine and Gas turbine
CPP	Controllable Pitch Propeller
CI	AHP Consistency Index
CR	AHP Consistency Ratio
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DANP	DEMATEL-ANP
D_i	Performance Dimension
FPP	Fixed Pitch Propeller
F^c	VIKOR compromise solution
F^*	VIKOR ideal solution
G	AHP Pairwise Comparison Matrix
IFEP	Integrated Full Electric Propulsion
MCDM	Multiple-Criteria Decision-Making
RI	AHP Randomness Index
TERA	Techno-economic and Environmental Risk Assessment
T_D^α	Normalized Total Direct Influence Matrix
T_c^α	Normalized Influence Matrix
VIKOR	VIšekriterijumsko KOmpromisno Rangiranje in Serbian, translates to multicriteria optimization and compromise ranking
w_i	Criteria weight
W_c	Unweighted Supermatrix
W_c^*	Weighted Supermatrix
X	DEMATEL Initial Direct Influence Matrix

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1 Introduction

The overall design and construction of a ship usually matures over a development cycle lasting several years. The initial design process of the ship plays a significant part in the overall design with 70–80% of the life-cycle costs of a ship being committed or influenced by the decisions made during this part of the design [7, 17]. Development of the conceptual design of a ship forms a significant part of the initial design process. One of the key elements of the conceptual design of the ship is the development or selection of the architecture of the propulsion system. The architecture of the propulsion system and the overall ship design have significant mutual influence, with factors such as hull design adaptation to the selected propulsor configuration, propulsion equipment volume, deck area availability, fuel tank volume, occupation of deck area etc. With increased electrification of ships, the conceptual design of the propulsion system can also subsume the process of the conceptual design of the electric grid system of the ship.

Naval ship propulsion systems are designed to fulfill a large number of conflicting design criteria such as high speed, large endurance, low acoustic signatures, high flexibility of operation, survivability, etc. To fulfill such requirements, often 'combined' propulsion systems architecture like COGAG, CODAG, CODAG-E, CODELAG, etc., are applied. Such architectures basically involve application of multiple engines and drives integrated by flexible transmission systems to deliver the specified design criteria derived from the overall ship design objectives based on the operating or mission profile of the ship. Multiple operating modes, involving utilization of different engines or drives, are used to fulfill the various design criteria. The efficiency of such architectures is targeted at a 'system' level by designing for higher efficiency at the speed ranges where the ship would be operated for a majority of its operating time [2]. The design space exploration of such combined system architectures is, thus, a complex process aimed optimally addressing all the specified design requirements.

Plumb notes that while there have been many books, papers, and articles on the individual elements that make up a propulsion system, there are very few on the system design itself or on how to select a system for a ship [29]. Many investigations on the suitability of various propulsion equipment for various applications have been published, like for marine propulsion engines [39] and propulsors [16]. Webster et.al. [47] published the results of a US navy study undertaken for evaluation of technical and cost impacts of alternative propulsion methods for various types of surface ships based on the fossil-fuel-based energy plants contrasted with nuclear energy alternatives. Gully [14] presented an analysis of the performance of hybrid powertrains for naval and commercial ocean-going vessels based on simplified polynomial fit function models for propulsion equipment. These kinds of studies primarily describe the process of integration of propulsion systems but not on the overall process for design space exploration toward the decision-making process for a particular architecture of a ship propulsion plant. Palmer highlights that the design of a ship propulsion system requires close collaboration of the naval architect, with the marine engineers, who are principally responsible for the main propulsion plant while naval architects are responsible for the hydrodynamic and hull form characteristics of the ship and propellers [15]. The development of the most effective means of achieving a desired ship's speed also requires trade-offs between naval architects and marine engineers, with due regard for the vessel's intended use [15].

The traditional approach to ship design, is largely an ‘adhoc’ process, where experience, design lanes, rules of thumb, preference, and imagination guide the selection of design concepts for assessment. With such a process, often objective attributes are not adequately synthesized or presented to support efficient and effective decisions [41]. To address these issues, Stepanchick et.al. have proposed a ‘total system approach’ toward the ship design synthesis, based on a structured search of the design space based on the multi-objective consideration of effectiveness, cost, and risk. Strock et.al. proposed a ship synthesis approach based on optimization of the ‘Overall Measure of Effectiveness’ index for the overall ship calculated based on using expert opinion and experience against cost and risk. In these approaches, the propulsion system design is subsumed in the overall ship design process which looks at the propulsion system as a set of machinery alternatives, for which basic data are included in a system design database. The authors, based on their experience, opine that while this approach is more scientific than the more traditional ‘adhoc’ process, it often masks the considerations required to address all the aspects of the design of a complex propulsion system and usually yields better results when the considered propulsion system architectures are based on existing designs. Hence, the authors argue that a comprehensive techno-economic analysis process should be used for the selection of a ship propulsion system.

Techno-economic and Environmental Risk Assessment (TERA) is a concept developed at the Cranfield University that uses a framework of mathematical models to conduct design space exploration and trade-off studies in the areas ranging from taxation policies in civil aviation [24] to the selection of gas turbine engines for aero [25], industrial [20], and marine applications [9]. TERA analysis of ship propulsion system was presented by Tsoudis, Bonet etc., [3, 4, 9, 44] primarily focussing on merchant ships, which mostly operate at a high percentage of time at fixed power ratings, except for short periods when approaching or departing ports. Consequently, for merchant ships, economical operation at the sustained sea speed corresponding to the intended trade route is of primary importance [15]. Hence, these studies were primarily based on journey route-based analysis. On the other hand, the power plants for naval ships do not follow specific routes but are usually assigned mission areas. The design of a power plant of such ships must fully reflect the operating profile of a ship [15].

Multiple-Criteria Decision-Making (MCDM) has grown as a part of operations research, concerned with designing computational and mathematical tools for supporting the subjective evaluation of performance criteria by decision makers [23], and have been used as appropriate tools for decision-making, sustainability analysis in the energy sector [19, 21, 22, 36, 36]. Trivyza et al. have published a comprehensive review of the range of decision support methods for sustainable ship energy systems [43]. Frangopoulos has published a review of three levels of optimization: synthesis, design, and operation for ship energy systems while highlighting the importance of these methods, and the need for further research in the area [10, 11]. Majority of the applied decision support methods for enhancing the ship energy system sustainability employed a single criterion/objective, despite the fact that trade-offs among multiple criteria are required to identify the most sustainable option [36]. Among the MCDM approaches, AHP has been used more than other tools and approaches [23]. Ruschmeyer [30] and Shamasundara [38] used AHP for the selection of propulsion plant design based on defined requirements or design criteria. Brown applied a combination of AHP and 'Multi-Attribute Utility Theory' (MAUT) for the overall naval ship concept design process including the propulsion system architecture selection utilizing metrics for quantifying performance and risk [6]. However, none of these published methods for selection of propulsion plant design consider the degree of relationships between criteria in the analysis, while it is well established that many of the design criteria have significant relationships between them, which can influence the decision-making [32].

Further, based on the experience of the authors, it is often not possible to have mathematical models to generate results for some of the specified criteria in the early stages of design. For such criteria, a relative qualitative data from expert opinion could be used for the analysis. Brown utilized the expert-based opinion for optimization of ship design synthesis problems [6, 41].

In summary, with the level of complexity involved in combined propulsion plant designs, a process that addresses the design both from the viewpoint of the naval architect as well as the marine engineer could be key to a design that would meet the defined design criteria in the most effective way. This paper, thus, proposes a process for design space exploration for combined propulsion systems, aimed at addressing such requirements, through a techno-economic evaluation process for selecting evolving effective propulsion system architectures. The proposed process is based on a practical combination of 'quantitative' data based on model-based analysis and 'qualitative' data based on expert opinion for techno-economic analysis of ship propulsion plants against specified design criteria. The process also incorporates a procedure for analyzing and considering the degree of relationships between criteria in the process execution.

2 Overview of the proposed design space exploration process

The primary steps involved in the proposed process toward the design space exploration of the propulsion system are briefly described in the following paragraphs with the overview shown in Fig. 1. The process commences with processing the overall design requirements of the ship into design criteria for the propulsion system. Based on the hull parameters relevant for prediction of resistance, and the finalized propulsor configuration, the delivered power to the propulsors is calculated. Using this and the overall ship electrical load requirements, the design space is populated with multiple candidate propulsion system architectures, along with electrical power grid system, designed to meet the key design performance criteria for the propulsion system. This step is executed by domain experts to ensure that the elements of human expertise and experience are well integrated within the overall process. The approach would usually involve starting with simple propulsion system architectures and moving toward more complex designs to fulfill the defined performance criteria. The design space only includes 'feasible' propulsion system architectures by meeting the defined key design performance criteria, like maximum speed, endurance targets with consideration to the defined performance envelopes of the considered engines, drives and transmission systems. The candidate propulsion system architectures are created using engines from an existing limited pool of well-developed engines, integrated with the propulsors by a custom-designed mechanical, electric or hybrid transmission system.

The process continues with the development of performance models of the candidate propulsion system architectures. Simulation runs of these models are then used to generate performance data like ship speed, endurance, engine performance, plant fuel consumption, etc., of the candidate propulsion system architectures. Additional model-based evaluations for the candidate architectures include that of additional key design drivers like mass, occupied deck area

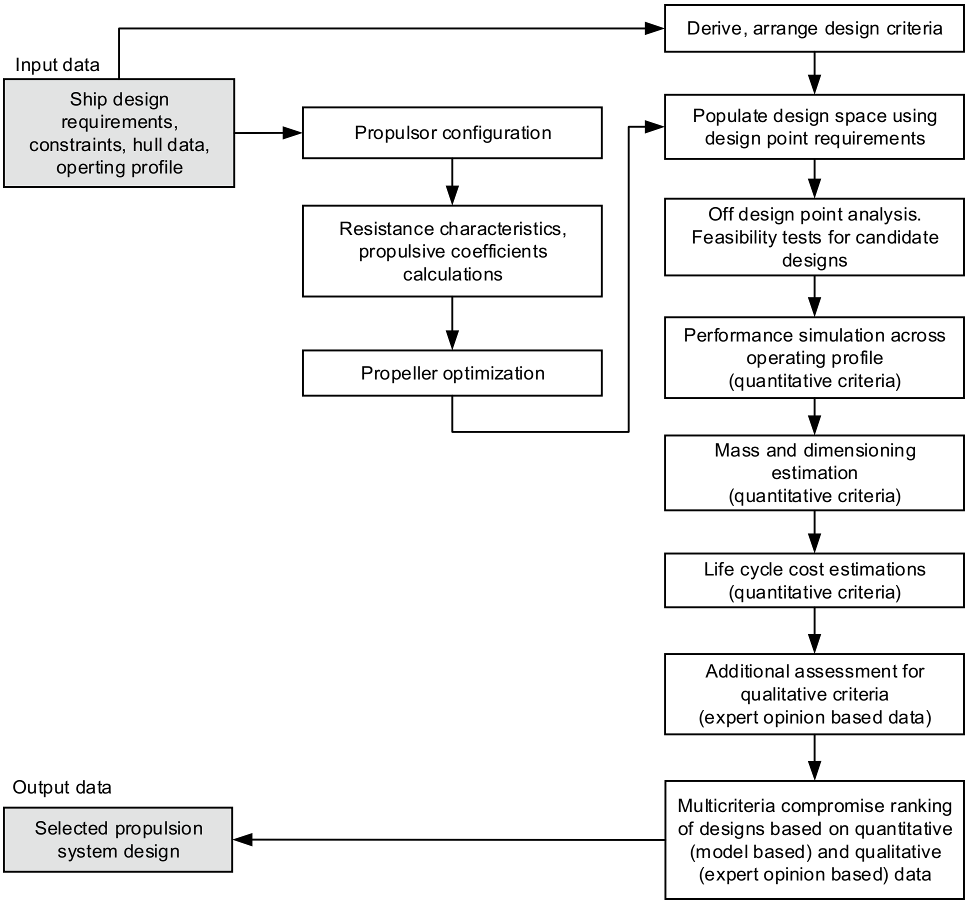


Fig. 1 Broad approach toward the conceptual design of propulsion system

and volume of individual equipment and their acquisition, maintenance, and operating costs, etc. For design criteria, like those related to stealth, maneuvrability, etc., where direct data for comparison may not be available at the early stages of ship design, expert opinion-based relative grading of the candidate propulsion system architectures is undertaken. The candidate propulsion system architectures in the design space are then compared based on the proposed TERA procedure to arrive at a 'compromise ranking' of the candidate architectures against the defined criteria for performance, costs, and risks.

3 Techno-economic and environmental risk assessment process

TERA is a concept developed at the Cranfield University that utilizes a framework of mathematical models to conduct design space exploration and trade-off studies in the areas ranging from selection of gas turbine engines for aero [25], industrial [12], and marine applications [9] to taxation policies in civil aviation [24]. The TERA modular framework consists of a set of core system models linked to economic, risk, environment models, to objectively assess and compare competing schemes by weighing investment of resources against performance and risk estimations. The overall scheme of TERA is usually integrated with optimisers such as real parameter 'Genetic Algorithm' for the optimisation of one or more goal functions which could range from fuel burn, engine noise, engine emissions to operating costs.

3.1 Overview of application of the MCDM process to TERA

In the present work, the design space is considered to be discrete since the design parameters cannot be continuously varied to have an optimal design, but only discrete points are available in the design space based on existing engine designs. Hence, the optimizer, as usually applied in TERA studies, could not be directly used for the study. To address these aspects, the standard optimizer in TERA was replaced with a hybrid MCDM algorithm, as shown in Fig. 2.

