

Review of methods for sustainability appraisals in ship acquisition

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Abstract Ship acquisition requires simultaneous consideration of environmental, economic, technological and social performance of candidate design solutions. During the last few decades, multi-criteria decision-making tools have gained popularity as an approach to assisting decision makers when appraising ship design. However, applications are limited to a few methods mostly within the value function class. In this review, we explore the applicability of 12 multi-criteria decision-making methods for typical decision contexts in ship acquisition. Technical and practical method properties are defined before their operational value for evaluations in ship acquisition is assessed. Our results show that a wide range of methods currently not applied offer promising properties in these contexts.

Keywords Ship acquisition · Design · Multi-criteria decision making · MCDM · Method selection · Sustainability appraisal

1 Introduction

Ship acquisition includes the strategic planning, problem preparation, generation of alternatives and commercial activities necessary to support the introduction of new tonnage in a ship-owning company (Cushing 2003). Due to the size, complexity and long lifespan of a ship, decision makers must apply systematic judgement in acquisition

planning and decision making. The conventional techno-economic performance assessments of a ship are now supplemented with environmental and safety impact considerations to consider the wider sustainability performance over her lifecycle (Ölçer et al. 2004). This system boundary expansion adds to the complexity of the decision-making process, involving multiple, often conflicting objectives and criteria. In order to critically appraise sustainability performance, formality and explicit consideration of stakeholder value are necessary.

Ship designers and other primary decision makers involved in new ship acquisition must consider performance during all stages of the ship design process. A ship design evolves in an iterative manner through conceptual, preliminary, contract and detailed design stages. In each step, design parameters such as dimensions, weight, capacities, layout, hull form and systems are revisited until a well-balanced, feasible and preferable solution is identified. The sequencing of these decisions within each stage may differ depending on both the type of ship and strategy of the design team. An excellent overview of various ship design process models is provided in (Andrews et al. 2009; Erikstad and Andrews 2015).

Conceptual ship design defines main characteristics of the ship and allows for basic techno-economic assessments to be made (Eyres and Bruce 2012). This phase often precedes the outline specification, detailing main requirements, objectives and constraints from owners and other invested parties (Erikstad 1996). Preliminary design refines the concept, and more knowledge about the design is acquired. This allows for more sophisticated assessments of lifecycle properties such as environmental and safety performance. At this stage, designers may submit a tender, leaving ship-owning companies with various solutions to compare and evaluate (Dokkum 2011). Contract design

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further forms the basis for agreement between owner and builder and includes precise features of hull, seakeeping, powering and maneuvering. Finally, detailed design (or post-contract design) also adds detailed working plans with instructions for construction and installation for fitters, welders, outfitters and other (Wijnolst and Wergeland 2009).

The introduction of computer-aided ship design (CASD) tools has had a profound impact on ship design decision-making process throughout the last five decades (Nowacki 2010). This transition is founded in design theory literature and encompasses knowledge-based design (Coyne 1990), catalog design (Pahl et al. 2007), decision-based design (Mistree et al. 1990, 1991) and optimal design (Papalambros and Wilde 2000). CASD tools allow for rapid and precise generation of graphical representations of ship design with problem-solving capabilities for determining hull form, general arrangement, hydrostatic and hydrodynamic calculations among others. Today, these tools may be viewed as integrated expert systems, constituted by a knowledge base and an inference engine. The knowledge base stores facts about the world and may contain design knowledge and experience from past projects as well as scientific principles and rules, i.e., a form of design catalog. The inference engine is the algorithmic treatment of knowledge to synthesize new information. Inference processes necessary to support design decision making are abduction (synthesis), induction (generation of new knowledge) and deduction (performance assessment) (Coyne 1990; Erikstad 1996). This article concerns performance assessment and aims to evaluate the operational value of various inference logics for decision contexts in ship acquisition.

Designers and other stakeholders must often consider various design solutions across multiple performance metrics during ship acquisition. For this purpose, multi-criteria decision-making (MCDM) methods have been devised and applied. These decision algorithms induce an order on a set of alternatives based on the following information:

- Design descriptions of candidate design solutions
- Criteria to measure performance of solutions
- Preference statements to indicate relative importance between criteria (weights, rank of criteria, etc.)

A wide range of methods are available to analysts aiming to support decision making in ship acquisition. The problem for the analyst is therefore to identify an adequate method for the decision context at hand. To the knowledge of the authors, there are currently no reviews of such methods for ship acquisition decision contexts. To critically evaluate the operational value of methods in ship acquisition, we will first explore previous applications and

examine the type and nature of information available. We identify important method properties to take into account in method selection, before defining properties for 12 well-tested and validated MCDM methods. Finally, we discuss the use of these methods in various decision contexts and offer a generic approach to method selection for ship design appraisals.