A large number of MCDM methods are available that could be used for the defined design space exploration problem for the present study. MCDM methods have been applied to select a ship propulsion system from competing architectures in the past, as described in Sect. 1. The major drawback of these applications has been that the degree

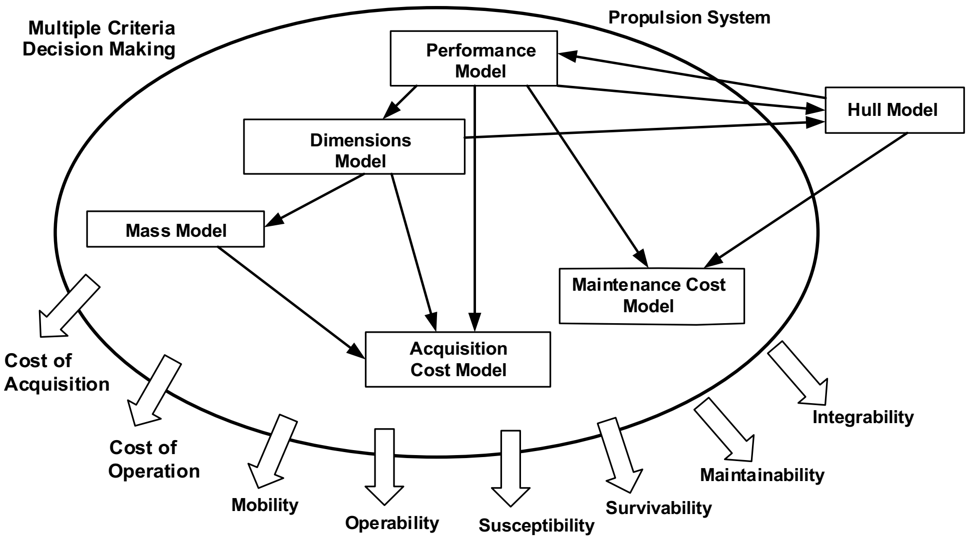


Fig. 2 TERA with multiple-criteria decision-making

of relationships between criteria has not been considered for such analysis. The degree of relationships between the considered criteria can play a significant role in the finally derived weights for these criteria and, thus, the final decision [32]. Hence, a key requirement identified for the MCDM methods to be applied was the consideration of degree of relationships between criteria for the decision-making process. Further, for a large set of criteria, a model-based 'quantitative' evaluation scores of certain design criteria was not practical, considering the involved effort or due to lack of information as is typical during the early stages of the ship design process. However, this gap can be effectively bridged using expert opinion-based comparative or 'qualitative' evaluation for comparing candidate architectures for such criteria. Hence, the MCDM methods to be applied to the present work would also need to address this requirement. The present work, thus, utilizes a more evolved hybrid process to execute the MCDM procedure. Based on the specific characteristics of the various parts of the MCDM process that need to be carried out, specific methods were selected and integrated to make a robust procedure for executing TERA.

The three distinctive steps that have been used to execute the applied MCDM procedure for the present study are: creation of criteria clusters and organization into a hierarchal and network, calculation of the global weights of the set of criteria, application of criteria weights to the evaluation scores of the candidate architectures across criteria to rank and select the most suitable architecture. The various factors forming the basis of the selection of the MCDM algorithms are described in the following paragraphs.

The AHP method [34] is used to decompose the decision problem into a hierarchy of sub-problems and the decision makers evaluate the relative importance of the various elements by pairwise comparisons. AHP converts these evaluations to numerical values, which are used to calculate a score for each alternative [33]. The Analytic Network Process (ANP) is a generalization of the AHP [31, 35], wherein the decision-making problems are modeled as networks, instead of hierarchies as with the AHP. If dependencies exist between criteria, application of ANP is more appropriate than AHP, as the dependencies and feedback between the decision-making elements can be modeled to calculate more accurate weights of these elements [18]. However, the pairwise comparison matrix method used in the ANP process, when applied to a complex problem such as the one for propulsion architecture selection, can become difficult to implement practically. The 'Decision-Making Trial and Evaluation Laboratory' (DEMATEL) method is often used to overcome this, by analyzing the cause-and-effect interrelationships between the criteria by analyzing the degree and type of influence they exert on each other [45]. There are various methods of integrating the DEMATEL with ANP, with one of the most popular being the DEMATEL–ANP (DANP) method [8, 13]. In the DANP method, DEMATEL method is used to determine the interrelationship among the main dimensions (criteria clusters) as well as the relationships between the criteria for each dimension instead of the pairwise comparison method, rest of the method being same as the ANP process.

For selection of a design alternative from a set of alternatives, AHP can be used quite effectively. However, based on the experience gained during the development of the present MCDM procedure, it was realized that direct application of AHP is not best suited for comparison of designs using a combination of 'qualitative' and 'quantitative' comparisons of the candidate architectures. To address this aspect, the VIKOR method ('VIšekriterijumsko KOmpromisno Rangiranje' in Serbian, translates to multicriteria optimization and compromise ranking) was selected. The VIKOR method is a well-suited method used to rank and select the 'best suited alternative' from a finite set of alternatives in having conflicting and non-commensurable attributes [26]. This method is based on the concept of multicriteria ranking index based on the measure of 'closeness' to the 'ideal' solution.

In summary, for the proposed MCDM-based TERA procedure, DANP has been used for determining the criteria weights where relationships exist between criteria, while AHP has been used for the same where the criteria are considered to be independent. Once the global weights of the criteria have been determined using the DANP–AHP hybrid method, the alternatives in the form of candidate propulsion system architectures are compared using the VIKOR method. The overview of the proposed MCDM procedure is shown in Fig. 3.

3.2 Proposed MCDM-based TERA procedure

3.2.1 Establishing hierarchal, network structure for evaluation criteria

In general, for any ship propulsion plant, the selection criteria for propulsion machinery selection include acquisition cost, functional reliability, weight, space requirements, specific fuel oil consumption, fuel type and fuel cost, repair cost, maintenance cost, maneuvrability, noise and vibration, etc. [28, 37]. The design criteria for ship propulsion systems in naval ships, in the context of the overall ship design requirements, have been presented extensively in the works of Brown et.al. [5, 6, 42]. For the present work, the authors have used their experience along with these references to derive the design criteria to be applied.

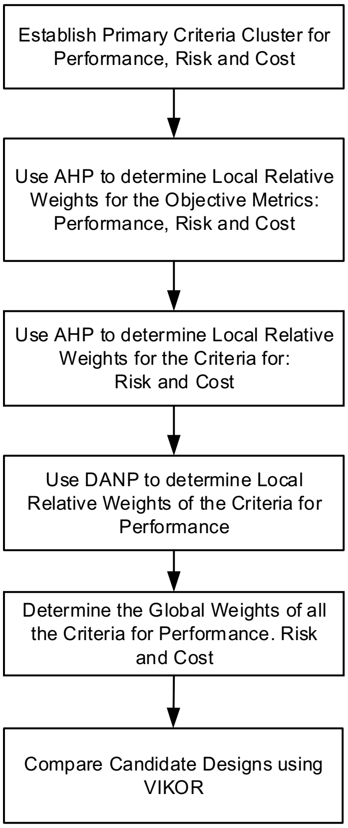


Fig. 3 Overview of the proposed MCDM procedure

The derived design criteria for the MCDM problem were organized into the combination of hierarchal, network structure as shown in Fig. 4. The overall objective for organizing the evaluation criteria in this form is to arrive at the global weights of each of the criteria, signifying their relative importance in context of the final decision, against which the candidate architectures would be evaluated. The problem is organized with the main 'Objective' defined as 'select the best-suited feasible architecture' at top of the hierarchy with the 'Objective Metrics': 'Performance', 'Cost', and 'Risk' at the next level. The 'Objective Metric', 'Performance', are divided into 'Performance Dimensions' which are further classified into individual set of criteria under each. All the 'Performance Dimensions' as well their individual sets of criteria are considered to have significant interrelations; hence, the entire 'Objective Metric' of 'Performance' is considered as a network as opposed to a hierarchy. The DANP method is, thus, used for calculation of the relative weights of the criteria under 'Performance'. The 'Objective Metrics' of 'Cost' and 'Risk' are directly defined by individual sets of criteria. The individual sets of criteria for 'Cost' and 'Risk' are considered to be independent; thus, AHP is used to evaluate the weights of these. AHP is also used to calculate the relative weights of the 'Objective Metric' of 'Performance', 'Cost', and 'Risk' which were then applied to the relative weight of criteria under them to determine the global weights of the entire set of criteria. Here, a more arbitrary experience-based metric could also be used instead of application of AHP. The candidate architectures are shown at the bottom of the diagram.

In the figure, the hierarchal part of the structure has been shown connected with arrows while the network part of the structure has been shown connected with lines without arrows. The criteria treated as 'quantitative' and 'qualitative' have been indicated, with the 'quantitative' criteria distinguished by the dashed boxes. It should be noted that since the candidate architectures have already been tested for 'feasibility' in terms of the basic defined criteria for the ship propulsion plant in terms of achieving 'surge speed', 'cruise speed', 'endurance', the term 'feasible' has been used in the objective. The terminology used for the defined criteria has been shown in Table 1.

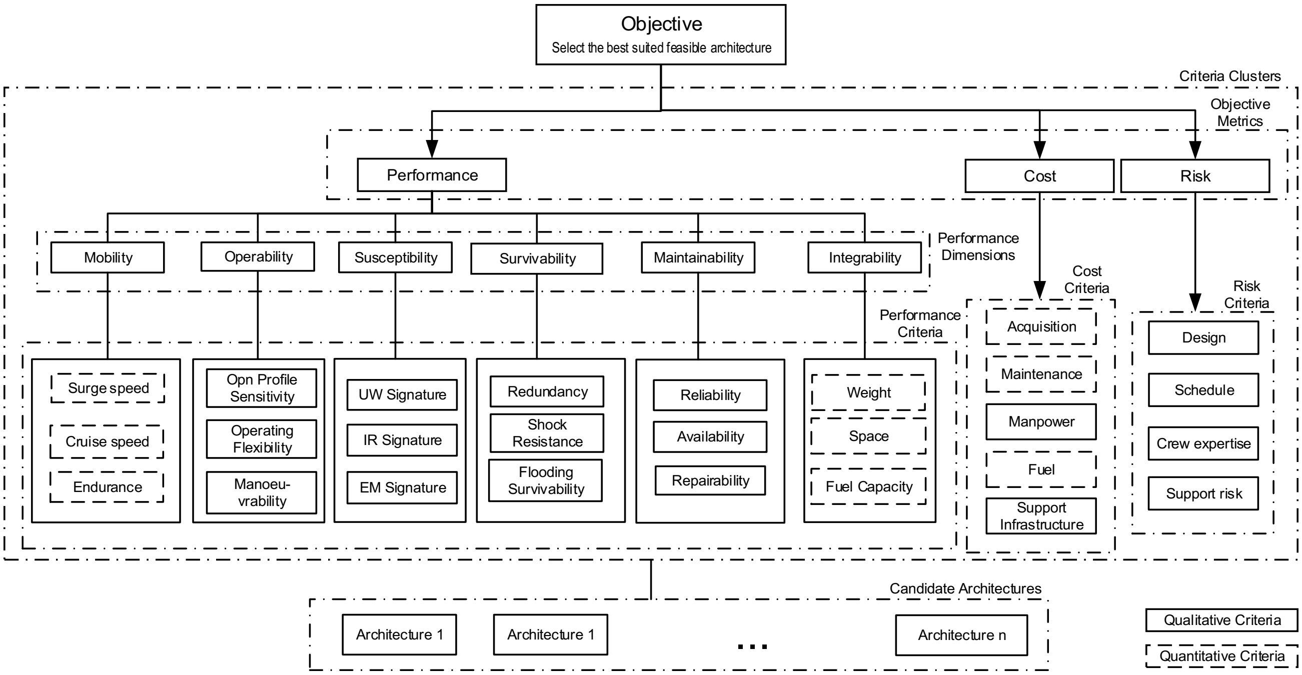


Fig. 4 Design criteria for the MCDM problem in a combination of hierarchal, network structure

3.2.2 Calculation of criteria weights

The DANP procedure is used to calculate the local relative weights of the criteria from the ‘Objective Metric’ of ‘Performance’. The DEMATEL method is first used to derive the degree of relationships between the ‘Performance Dimensions’$D_1, D_2, D_3, \ldots .D_n$, with each ‘Dimension’ having its respective individual set of criteria under it. The set of criteria of ith ‘Dimension’ is denoted by $c_{i1}, c_{i2} \cdots c_{im_i}$ where $m_1, m_2, m_3, \ldots .m_n$ are the number of criteria, respectively, for each of the ‘Dimensions’. The DEMATEL process starts with the creation of ‘Initial Direct Influence Matrix’, X created by averaging the ‘Expert Direct Influence Matrices’, obtained using the expert-based evaluations of mutual influence for the ‘Dimensions’$D_1, D_2, D_{3,} \ldots, D_n$:

$$X = [x_{ij}]_{n\times n} = \begin{array}{c|cccc} & D_1 & D_2 & \cdots & D_n \\ \hline D_1 & 0 & x_{12} & \cdots & x_{1n} \\ D_2 & x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_n & x_{n1} & x_{n2} & \cdots & 0 \end{array} \tag{1}$$

where x_{ij} defines the ‘degree of direct influence’ of D_i on D_j on a scale of 0–4 with each numeric signifying: ‘No influence’, ‘Low influence’, ‘Medium influence’, ‘High influence’, and ‘Very high influence’. The DEMATEL process is then used to calculate the ‘Normalized Total Direct Influence Matrix’ T_D^α. Using a similar process, the degree of relationship between the individual criteria under each of ‘Performance Dimensions’ is further calculated to create the set of matrices for the criteria, $T_c^{\alpha ij}$, for the sets of criteria under the dimensions. With this set of matrices, the overall ‘Normalized Influence Matrix’ T_c^α is set up as:

$$T_c^\alpha = \begin{array}{cc|cccc} & & D_1 & D_2 & & D_n \\ & & c_{11} \cdots c_{1m_1} & c_{11} \cdots c_{1m_2} & & c_{11} \cdots c_{1m_n} \\ \hline D_1 & \begin{matrix} c_{11} \\ \vdots \\ c_{1m_1} \end{matrix} & T_c^{\alpha 11} & T_c^{\alpha 12} & \cdots & T_c^{\alpha 1n} \\ D_2 & \begin{matrix} c_{11} \\ \vdots \\ c_{1m_2} \end{matrix} & T_c^{\alpha 21} & T_c^{\alpha 22} & & T_c^{\alpha 2n} \\ & & \vdots & \vdots & \ddots & \vdots \\ D_n & \begin{matrix} c_{11} \\ \vdots \\ c_{1m_n} \end{matrix} & T_c^{\alpha n1} & T_c^{\alpha n2} & \cdots & T_c^{\alpha nn} \end{array} \tag{2}$$

Each submatrix $T_c^{\alpha ij}$, in T_c^α, is written as:

$$T_c^{\alpha ij} = \begin{array}{c|cccc} & c_{j1} & c_{j2} & \cdots & c_{jm_j} \\ \hline c_{i1} & t_{c_{11}}^{\alpha ij} & t_{c_{12}}^{\alpha ij} & \cdots & t_{c_{1m_j}}^{\alpha ij} \\ c_{i2} & t_{c_{21}}^{\alpha ij} & t_{c_{22}}^{\alpha ij} & \cdots & t_{c_{2m_j}}^{\alpha ij} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{im_i} & t_{c_{m_i1}}^{\alpha ij} & t_{c_{m_i2}}^{\alpha ij} & \cdots & t_{c_{m_im_j}}^{\alpha ij} \end{array} \tag{3}$$

with each element $t_{c_{pq}}^{\alpha ij}$ representing the normalized ‘influence’ $t_c^{\alpha ij}$ of criteria c_{ip} on c_{jq}.

Table 1 Description of evaluation criteria

Objective Metric	Performance Dimension	Criteria	Criteria Abbreviation	Criteria Ref. No
Performance	Mobility (D1)	Surge speed	P-Surg.spd.	PC11
		Cruise speed	P-Cruis.spd.	PC12
		Endurance	P-Endur.	PC13
	Operability (D2)	Op. profile sensitivity	P-OP.Sens.	PC21
		Operation flexibility	P-Opn.Flex.	PC22
		Maneuvrability	P-Manuev.	PC23
	Susceptibility (D3)	UW Noise	P-UW.Noise	PC31
		IR Signature	P-IR Sign.	PC32
		EM Signature	P-EM Sign.	PC33
	Survivability (D4)	Redundancy	P-Redund.	PC41
		Shock Resistance	P-Shock.R.	PC42
		Flooding Survivability	P-Fld.Surv.	PC43
	Maintainability (D5)	Reliability	P-Reliab.	PC51
		Availability	P-Availab.	PC52
		Repairability	P-Repair.	PC53
	Integrability (D6)	Weight	P-Weight	PC61
		Space	P-Space	PC62
		Fuel capacity	P-Fuel.Cap.	PC63
Cost		Acquisition	C-Acq.	CC1
		Maintenance, Life Cycle	C-Maint.	CC2
		Manpower, Life Cycle	C-Man.Pow.	CC3
		Fuel, Life Cycle	C-Fuel.	CC4
		Support Infrastructure	C-Sup.Infr.	CC5
Risk		Design	R-Design	RC1
		Shipbuilding Schedule	R-Sched.	RC2
		Crew Expertise	R-Crw.Expr.	RC3
		Support Infrastructure	R-Support	RC4

To apply the ANP procedure, ‘Unweighted Supermatrix’ W_c is arranged as

$$W_c = \begin{array}{cc|cccc} & & \begin{array}{c} D_1 \\ c_{11} \cdots c_{1m_1} \end{array} & \begin{array}{c} D_2 \\ c_{21} \cdots c_{2m_2} \end{array} & & \begin{array}{c} D_n \\ c_{n1} \cdots c_{nm_n} \end{array} \\ \hline D_1 & \begin{array}{c} c_{11} \\ \vdots \\ c_{1m_1} \end{array} & W_c^{11} & W_c^{12} & \cdots & W_c^{1n} \\ D_2 & \begin{array}{c} c_{21} \\ \vdots \\ c_{2m_2} \end{array} & W_c^{21} & W_c^{22} & \cdots & W_c^{2n} \\ & & \vdots & \vdots & \ddots & \vdots \\ D_n & \begin{array}{c} c_{n1} \\ \vdots \\ c_{nm_n} \end{array} & W_c^{n1} & W_c^{n2} & \cdots & W_c^{nn} \end{array} \tag{4}$$

where each submatrix W_c^{ij} is calculated as:

$$W_c^{ij} = \left(T_c^{\alpha ji}\right)' = \begin{bmatrix} t_{c_{11}}^{\alpha ji} & t_{c_{21}}^{\alpha ji} & \cdots & t_{c_{m_j1}}^{\alpha ji} \\ t_{c_{12}}^{\alpha ji} & t_{c_{22}}^{\alpha ji} & \cdots & t_{c_{m_j2}}^{\alpha ji} \\ \vdots & \vdots & \ddots & \vdots \\ t_{c_{1m_i}}^{\alpha ji} & t_{c_{2m_i}}^{\alpha ji} & \cdots & t_{c_{m_jm_i}}^{\alpha ji} \end{bmatrix} \tag{5}$$

Thereafter, the degree of relationships between the ‘Performance Dimensions’ is used to weigh the appropriate portions of the ‘Unweighted Supermatrix’ to get the ‘Weighted Supermatrix’, using:

$$W_c^* = T_D^\alpha W_c \tag{6}$$

The ‘Weighted Supermatrix’ W_c^* is then solved by raising it to a sufficiently large power h until it converges and becomes a long-term stable supermatrix:

$$\lim_{h \to \infty} \left(W_c^*\right)^h \tag{7}$$

This stable supermatrix gives the set of local relative weights of all the criteria in the ‘Objective Metric’ of

‘Performance’ under the various ‘Performance Dimensions’, written as:

$$\left(w_{p1}, w_{p2}, w_{p3,} \dots\right) \tag{8}$$

In the AHP method [34], the relative weights $w_1, w_2, w_{3,} \dots, w_n$ for n criteria $C_1, C_2, C_{3,} \dots, C_n$ are obtained by solving the following eigenvector problem:

$$Gw = \lambda_{\max} w \tag{9}$$

where G is the ‘Pairwise Comparison Matrix’, w is the priority eigenvector associated with the principal eigen value $\lambda_{\max}$. ‘Consistency Index’ CI and ‘Consistency Ratio’ CR are calculated to verify the consistency of the comparison matrix, defined as:

$$CI = \frac{\left(\lambda_{\max} - n\right)}{n-1}; CR = \frac{CI}{RI} \tag{10}$$

where Randomness Index (RI) indicates the average Consistency Index over numerous random entries of the reciprocal matrices with same orders, that is taken from the lookup table defined by Saaty [33], based on the order of the comparison matrix. If $CR \le 0.1$, the estimate is accepted; otherwise, a new comparison matrix is solicited. Using the AHP method, the sets of local relative weights of the criteria in the ‘Objective Metric’ of ‘Cost’ and ‘Risk’ are determined, respectively, as follows:

$$\left(w_{c1}, w_{c2}, w_{c3,} \dots\right), \left(w_{r1}, w_{r2}, w_{r3,} \dots\right) \tag{11}$$

The AHP method is again applied, in a similar way, to calculate the local relative weights for the comparison between ‘Objective Metrics’, ‘Performance’, ‘Cost’, and ‘Risk’ to get the relative weights:

$$\left(w_{\mathrm{pe}}, w_{\mathrm{co}}, w_{\mathrm{ri}}\right) \tag{12}$$

The calculated local relative weights for the comparison between ‘Objective Metrics’, ‘Performance’, ‘Cost’, and ‘Risk’; are thereafter loaded onto the sets of local weights calculated for the ‘Objective Metrics’ to arrive at the set of global relative weights of all the criteria (w_P, w_C, w_R) as follows:

$$\begin{aligned}
w_P &= w_{P1}, w_{P2}, w_{P3,} \cdots = w_{pe}.\left(w_{p1}, w_{p2}, w_{p3,} \dots\right) \\
w_C &= w_{C1}, w_{C2}, w_{C3,} \cdots = w_{co}.\left(w_{c1}, w_{c2}, w_{c3,} \dots\right) \\
w_R &= w_{R1}, w_{R2}, w_{R3,} \cdots = w_{ri}.\left(w_{r1}, w_{r2}, w_{r3,} \dots\right)
\end{aligned} \tag{13}$$

3.2.3 Determination of evaluation scores for candidate architecture

Once the global relative weights for the criteria have been found, evaluation scores are calculated for each of the candidate architectures against all the criteria. For all the ‘quantitative’ criteria, ‘Poseidon + ’ is used to determine the evaluation scores based on performance simulation runs across the entire range of performance of the propulsion system, in the various operating modes of the system (combination of engines, engine power, and propeller pitch) as envisaged for the candidate architectures. For the defined ‘qualitative’ criteria, a group of experts independently provide a relative evaluation score of each of the candidate architecture using the pairwise comparison as per the AHP method described earlier. These evaluation scores are averaged and then the AHP method is applied to arrive at the final evaluated scores.

3.2.4 Selection of best-suited candidate architecture using VIKOR

With the global relative weights of all the criteria as well as, evaluation scores of the determined, the VIKOR method is used to find the ‘best suited’ architecture from the set of feasible candidate architectures. In VIKOR terminology, the candidate architectures would be termed as the ‘alternatives’, while the ‘best suited’ architecture would be called the ‘compromise solution’ that is closest to the ‘ideal solution’. The term ‘compromise’ denotes the mutual concessions made between the alternatives [26]. The concept can be illustrated using Fig. 5, where the alternatives are being assessed across a two-dimensional decision space defined by two criteria with f_i being the ‘evaluated score’ of an alternative for the ith criterion. The ‘compromise solution’ F^c

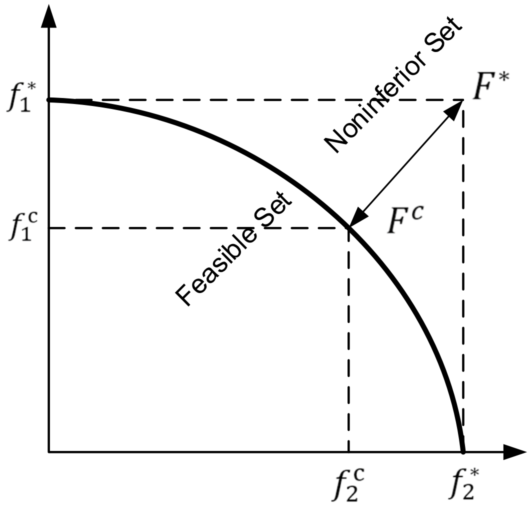


Fig. 5 VIKOR method for finding ‘compromise’ solution

is a ‘feasible solution’ that has been found, ‘closest’ to the ‘ideal solution’ F^*, by mutual concessions, $\Delta f_1 = f_1^* - f_1^c$ and $\Delta f_2 = f_2^* - f_2^c$ [27].

VIKOR method is based on the Lp-metric$L_{p,j}$, or the measure of distance to ideal solution [27]. For a set of alternatives, $(a_1, a_2, \ldots, a_j, \ldots, a_r)$ being evaluated for criteria $(C_1, C_2, C_{3,..}, C_{i,} \ldots, C_n)$ with corresponding global weights$(w_1, w_2, w_{3,} \ldots, w_n)$, $L_{p,j}$ can be written for the alternative a_j with f_{ij} being its ‘evaluated score’ for the criteria C_i representing a ‘benefit function’ as:

$$L_{p,j} = \left\{ \sum_{i=1}^{n} \left[w_i \left(f_i^+ - f_{ij}\right) / \left(f_i^+ - f_i^-\right) \right]^p \right\}^{1/p} \tag{14}$$

$1 \le p \le \infty; j = 1, 2, \ldots, r.$

where:

$$f_i^+ = \max_j f_{ij}, f_i^- = \min_j f_{ij}$$

As a part of the VIKOR procedure, for each alternative, a_j, being evaluated against a criteria C_i, metrics S_j, R_j, Q_j are calculated using the w_i, f_{ij}, and coefficient v. Coefficient v is the ‘strategy coefficient’ set by the decision maker with $v \in [0, 1]$. The values of v higher than 0.5 indicate that the decision maker is more focused toward satisfying most of the criteria, while values lower then 0.5 indicate that the decision maker is more focused toward minimizing individual differences from ideal solution. Coefficient v is usually set to a value 0.5 to start the procedure.

The alternatives $a_1, a_2, \ldots, a_j, \ldots, a_r$ are ranked in the order of priorities based on the values of S_j, R_j, Q_j with their lower values considered as ‘better’ values. The ‘best alternative’ or the most suitable ‘compromise solution’ is selected as the one ranked by the lowest value of Q. The ‘best alternative’ is checked for validity for having ‘acceptable degree of advantage’ and ‘acceptable stability in decision making’. If both the conditions are not satisfied, then a set of ‘compromise solutions’ may be selected by the decision makers based on additional considerations. [27].

3.3 Performance, dimensioning, and cost models

Since this paper focuses on the overall decision-making process for the selection of an optimal propulsion plant, it does not describe the performance, dimensioning, and costing models in detail, which is another subject by itself. A brief overview of these applied models is presented below.