2 Materials and methods

2.1 MCDM applications in ship acquisition

The application of MCDM methods to appraise ship design has steadily grown during the last two decades. If we examine this body of the literature, as displayed in Table 1, we may make a few considerations with regard to characteristics of decision contexts in ship acquisition.

Firstly, our concern is with the type of data utilized in various decision contexts. If we consider measurement scales, we may differentiate between cardinal and ordinal scales. Ordinal scales only allow determining a rank order of elements in a set while cardinal scales (on interval or ratio level) additionally help determine the distance between elements. As an example, safety might be determined to be low, moderate or high on a verbal scale or cardinally determined by a continuous parameter such as accidental oil outflow as seen in (Papanikolaou et al. 2010). From previous literature, we see that criteria scales during conceptual and preliminary design more often are cardinal, while scales at the point of investment more often are on ordinal scales. This is coherent with the fact that maturity of the design description increases during the process, allowing for higher-level considerations in later stages of the acquisition process. Overall maintainability or reliability might for instance be better assessed in an ordinal fashion based on owner, designer and yard expertise, as seen in (Yang et al. 2009).

Secondly, and surprisingly, we see that the ranking of criteria is usually made in a cardinal manner during both design and investment appraisals. At the point of investment, this information should be readily available since owners may be able to express their preferences with this degree of precision if support from analysts is given. In the design process, preference statements on criteria without involvement of owners should intuitively be less precise or at least difficult to determine. When we further examine these case studies, we see that weights often are derived via the entropy method or eigenvector method. In the first approach, weights are not subjectively derived, but assigned to criteria based on the performance differences for alternatives across these criteria. More importance is allocated to criteria where alternatives have very different

Table 1 Methods applied in ship acquisition decision contexts

Decision context	Method	Criteria scales	Preferences on criteria	References
Considerations during the design process	Fuzzy TOPSIS	Mixed	Cardinal	Ölçer et al. (2004), Ölçer and Odabaşı (2005)
	AHP, rigid least square	Cardinal	Cardinal	Song et al. (2006)
	Evidential reasoning (ER)	Mixed	Cardinal	Xie et al. (2008)
	TOPSIS, entropy weights	Cardinal	Cardinal	Xuebin (2009)
	Ma, Fan, Huang method	Cardinal	Cardinal	Barone et al. (2005)
Considerations at the point of investment	AHP	Mixed	Cardinal	Leheta (2005), Rousos and Lee (2012)
	Fuzzy AHP	Cardinal	Ordinal	Bulut et al. (2012, Duru et al. (2012)
	Fuzzy AHP	Mixed	Cardinal	Bulut et al. (2010)
	Fuzzy if-then rule	Mixed	Ordinal	Wibowo and Deng (2012)
	ER (fuzzy)	Mixed	Cardinal	Yang et al. (2009)

outcomes and less importance to criteria where alternatives have similar outcomes. The eigenvector method derives weights based on statements of relative performance of pairs of criteria, often supported by a verbal (ordinal) scale that helps decision makers express their subjective opinion on the matter. These approaches reveal that quantitative weight assignment during the design process might be a difficult task, and the available data might be both ordinal and cardinal, depending on the involvement of owners and experience of the design team.

Table 1 also shows that with the exception of the fuzzy approach evidential reasoning (ER), TOPSIS and AHP are the main methods applied. These are highly compensatory as they permit trade-offs between advantages and disadvantages across criteria. If we further examine typical criteria used in these decision-making contexts, as summarized in Table 2, we see that these are rather heterogeneous. This raises concern of the compensatory nature of MCDM methods when applied to ship design appraisals. For instance, owners or designers might find it problematic that crew safety is sacrificed to improve maintainability of equipment. Another important point when appraising ship design is that sustainability performance is better safeguarded in methods that are not fully compensatory (Polatidis et al. 2006). If we revisit the design process and consider approaches for synthesizing solutions, we see that there is room for a nuanced perspective on whether or not compensation is allowed. Type of criteria and aspects covered are related to strategies for design development. One approach is to develop novel designs based on optimization models or other forms of creation (Cushing 2003; Erikstad 1996). These approaches often aim to maximize techno-economic performance subject to a set of constraints, as seen in (Papanikolaou et al. 2010; Žanić and Čudina 2009). In these instances, trade-offs are typically unproblematic. A second approach is to identify a reference vessel of known design to constitute a basis design, which

is further developed into a solution meeting specific requirements of owners (Cushing 2003; Erikstad 1996). Selecting between existing solutions to identify the best reference vessel allows for diverse criteria modeling and utilization of validated empirical data from ship operations, as seen in (Xie et al. 2008). A general remark is that ship design appraisals should be used with less compensatory methods when the design description is rich and heterogeneity among criteria is high. This concern with regard to compensation also applies to appraisals at the point of investment, which, as previously mentioned, requires considering a diverse set of criteria.