As a part of the present work, a component-based modelling tool, ‘Poseidon + ’, was developed, to enable efficient modelling studies for the multiple candidate architectures under consideration, with their respective operating modes with different combinations of engines. Poseidon + enables the assembly of engines as well as the whole plant in the same framework, thus integrating all the elements needed for such modelling requirements into a single modelling and simulation environment. Performance evaluation using ‘Poseidon + ’ is used to initially check the feasibility of the created designs and then used to generate the performance data for candidate architectures in the design space.

The dimensioning and costing data for the candidate architectures in the design space used for the TERA analysis are based on an average representation of the equipment mass, dimensions, and acquisition cost in the form of simple regression-based models irrespective of the manufacturer, rather than using data of specific equipment considered in the candidate designs. Such models are not widely published; though some generic information on the subject can be referred to from publications [40, 48]. The dimensioning and cost models used for the present work are primarily based on the regression data models published by van Es [46], corrected by the authors where it was deemed necessary. The data used by van Es are based on a combination of first principle-based dimensioning and data from the manufacturers, mostly derived from software tool GES (Dutch abbreviation for Integrated Energy Systems), developed by TNO (Netherlands Organisation for Applied Scientific Research). TERA often utilizes detailed physics-based models for predicting maintenance, and thus life-cycle costs. To limit the overall scope of work, the predicted maintenance costs used in the present work have been again derived from the simplified regression-based models based on averaged operating time-based maintenance costs by van Es. These models can be easily replaced with more evolved models, if available to the user, without effecting the overall process for analysis.

4 Application of the proposed process for a notional destroyer

4.1 Input data for design

The primary parameters of the notional destroyer design considered for design of the propulsion system are summarized in Table 2. It should be noted that while the standard approach of TERA usually includes the environmental element in the analysis, in the presented case study, the criteria for environmental element have not been included as it is often excluded from the specified design criteria of naval warships. However, the environmental design criteria can also be added to the criteria being applied to the TERA, if deemed necessary for the analysis. The considered operational profile of the ship was derived based on the data published by Anderson [1] for such applications, as shown

Table 2 Primary parameters of the considered notional destroyer

Parameter	Value
Displacement	9500 metric tons approx
Length	150 m approx
Surge speed	> 30 knots
Cruise speed	> 18 knots
Ship operation per year	3500 h
Endurance	> 4000 nm @ > 15 knots speed
Fuel tank capacity	< 1000 metric ton
Propeller diameter	5 m approx
Auxiliary electrical load	4.2 MWe

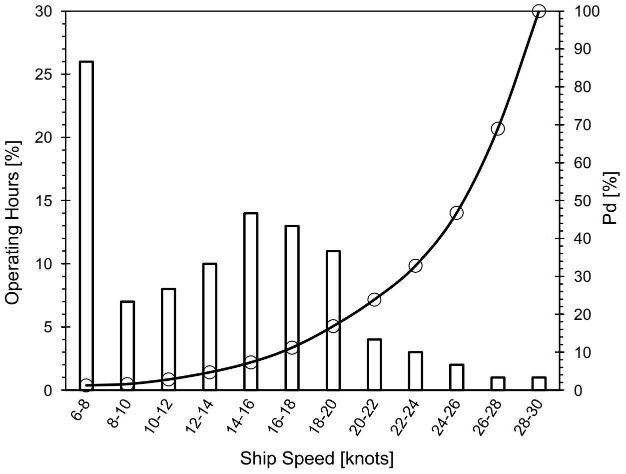


Fig. 6 Operating profile superimposed with propeller delivered power required

in Fig. 6. The propulsor configuration considered was twin FPP or CPP. The overall average ship electrical load was considered to be 4.2 MWe.

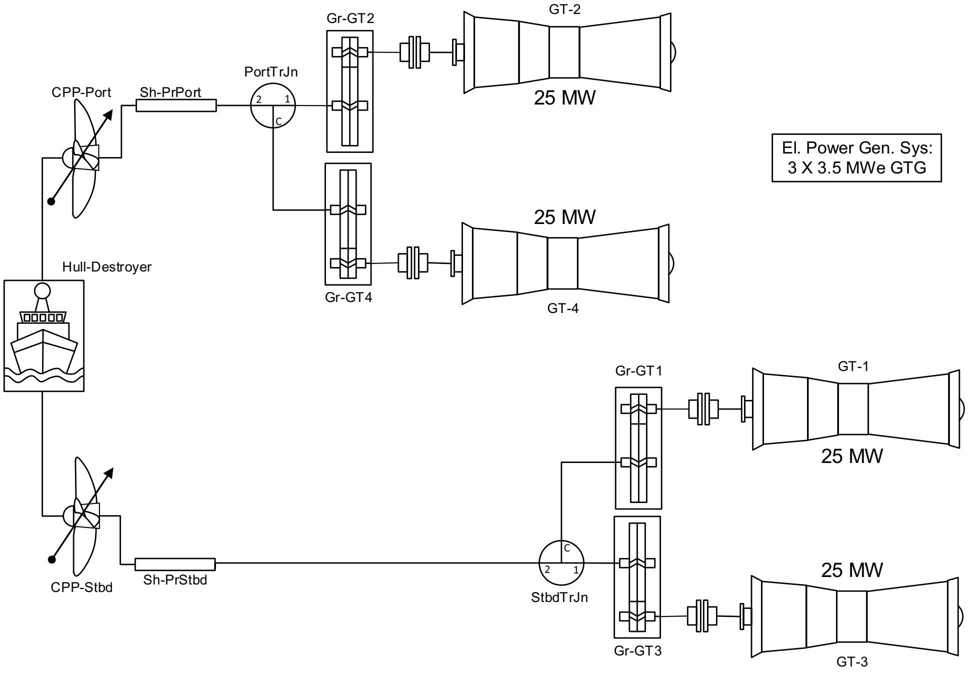
4.2 Candidate propulsion system architectures

Based on the given design requirements, as a first step, the delivered power needed across the operating profile was calculated as shown in Fig. 6. Based on the modeled hull resistance and the optimized propeller design, candidate propulsion system architectures were created. The five feasible candidate propulsion system architectures considered for the final analysis are shown in Figs. 7, 8, 9, 10, 11, which are specific configurations of COGAG, CODAG, CODAG-E (Combination of Diesel engine, Gas Turbine and Electric), CODELAG, and IFEP. For all designs except IFEP, a common CPP design was selected for the propulsor configurations for reversing of the propellers, while an FPP design was considered for the IFEP since the reversing of the propeller can be executed using the electric motors. Both the CPP design and FPP were considered to have the same design parameters except for the hub size.

4.3 Performance modelling results

For each of the candidate architectures, basic engine–propeller matching and feasibility analysis were undertaken using Poseidon +. The developed models of each of the candidate architectures were used to run the propulsion and power generation system in various modes of operation to capture the performance characteristics of the system. One of the

Fig. 7 Candidate propulsion system architecture alternative A1, COGAG



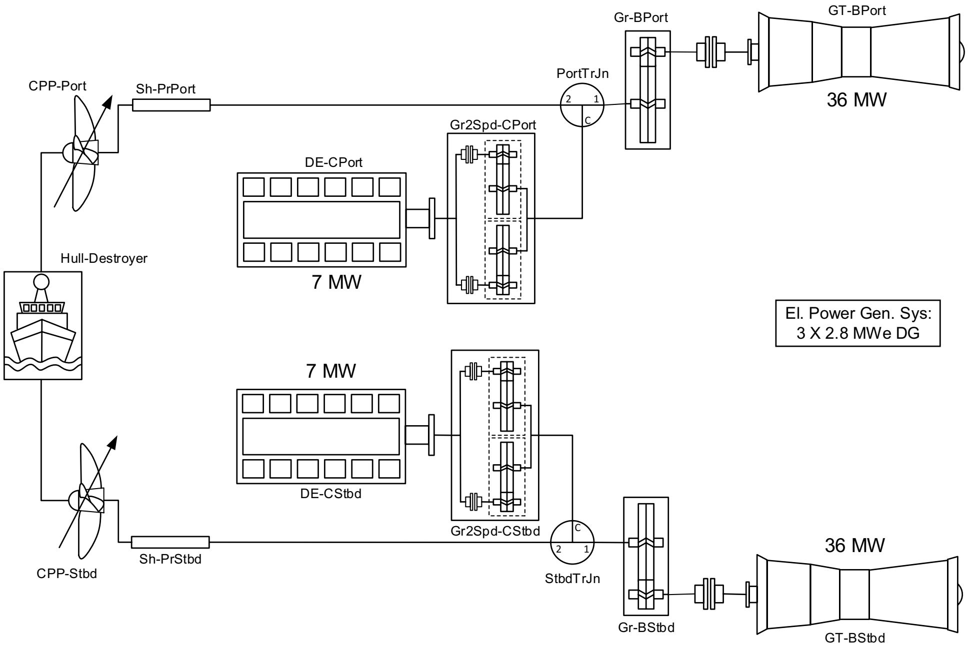


Fig. 8 Candidate propulsion system architecture alternative A2, CODAG

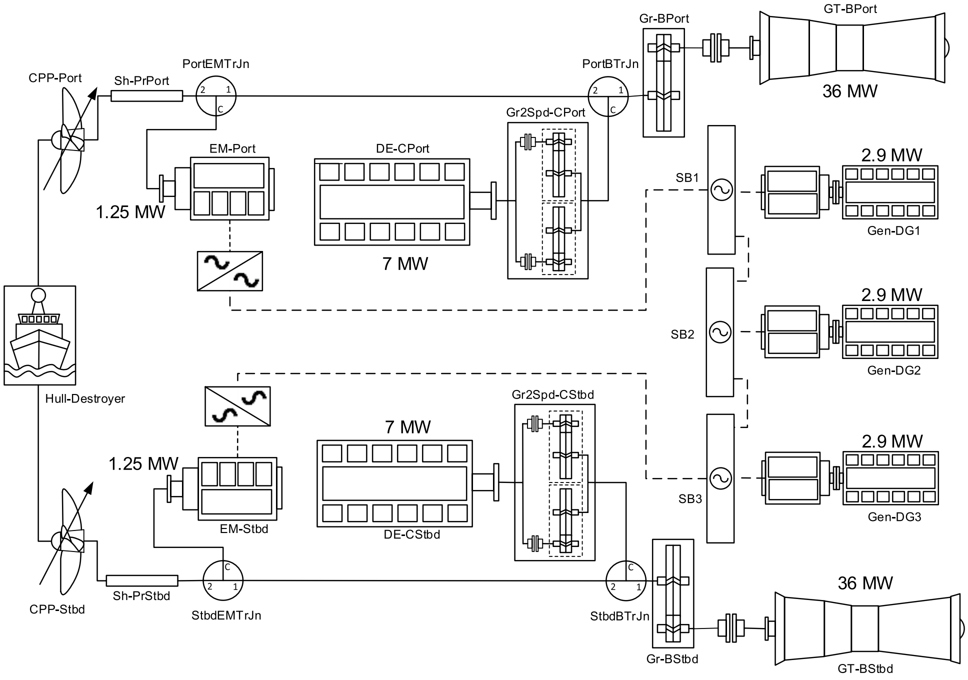


Fig. 9 Candidate propulsion system architecture alternative A3, CODAG-E

primary characteristics of interest in such trade-off studies is the overall consumption of fuel by the ship energy system, shown for each candidate architecture in Fig. 31. These operation drive modes also consider the engine envelope limitations so that only feasible operating points are considered for the analysis. The data from these characteristics were used to calculate the overall operating costs due to fuel consumption based on the defined operating profile. The comparative bar graphs for the candidate architectures with respect to maximum surge speed, cruising speed, endurance (range) based on tank capacity are shown in Figs. 12, 13, 14, respectively.

4.4 Dimensioning and costing estimations

The dimensioning and costing models, as introduced in sect. 3.3, were used for calculating the overall mass and occupied deck area for each of the candidate architectures. The computed values include the propulsion equipment as well as the power generation equipment, so as to have a

Fig. 10 Candidate propulsion system architecture alternative A4, CODELAG

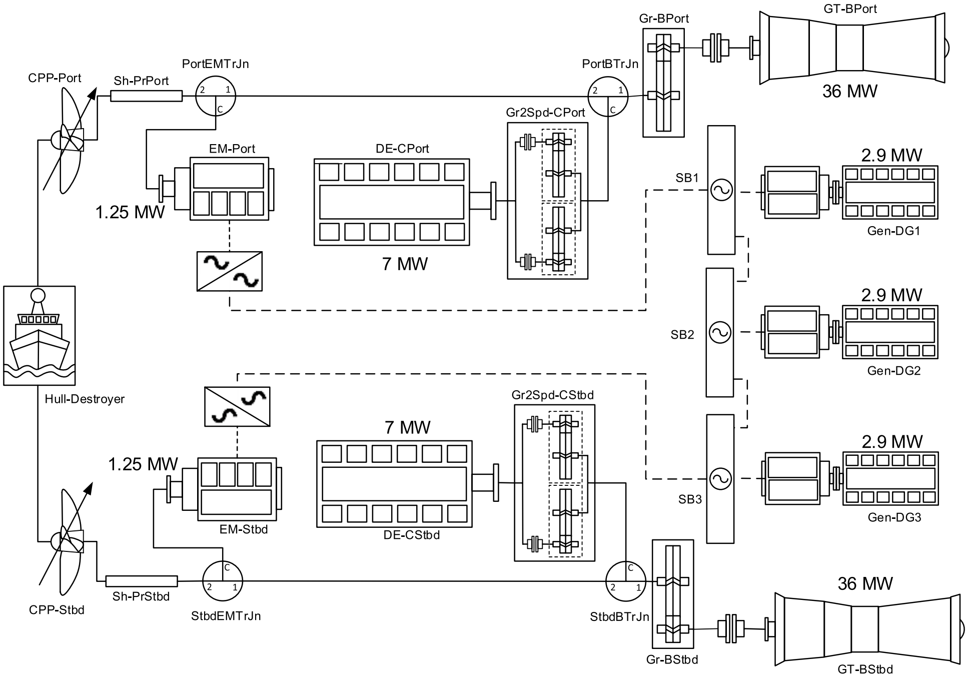
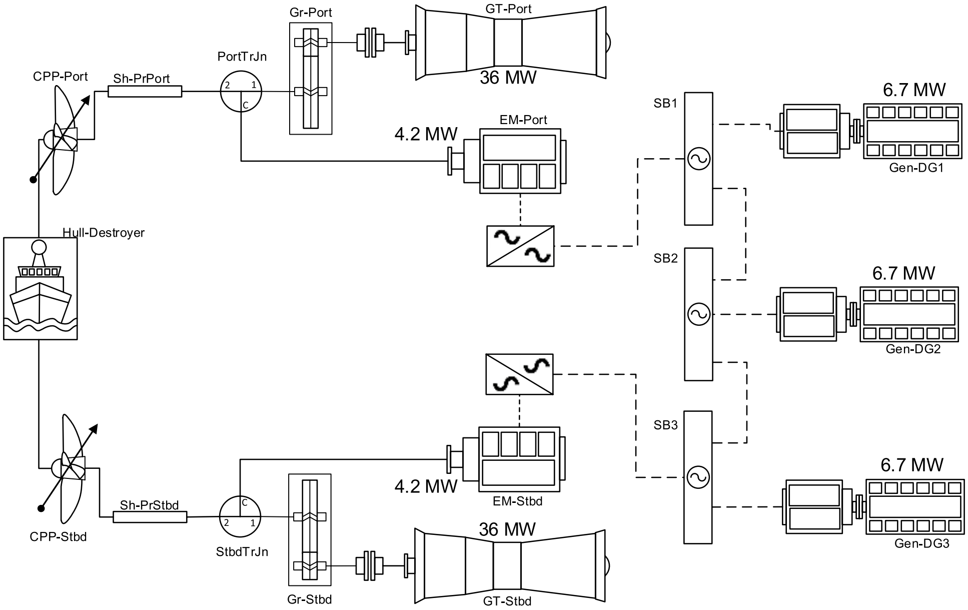


Fig. 11 Candidate propulsion system architecture alternative A5, IFEP



homogeneous comparison of the architectures where the ship electric system and propulsion system are connected (like CODELAG, CODAG-E, IFEP) with the ones where these systems are independent (like COGAG, CODAG). These estimations include the primary equipment but not the auxiliary systems related to this main equipment as well as low voltage switchboards. The comparative bar graphs of the various architectures in terms of mass and occupied deck area are shown in Figs. 15 and 16, respectively. The acquisition costs from the models have been adapted to the year 2021 for inflation, considered to be at an average rate of 2% per year.

The maintenance costs have been calculated as follows. The overall operating hours of the propulsion equipment were first calculated based on the drive modes required to achieve certain speeds, which basically defines which equipment would be running with the respective drive mode in application. The operating times at various speeds were calculated based on the defined operating profile, which defines the 'time bands' for operation at various speeds, and the overall operating hours of the ship per

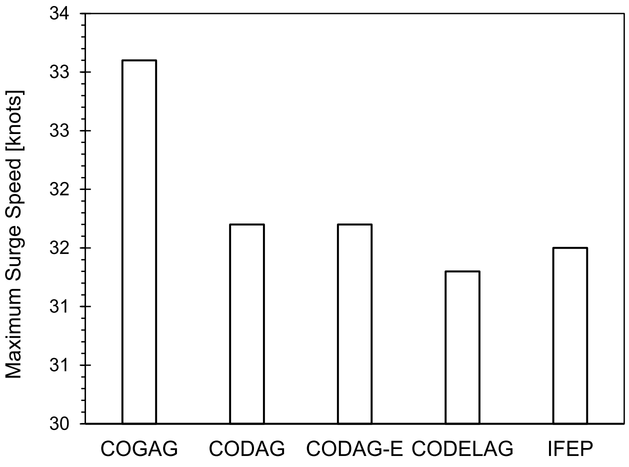


Fig. 12 Maximum surge speed for candidate architectures

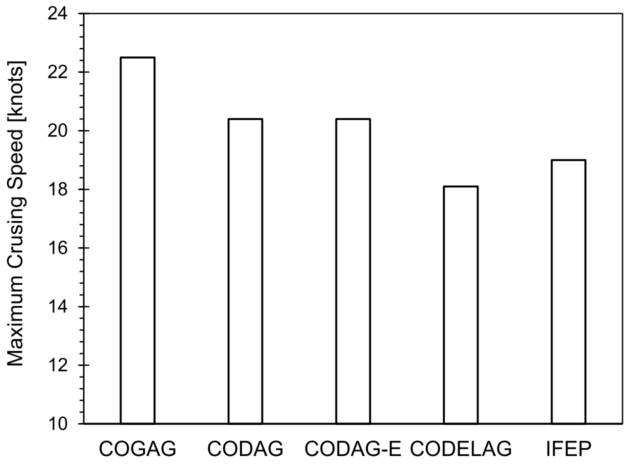


Fig. 13 Maximum cruising speed for candidate architectures

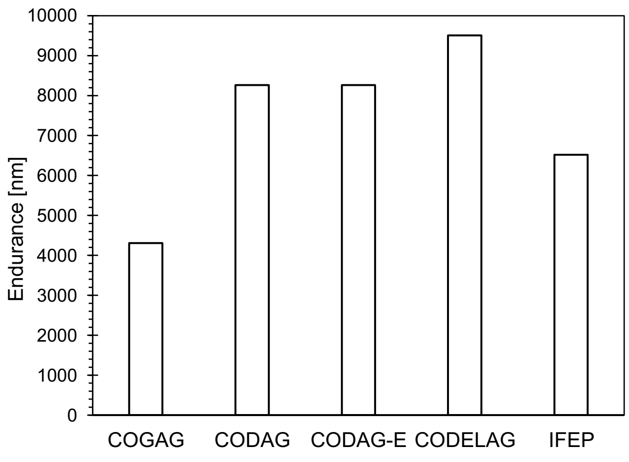


Fig. 14 Endurance (range) for tank capacity of 1000 tons, ship speed of 15 knots for candidate architectures

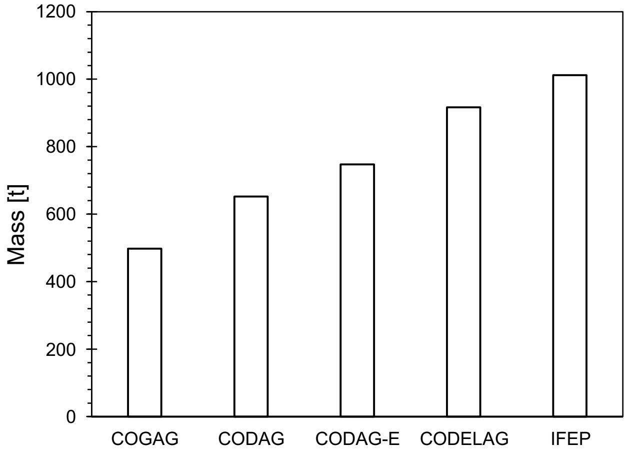


Fig. 15 Comparitive mass of the main propulsion and power generation equipment

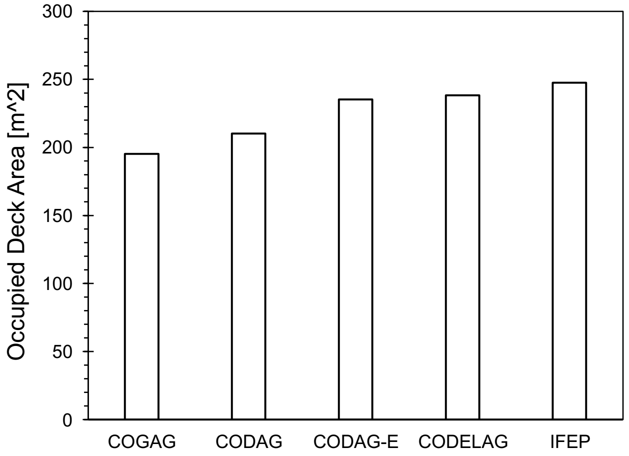


Fig. 16 Comparitive occupied deck area of main propulsion and power generation equipment

year. Based on the overall operating hours of the propulsion equipment, the maintenance costs were then estimated based on the defined operation-based maintenance models. Similarly, the cost of fuel over the life cycle of the ship was calculated using the operating hours at various 'speed bands', the applicable operating drive mode and the corresponding overall fuel rates previously computed, and then applying the overall operating hours of the ship per year. The average cost of fuel was derived from the US Defense Logistics Agency (DLA) Energy publication for 2020, adapted to the year 2021 for inflation, considered to be at an average rate of 2% per year. The comparative lifetime costs in terms of acquisition maintenance and fuel costs are shown in Fig. 17.

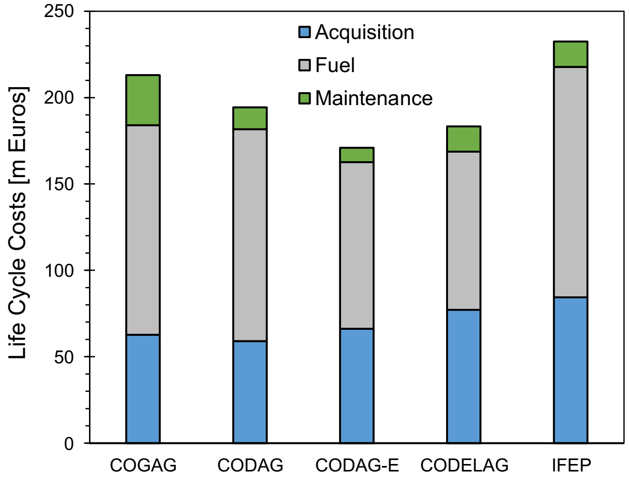


Fig. 17 Comparitive life-cycle costs of the main propulsion and power generation equipment

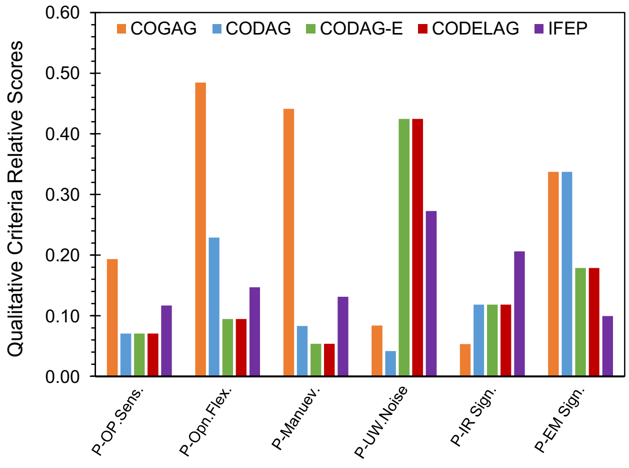


Fig. 18 Relative scores of candidate architectures against qualitative criteria (P4–P9)

4.5 Relative scores for candidate architectures against qualitative criteria

For the evaluation of the candidate architectures against the qualitative criteria (P4–P15, C3, C5, R1–R4), the author again used discussions with experienced colleagues from the domain, to undertake an AHP-based pairwise comparison method to arrive at the relative evaluation scores for the candidate architectures. The computed relative scores for the candidate architectures against the qualitative criteria are shown in Figs. 18, 19, 20.