2.2 MCDM methods considered

MCDM methods offer support for both design and selection problems. In design problems, multi-objective decision-making (MODM) methods implicitly define solutions. In selection, a discrete set of alternatives is given and further analyzed by multi-atrrite decision-making (MADM) methods. Our assessment is applicable in situations where a decision problem has been structured such that the objectives and criteria of decision makers have been identified along with a set of admissible ship design alternatives. At this point, let us consider the problem $\text{Max}\{k_1(a), \dots, k_m(a) | a \in A\}$ where A is a finite set of n design alternatives and F is a family of m criteria to be maximized. For these situations, we will describe and evaluate 12 well-tested and validated MADM methods within three classes: elementary, outranking and value function. A brief description of the methods considered is provided in Table 3.

Elementary methods are simple approaches that do not require weights to be determined (Hwang and Yoon 1981). Although these methods consider problems from a multi-criteria perspective, the ordering of alternatives is often built on the performance of one or a few criteria. From this

Table 2 Criteria for ship design appraisals

Criteria	References	Criteria	References
<i>Economic</i>		<i>Technological</i>	
Capital expenditure	Barone et al. (2005), Leheta (2005), Rousos and Lee (2012), Song et al. (2006), Ölçer and Odabaşı (2005)	Maintainability	Wibowo and Deng (2012)
Operational expenditures	Bulut et al. (2010), Ölçer and Odabaşı (2005)	Reliability	Yang et al. (2009, Ölçer and Odabaşı (2005)
Return on investment (ROI)	Bulut et al. (2012)	Producibility	Ölçer et al. (2004)
Required freight rate (RFR)	Song et al. (2006), Xie et al. (2008)	Speed	Bulut et al. (2010, 2012), Duru et al. (2012), Leheta (2005), Wibowo and Deng (2012)
Net present value (NPV)	Bulut et al. (2010), Rousos and Lee (2012), Song et al. (2006), Xie et al. (2008)	Payload capacity	Leheta (2005), Xuebin (2009), Ölçer et al. (2004)
Return on equity (ROE)	Bulut et al. (2010), Duru et al. (2012)	Maneuverability	Xie et al. (2008, Ölçer and Odabaşı (2005)
Internal rate of return (IRR)	Leheta (2005), Rousos and Lee (2012), Song et al. (2006)	Equipment performance	Xie et al. (2008)
Payback period	Song et al. (2006), Xie et al. (2008)	Noise	Ölçer and Odabaşı (2005)
Hire base	Xie et al. (2008)	Vibration	Ölçer and Odabaşı (2005) Yang et al. (2009)
Insurance cost	Wibowo and Deng (2012)		
Fuel cost	Bulut et al. (2010, 2012), Duru et al. (2012), Leheta (2005), Wibowo and Deng (2012), Yang et al. (2009))		
Crew cost	Wibowo and Deng (2012), Yang et al. (2009)		
Store consumption	Yang et al. (2009)		
<i>Safety</i>		<i>Environmental</i>	
Stability and seakeeping	Leheta (2005), Xie et al. (2008), Ölçer et al. (2004)	Air emissions	Yang et al. (2009)
Survivability	Ölçer et al. (2004)	Life cycle impacts	Ölçer et al. (2004)
Fire protection	Xie et al. (2008)	Pollution prevention	Yang et al. (2009)
Crew safety	Leheta (2005)	Expected spill size	Rousos and Lee (2012)

class, we examine the Lexicographic method and Maximax/Maximin.

Outranking methods attempt to evaluate the assertion that an alternative outranks another based on proof built from combining performance across criteria and importance of criteria. For any relation, criteria may be split into a concordant coalition supporting the assertion and a discordant coalition opposing it. The main difference between outranking methods is how concordance and discordance are measured and aggregated to produce a final ranking. ORESTE, Regime, ELECTRE II and III, MELCHIOR and PROMETHEE I and II are outranking methods considered in our review.