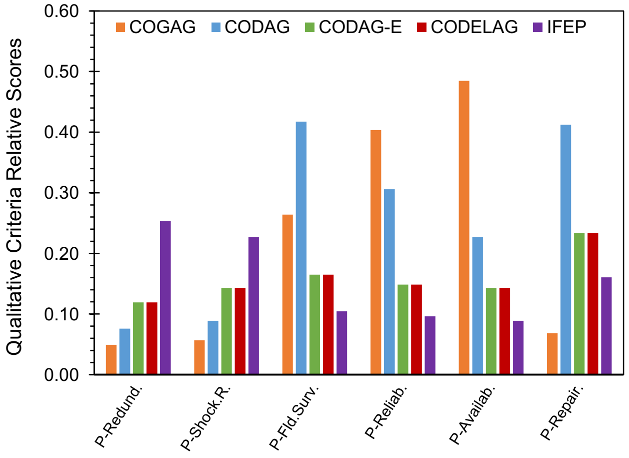


Fig. 19 Relative scores of candidate architecture against qualitative criteria (P10–P15)

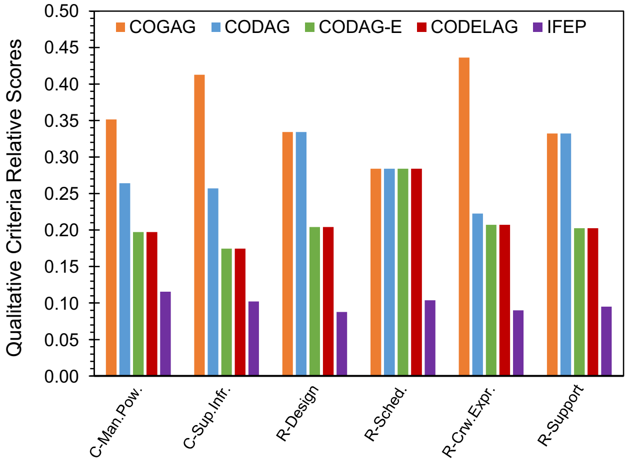


Fig. 20 Relative scores of candidate architecture against qualitative criteria (C3, C5, R1–R4)

4.6 Determination of criteria weights for MCDM analysis

4.6.1 Using DEMATEL to determine local weights of objective metric 'performance'

For the 'Objective Metric', 'Performance', the degrees of relationships between the performance criteria dimensions were determined using various steps, as described in Sect. 3.2.2. The authors used interactions with colleagues working in this domain to create the scores for evaluating the 'Initial Direct Influence Matrix' for the 'Performance Dimensions' from which the calculated 'Direct Influence Matrix' for 'Performance Dimensions' was calculated as shown in Table 3. From the calculated degree of relationship, 'U + W' and 'U − W' metrics, the 'Network Relationship Map' (NRM) was obtained, as

Table 3 Normalised direct influence matrix for performance dimensions

Dimension	D1 Mobility	D2 Operability	D3 Susceptibility	D4 Survivability	D5 Maintainability	D6 Integrability
D1 Mobility	0.0000	0.1875	0.1250	0.0000	0.0000	0.2500
D2 Operability	0.0625	0.0000	0.0000	0.0000	0.0000	0.1250
D3 Susceptibility	0.0000	0.0000	0.0000	0.0000	0.1250	0.2500
D4 Survivability	0.0000	0.0000	0.0000	0.0000	0.1875	0.2500
D5 Maintainability	0.0625	0.0000	0.0000	0.1875	0.0000	0.1250
D6 Integrability	0.1250	0.0000	0.1250	0.0625	0.0625	0.0000

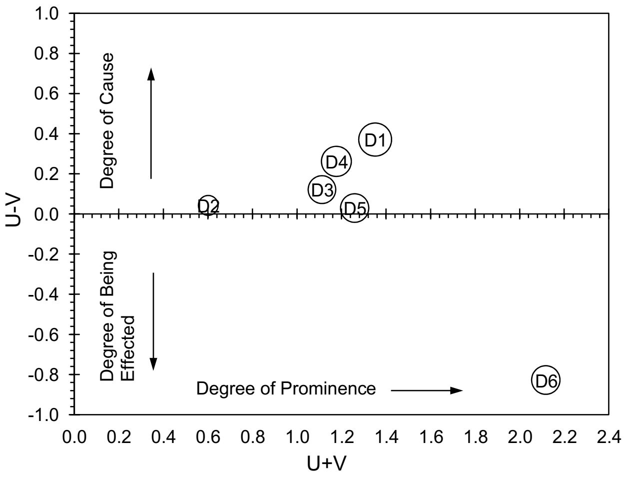


Fig. 21 Network Relationship Map (NRM) for Performance Dimensions

shown in Fig. 21. The NRM shows the ‘degree of prominence’ vs. the ‘degree of effect’ or ‘degree of being effected’. As can be observed from in Fig. 21, in terms of ‘degree of prominence’, the ‘Performance Dimension’, ‘D6’ or ‘Integrability’, is the highest while ‘D2’ or ‘Operability’, is the lowest. On the other hand, ‘Performance Dimension’ ‘D1’ or ‘Mobility’ provides the highest ‘degree of cause’, while ‘D6’ or ‘Integrability’ shows the highest ‘degree of being effected’.

The DEMATEL procedure, as described for 'Performance Dimensions', was repeated for the performance criteria under the respective dimensions with significant relations. After completion of the DEMATEL procedure for determining the influence matrices for the performance dimensions as well as the criteria sets belonging to the performance dimensions with significant relationships, the ANP procedure was applied. Initially, the Unweighted Supermatrix was set up as shown in Table 4. The 'Weighted Supermatrix' was calculated from the 'Unweighted Supermatrix', after application of the DEMATEL weights calculated for the 'Performance Dimensions'. Thereafter, the 'Weighted Supermatrix' was raised to the power of five to finally obtain the converged solution which gives the local weights for the criteria belonging to the 'Performance Objective Metric', as depicted graphically in Fig. 22.

4.6.2 Using AHP to determine local weights of cost and risk criteria

For the criteria set belonging to Objective Metric, Cost, and Risk, the process of AHP was used to determine the local weights for the respective criteria sets, following the procedure described in Sect. 3.2.2. Again, for this procedure, the authors used interactions with colleagues working in this domain to undertake the pairwise comparison for the respective criteria sets. Consistency checks for the comparison matrices were also undertaken. The calculated local weights of the ‘Objective Metrics’ of ‘Cost’ and ‘Risk’, calculated using the AHP procedure, are graphically depicted in Fig. 23.

4.6.3 Calculation of global weights for set of criteria

For calculating the global weights for the criteria considered, different ‘application cases’ with overall weights attached to the ‘Objective Metrics’ of ‘Performance’, ‘Cost’, and ‘Risk’ were considered, as shown in Table 5. The relative weights of the ‘Objective Metrics’ were derived for these ‘application cases’ by varying the relative weights of ‘Performance’, ‘Cost’, and ‘Risk’ (Fig. 24). In a practical application, the ship owner, designer, or builder would attach these weights based on the considerations of the role of the ship along with the perspective of the analysis. Based on each of these application cases, the overall computed global weights for the entire set of criteria have been graphically compared in figures from Figs. 25, 26, 27, 28, 29, also showing the relative weights used for the ‘Objective Metrics’ of ‘Performance’, ‘Cost’, and ‘Risk’ across the various test cases.

5 Results and discussion

5.1 Objective comparison of candidate propulsion architectures using VIKOR

The VIKOR method, as described in Sect. 3.2.4, was used to arrive at the final ranking of the candidate architecture in terms of preference based on the defined criteria. The set of metrics, obtained from both the quantitative and qualitative criteria, for each of the candidate design architecture

Table 4 Unweighted ANP Supermatrix

		D1			D2			D3			D4			D5			D6		
		PC11	PC12	PC13	PC21	PC22	PC23	PC31	PC32	PC33	PC41	PC42	PC43	PC51	PC52	PC53	PC61	PC62	PC63
D1	PC11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1788	0.2105	0.1761
	PC12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2914	0.3684	0.2264
	PC13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5298	0.4211	0.5975
D2	PC21	0.3220	0.3373	0.3902	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC22	0.4576	0.4699	0.4390	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC23	0.2203	0.1928	0.1707	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D3	PC31	0.3001	0.3999	0.3478	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6667	0.6667	0.5556
	PC32	0.3998	0.3251	0.3478	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.3333	0.3333
	PC33	0.3000	0.2751	0.3043	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111
D4	PC41	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5556	0.6667	0.6667	0.0000	0.0000	0.0000
	PC42	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2222	0.1667	0.1667	0.0000	0.0000	0.0000
	PC43	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2222	0.1667	0.1667	0.0000	0.0000	0.0000
D5	PC51	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3756	0.3357	0.5660	0.5385	0.5760	0.6383	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC52	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1629	0.2028	0.1132	0.3258	0.3280	0.2553	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4615	0.4615	0.3208	0.1357	0.0960	0.1064	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D6	PC61	0.2658	0.2414	0.0000	0.4200	0.4545	0.4545	0.4296	0.3889	0.3889	0.4414	0.4918	0.4464	0.3000	0.3000	0.2667	0.0000	0.0000	0.0000
	PC62	0.3544	0.3218	0.0000	0.4200	0.4545	0.4545	0.4148	0.4556	0.4861	0.4144	0.4098	0.4643	0.4000	0.4000	0.4667	0.0000	0.0000	0.0000
	PC63	0.3797	0.4368	1.0000	0.1600	0.0909	0.0909	0.1556	0.1556	0.1250	0.1441	0.0984	0.0893	0.3000	0.3000	0.2667	0.0000	0.0000	0.0000

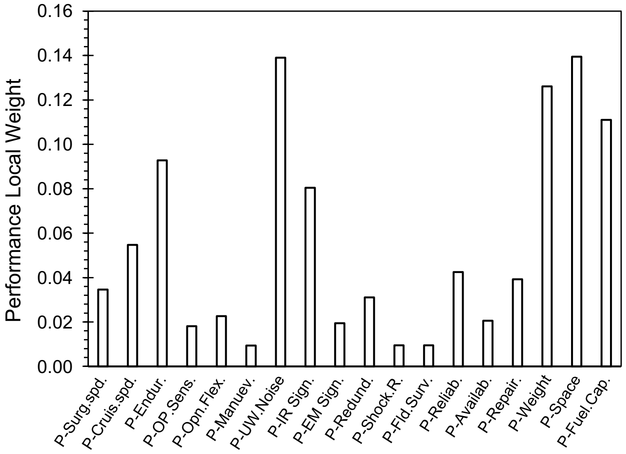


Fig. 22 Local weights for the criteria set of Performance Objective Metric

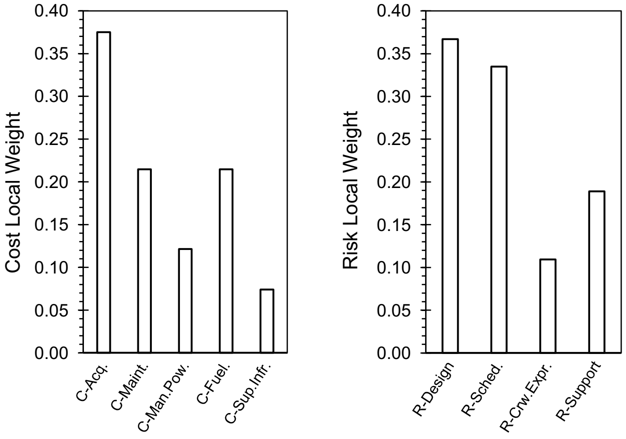


Fig. 23 Local weights for the criteria sets belonging to the Objective Metrics, Cost, and Risk

alternatives were arranged in a tabular format serving as the input data for the VIKOR analysis. The VIKOR analysis was undertaken for the application cases, with the value of the 'strategy coefficient' as $v = 0.5$, to have a balance between minimizing individual differences from ideal solution (for $v < 0.5$) and satisfying most of the criteria (for $v > 0.5$). The candidate design architectures were rated by calculating the VIKOR parameters S, R, Q and the best-suited architectures were identified based on the alternative with the lowest score of Q, for all the application cases. The results of the determined values of S, R, Q and the ranking for each of the application cases, with the balanced $v = 0.5$ 'strategy coefficient', are shown in Table 6. For the best-suited alternative identified, further verification is done for meeting the conditions of 'acceptable advantage' and 'stability in decision making'. The results of this analysis are shown in Table 7.

For each of the application cases, a sensitivity analysis was undertaken for variation of the ranks to the 'strategy coefficient' v by varying it between 0 and 1 at increments of 0.1 to evaluate the robustness and steadiness of the solution. Further, since the final ranks of the candidate architectures are primarily based on the VIKOR metric 'Q', sensitivity of the metric 'Q' to variation in the 'strategy coefficient' v was also undertaken. The results of this analysis are shown in Fig. 30.

5.2 Summary of results

For the final decision-making, the strategy coefficient $v = 0.5$ was primarily considered to have a 'balanced' decision across all the application cases. For all the application cases except Case 2B, the defined CODAG candidate architecture emerges as the architecture that is ranked first or the best-suited architecture. In Case 2B, CODAG-E emerges as the best-suited architecture. For all the application cases, COGAG emerges as the architecture ranked in second place. CODAG-E was ranked third in all cases, except Case 2B where CODAG was ranked third. The IFEP candidate architecture was consistently ranked fourth across all the application cases. Based on the analysis of the ranking for the criteria for 'acceptable advantage' and 'stability in decision making', it can be observed that even though the CODAG architecture is ranked first in all the application cases except Case 2B, it does not satisfy the criteria of acceptable advantage in any of these application cases. This implies that the degree of preference of the CODAG architecture is very close to the second-rated COGAG architecture in all the application cases except Case 2B. Hence, in these

Table 5 Cases considered for analysis of alternatives or candidate architectures

Case	Description
Case 1	'Performance' 'Cost', and 'Risk' equally weighted
Case 2A	'Performance' weighted moderately higher than 'Cost' and 'Risk'; 'Cost' and 'Risk' equally weighted
Case 2B	'Performance' weighted significantly higher than 'Cost' and 'Risk'; 'Cost' and 'Risk' equally weighted
Case 3	'Risk' weighted moderately higher than 'Performance' and 'Cost'; 'Performance' and 'Cost' equally weighted
Case 4	'Cost' weighted moderately higher than 'Performance' and 'Risk'; 'Performance' and 'Risk' equally weighted
Case 5	Distributed weights: 'Performance' with the highest weight, 'Risk' weighted moderately higher than 'Cost'

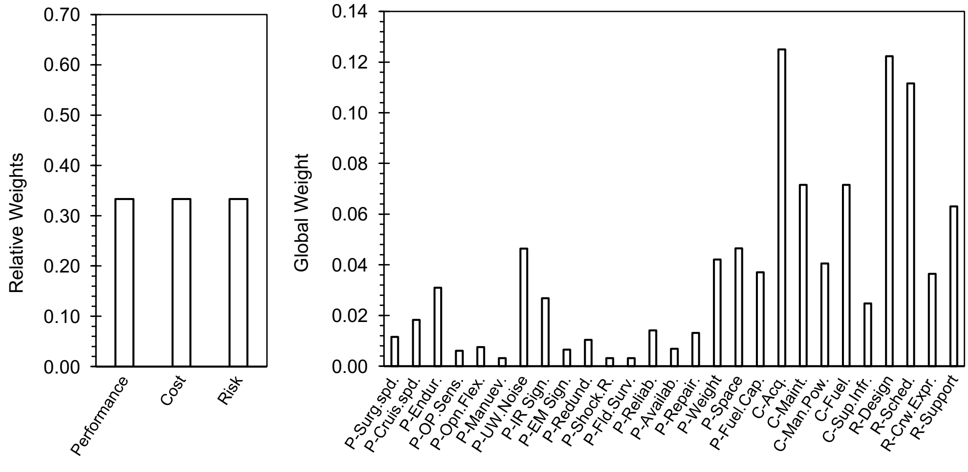


Fig. 24 Global weights of the set of criteria for Application Case 1

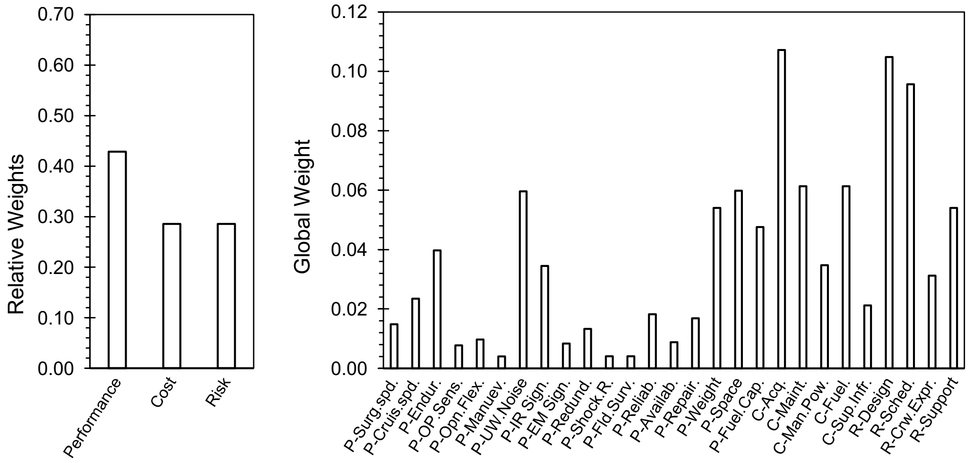


Fig. 25 Global weights of set of criteria for Application Case 2A

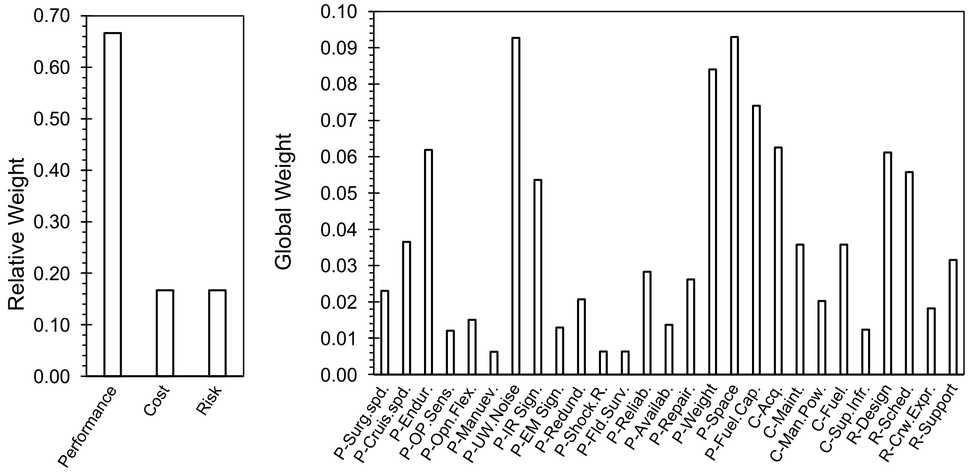


Fig. 26 Global weights of set of criteria for Application Case 2B

cases, the decision makers could also select the COGAG architecture as the preferred architecture, based on certain compromises across some of the criteria. The criterion of 'stability of the decision-making' is satisfied for both the CODAG and the COGAG architectures in all these cases. For application Case 2B, even though CODAG-E emerges as the most preferred architecture based on the ranking, it does not satisfy both the criteria for 'acceptable advantage' and 'stability in decision making'. Hence, here too, COGAG

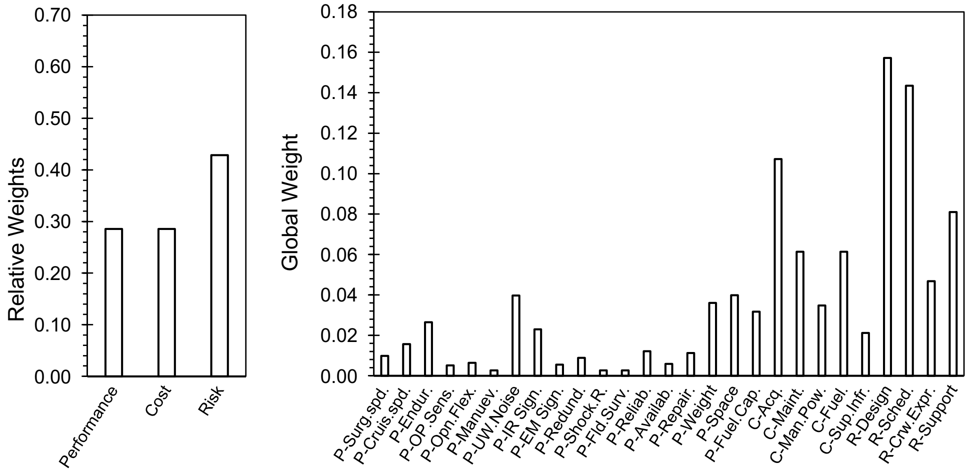


Fig. 27 Global weights of set of criteria for Application Case 3

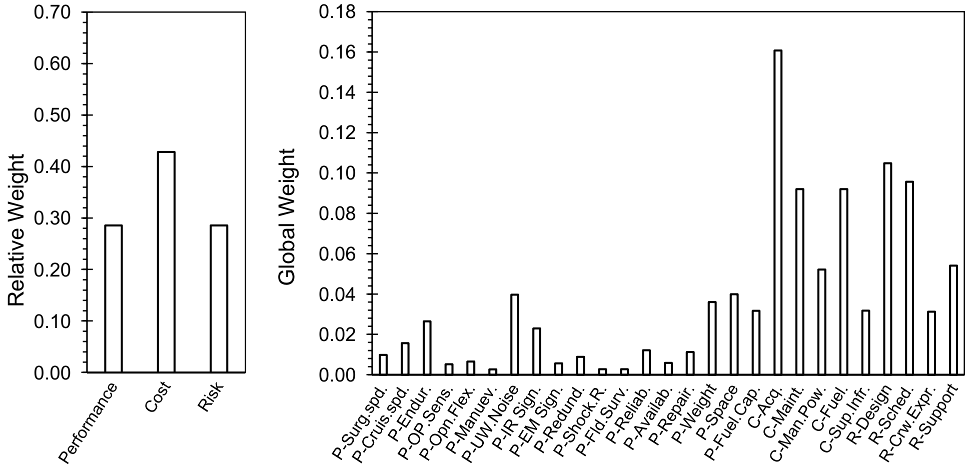


Fig. 28 Global weights of set of criteria for Application Case 4

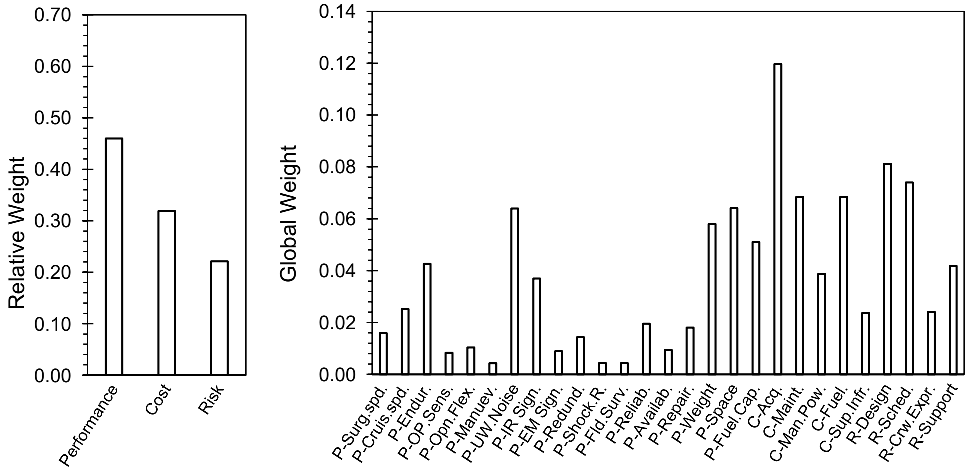


Fig. 29 Global weights of set of criteria for Application Case 5

which is the second-rated architecture could be selected with certain compromises.

An interesting observation that can be made from this analysis is the overall influence of the operating profile and engine operating envelopes on the overall fuel consumption by the ship propulsion plant. While it can be seen in Fig. 31 that the CODAG architecture provides an overall lower fuel consumption compared to the COGAG plant, the overall lifetime fuel consumption costs for both these architectures, as seen in Fig. 17, are not significantly different. This can

Table 6 Computed VIKOR metrics S, R, Q and determined ranks, with $v = 0.5$

		COGAG	CODAG	CODAG-E	CODELAG	IFEP
		A1	A2	A3	A4	A5
Case 1	**S**	0.30	0.26	0.44	0.83	0.39
	R	0.07	0.05	0.09	0.13	0.13
	Q	0.17	0.00	0.41	1.00	0.62
Case 2A	**S**	0.33	0.29	0.45	0.80	0.39
	R	0.06	0.06	0.08	0.11	0.11
	Q	0.06	0.00	0.34	1.00	0.60
Case 2B	**S**	0.40	0.36	0.48	0.75	0.39
	R	0.08	0.09	0.08	0.09	0.09
	Q	0.23	0.49	0.16	1.00	0.53
Case 3	**S**	0.26	0.23	0.43	0.85	0.34
	R	0.06	0.05	0.08	0.16	0.11
	Q	0.10	0.00	0.33	1.00	0.36
Case 4	**S**	0.32	0.26	0.44	0.82	0.45
	R	0.09	0.07	0.11	0.16	0.16
	Q	0.19	0.00	0.41	1.00	0.67
Case 5	**S**	0.36	0.31	0.46	0.79	0.43
	R	0.07	0.06	0.09	0.12	0.12
	Q	0.10	0.00	0.35	1.00	0.63

		COGAG	CODAG	CODAG-E	CODELAG	IFEP
		A1	A2	A3	A4	A5
Case 1	**S**	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 2A	**S**	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 2B	**S**	3	1	4	5	2
	R	2	3	1	4	4
	Q	2	3	1	5	4
Case 3	**S**	2	1	4	5	3
	R	2	1	3	5	4
	Q	2	1	3	5	4
Case 4	**S**	2	1	3	5	4
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 5	**S**	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4

Table 7 Selection of best-suited candidate architecture and test of 'acceptable advantage' and 'stability of decision', with $v = 0.5$

	Best Suited Alternative	Acceptable Advantage (dQ)	Stability of Decision (S,R match with Q Rank)	Sensitivity to v
Case 1	CODAG	−0.08	S & R	L
Case 2A	CODAG	−0.18	S & R	L
Case 2B	CODAG-E	−0.17	R	L
Case 3	CODAG	−0.15	S & R	L
Case 4	CODAG	−0.06	S & R	L
Case 5	CODAG	−0.15	S & R	L

$dQ = \left[Q\left(a_Q^2\right) - Q\left(a_Q^1\right)\right] - DQ$

Sensitivity to v: *L* Low, *M* Medium, *H* High

be explained by the way these plants are considered for operation in the low-speed range of 6–8 knots that dominates the considered operating profile, as shown in Fig. 6. The COGAG plant is considered for operation in this speed range in the 'trailed shaft' mode by the operation of a single engine, which can be easily handled by gas turbines due to the large engine operating envelope. On the other hand, for the CODAG plant, the entire low speed of operation is considered to be undertaken using two diesel engines due to the rather limited engine operation envelope of the diesel engines which makes ship operations rather restrictive.

The sensitivity analysis undertaken with respect to the value of the strategy coefficient, v, shows that the ranking as well as the VIKOR metric, Q, are stable in the vicinity of the selected strategy coefficient of $v = 0.5$. Further, the plots for the sensitivity analysis of Q also provide a good insight into the degree of acceptable advantage that one solution provides over the other across the values of the strategy coefficient. The higher the distance between the Q lines for each of the candidate architectures, the better is the degree of acceptable advantage.

The CODAG design emerges as the preferred design due to the low acquisition as well as life-cycle costs and the relative simplicity of the design. The COGAG architecture provides advantages in terms of performance criteria like low mass, and occupied deck area, but has disadvantages of lowest overall plant efficiency across the operating profile and high life-cycle costs. The CODAG-E architecture provides advantages of low underwater noise and low life-cycle costs but has the disadvantages of high mass and occupied deck area. The CODELAG architecture provides relatively high plant efficiency, advantages toward some of the performance criteria, but has the disadvantages of high mass and occupied deck area. The IFEP architecture has disadvantages of high mass, occupied deck area as well as very high acquisition costs. Hence, the overall analysis undertaken using VIKOR provides fairly intuitive results. Overall, the more traditional architectures CODAG or COGAG architecture emerge as the preferred architectures and either of them could be selected by the decision makers with certain compromises. The more electric architectures were rated lower due to penalties of higher mass and occupied deck area despite some advantages they offer.

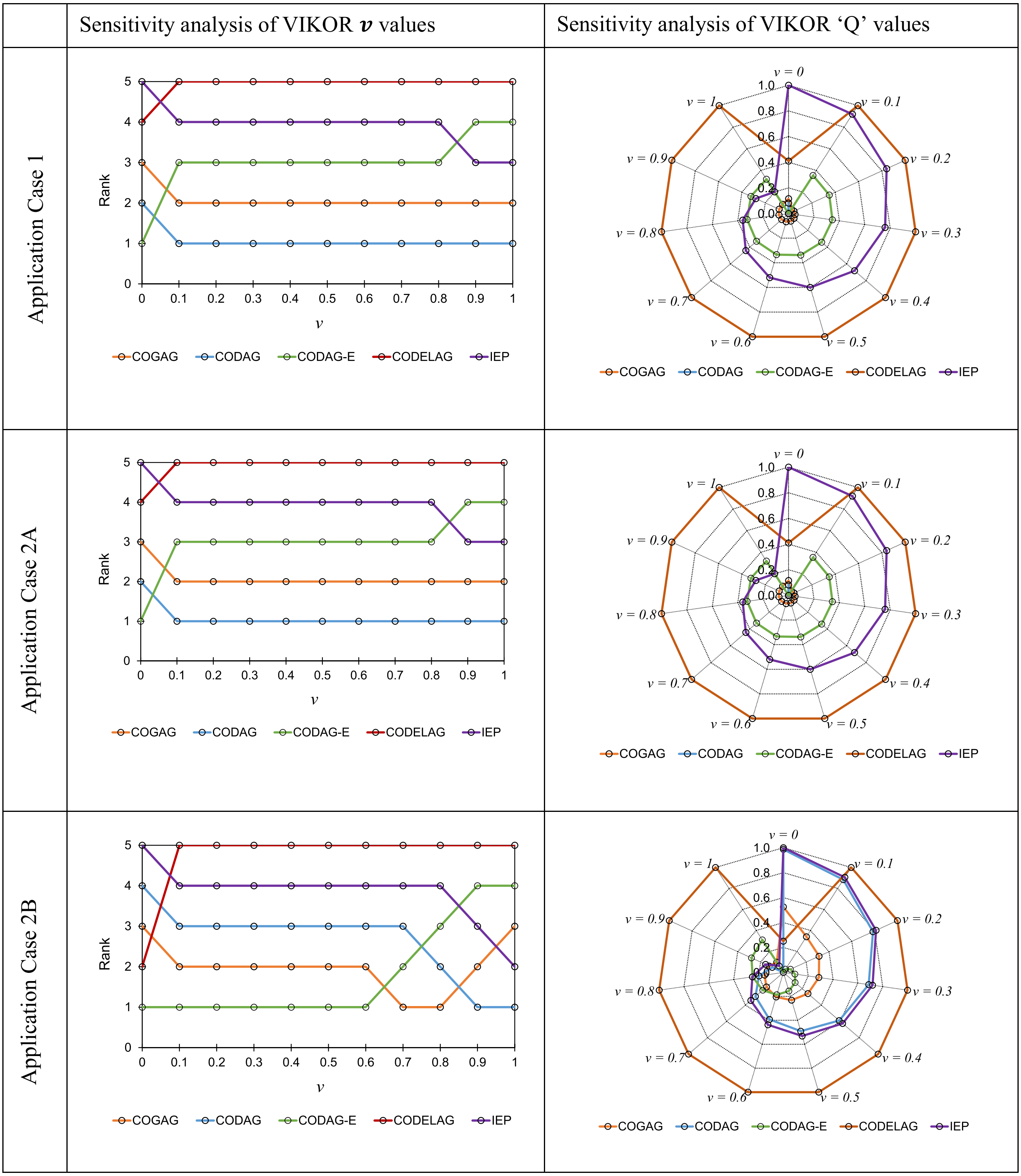


Fig. 30 Sensitivity analysis of VIKOR v,Q values for the Application Cases

6 Conclusion

During the initial design of a ship, the process of the propulsion system design is embedded into the process as one of the systems being addressed in the overall design. This often masks the considerations required to address all the aspects of the design of the propulsion system, especially in the context of combined propulsion plants which have

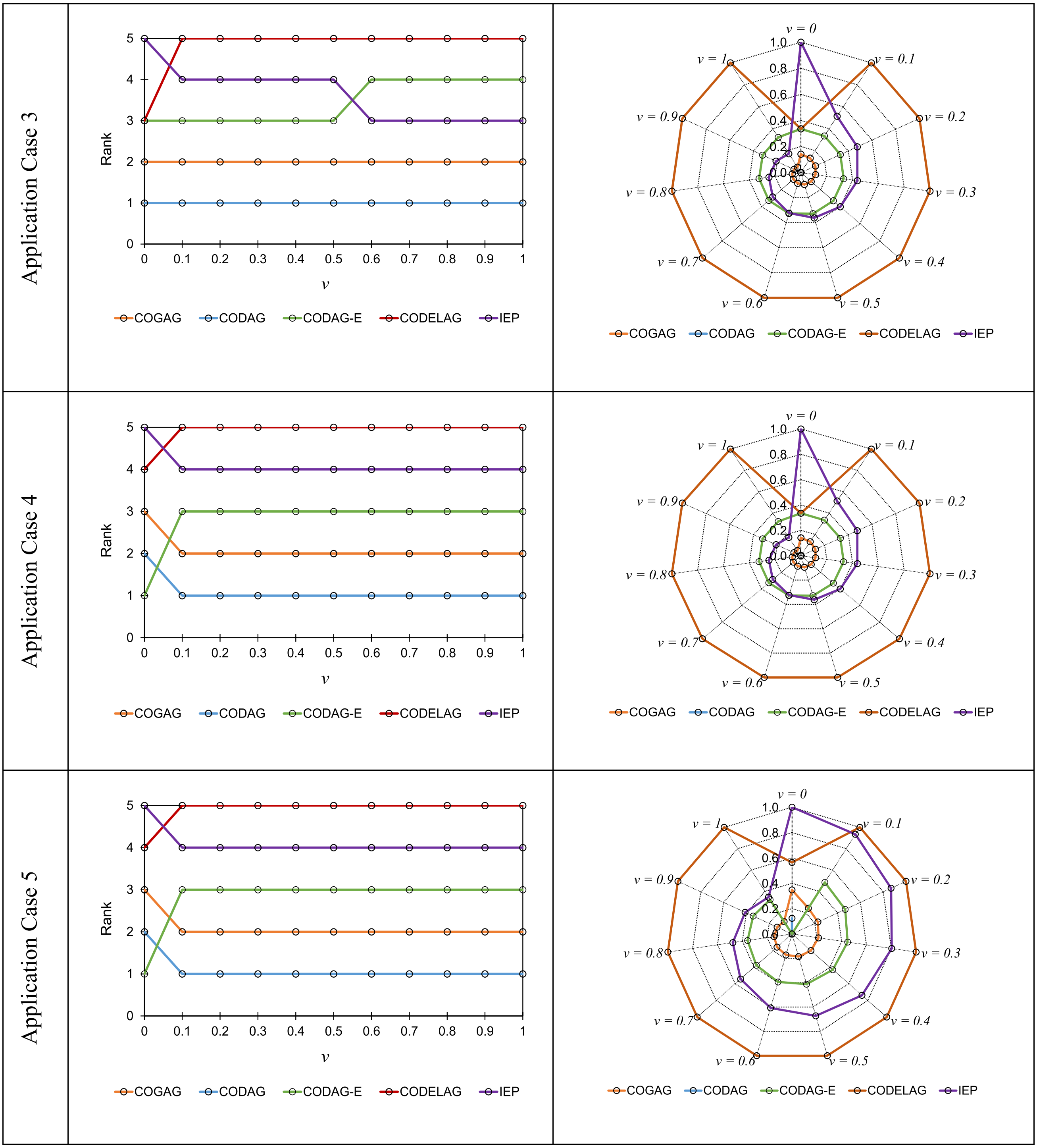
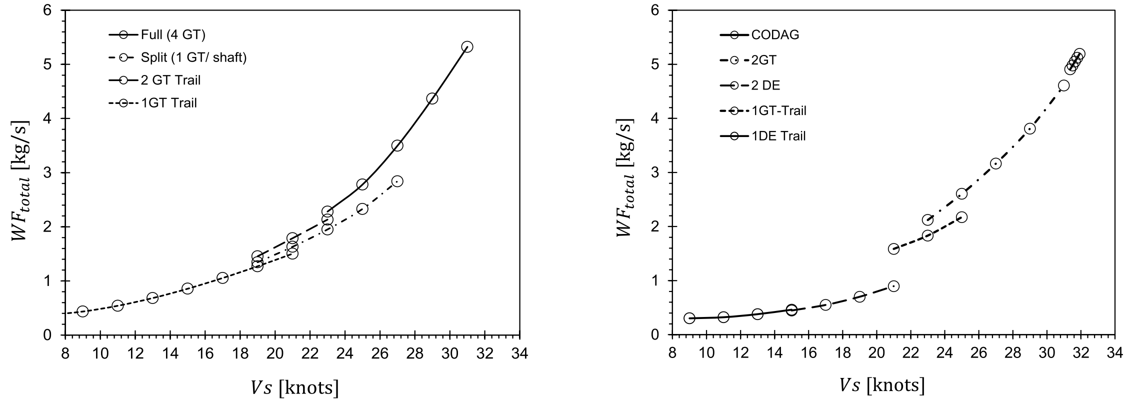


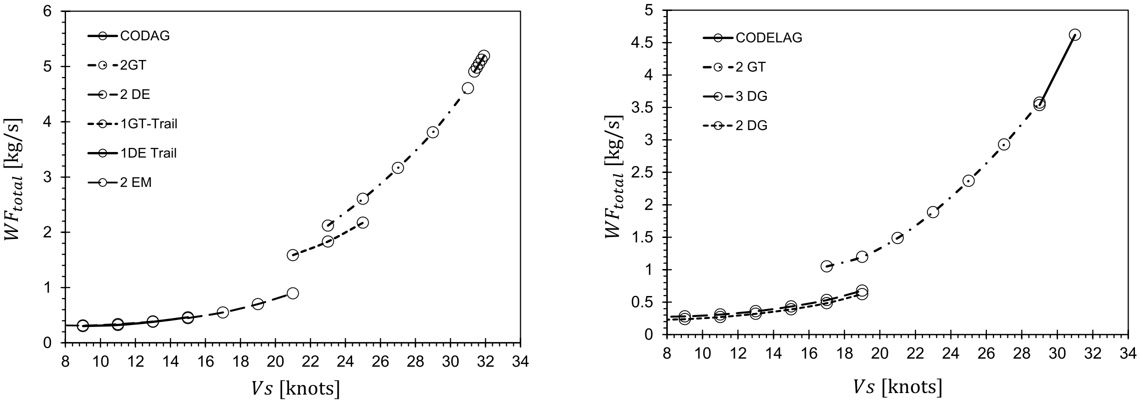
Fig. 30 (continued)

added design complexity. The proposed techno-economical model-based design space exploration process provides a model for approaching such designs with a quantifiable degree of preference of certain architectures in a design space over others in terms of design criteria of performance, cost, and risk. This proposed process utilizes a hybrid DANP–AHP–VIKOR-based MCDM method to undertake a TERA analysis to derive the best-suited architecture from the design space. This method includes a novel approach for evaluating the global weights of the design criteria for a propulsion system design, considering the mutual influence of design criteria on each other, which can be a significant



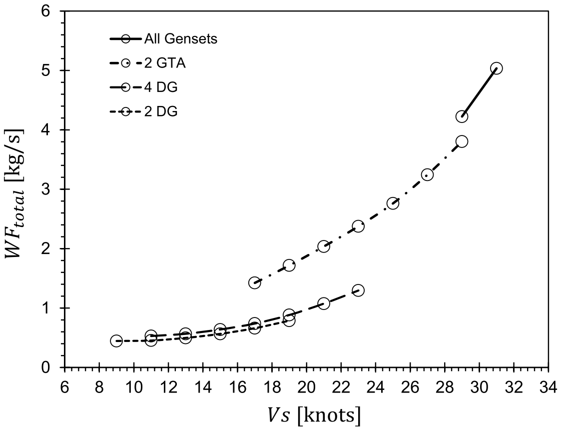
Candidate architecture A1: COGAG

Candidate architecture A2: CODAG



Candidate architecture: A3 CODAG-E

Candidate architecture A4: CODELAG



Candidate architecture A5: IFEP

Fig. 31 Fuel consumption curves for the candidate architectures

contributor to the criteria weights, and thus the final architecture selection. The method also finds a practical solution for combining 'quantitative' model-based results, with subject expert opinion-based 'qualitative' results for those aspects of designs where exact performance analysis is not possible during the early stages of ship design.

The proposed method has been demonstrated with an analysis for a notional destroyer where specific COGAG, CODAG, CODAG-E, CODELAG, and IFEP architectures have been objectively compared against the defined design criteria for a ship. With the analysis demonstrated, the more traditional architectures like CODAG and COGAG resulted as the preferred designs. The more electric architectures were rated lower due to penalties of higher mass and occupied deck area despite some of the advantages they offer in the flexibility of operation and performance. From this analysis, it can be inferred that with the present technological levels, to have more electric architectures selected for such ship designs, there must be more specific drivers for justification of such designs than the ones that have been considered for the present analysis. These drivers could be requirements such as extremely high energy requirements for ship weapon systems, specific low underwater noise requirements, etc. On the other hand, it should also be noted that these conclusions are not general conclusions for such combined architectures, but the specific architectures considered for the presented analysis under considered design criteria along with their defined and derived weights.

Based on the proposed method, an interesting further study could be its application to commercial ocean-going vessels, where the design criteria and metrics would vary significantly from naval vessels. The proposed method could be effectively used to find practical and effective solutions to the present-day design drivers that the propulsion and power systems of the commercial vessels face, ranging from low environmental emissions to other drivers, criteria like high performance, low capital expenditures (CapEx), operating expenses (OpEx), and life-cycle costs.

Data availability The dataset referred to in the aforementioned article can be provided by the corresponding author on a reasonable request.

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