Value function methods combine utility/value functions and weights to compute an overall value of alternatives. In these approaches, weights represent scaling constants rendering criteria scales comparable. TOPSIS, MAVT, AHP and UTA are methods considered in our review belonging to this class.

2.3 Evaluation properties

MCDM method reviews usually involve mapping properties of methods onto characteristics of a decision context. Important concerns in identifying an appropriate method for decision contexts are the *technical* capabilities of

Table 3 Methods considered in the review

Class	Method	Description	References
Elementary	Maximax/ Maximin	Alternative with the best performance on its strongest criterion (Maximax) or its weakest criterion (Maximin) is selected	See Hwang and Yoon (1981)
	Lexicographic	Alternatives are evaluated across an ordinal rank of criteria. Dominated alternatives are eliminated, and tied alternatives are further examined across the next criterion in the ordinal rank until a single alternative remains	
Outranking	ORESTE	Ordinal ranking of alternatives and criteria is used to construct a complete ranking on the set of alternatives before indifference and conflict analysis is conducted to produce a final rank of alternatives	See Roubens (1982)
	Regime	Pairwise comparisons of alternatives are used to construct a Regime matrix with indicators for dominance, equivalence and non-dominance across criteria. A total preorder is obtained by aggregating these weighted scores	See Hinloopen et al. (1983)
	ELECTRE II	Concordance and discordance indices are computed for all pairs of actions and used along with thresholds to build strong and weak outranking relations. These are further exploited to provide a partial preorder (semi-order)	See Roy and Bertier (1971)
	ELECTRE III	Concordance and discordance for an outranking relation are determined with pseudo-criteria and used to build a credibility index that offers a fuzzy interpretation of outranking relations. The index is further exploited to provide a partial preorder (semi-order) of alternatives	See Roy (1978)
	MELCHIOR	Criteria importance is determined by a binary relation before concordance and discordance indices are built and exploited to provide a partial preorder (semi-order)	See Leclercq (1984)
	PROMETHEE (I and II)	A preference function is defined on each criterion reflecting the preference intensity over deviations of criteria values. The outranking algorithm comparatively scores alternatives on each decision criterion and establishes their overall rank order through their weighted relative dominance over other alternatives across all criteria	See Brans and Vincke (1985)
Value function	TOPSIS	Positive and negative ideal points are defined for all criteria, and alternatives are ranked based on their aggregated distance to these points	See Hwang and Yoon (1981)
	MAVT	A partial value function for each criterion is built, and trade-offs between all pairs of criteria are examined to obtain weights. The aggregated value of alternatives is used to build a total preorder	See Fishburn (1970) and Keeney and Raiffa (1993)
	AHP	Pairwise comparisons of criteria and alternatives are used to derive weights and score alternatives. The aggregated value of alternatives is used to build a total preorder	See Saaty (1987)
	UTA	An ordinal rank of a subset of alternatives is disaggregated via a linear program to deduce marginal utility functions. These are further used to rank the full set of alternatives, giving a total preorder	See Jacquet-Lagrez and Siskos (1982)

methods in dealing with the available data, and their *practical* value, as shown in Table 4.

Technical properties cover permissible scales for input data and the degree of compensation allowed in the preference structure. As shown in Sect. 2.1, this could significantly differ between decision contexts. Data requirements relate to how alternatives in the set A are ranked based on criteria in F and furthermore how criteria in F are ranked according to importance, inspired by a method assessment framework applied by Moffett and Sarkar (2006). We will distinguish between methods that utilize ordinal or cardinal scales to measure this information. Ordinal scales are generally considered “weaker” than cardinal scales as they contain much less information (Roberts 1979), but are on

the other hand more flexible as they may be applied in situations where information is ordinal, cardinal or mixed (Moffett and Sarkar 2006). Furthermore, the extent to which the preference structure allows compensation between good and poor performance along criteria is an important technical property as it potentially affects how well a preferred solution balances sustainability aspects (Guitouni and Martel 1998; Polatidis et al. 2006; Roy and Słowiński 2013).

Practical properties relate to the cognitive burden put on decision makers during method application. Modeling requirements with regard to preference information is an important property, with extensive requirements reducing the applicability of methods in decision situations (De

Table 4 Selected properties for method evaluation

Aspect	Property	Description
Technical	Ranking of alternatives	Describes whether the method can handle ordinal and/or cardinal criteria
	Ranking of criteria	Describes whether the method requires no, ordinal or cardinal preference information
	Compensation	Describes to what extent the method is compensatory. For a strong sustainability interpretation, none or partial compensation is preferred
Practical	Computational complexity	Evaluation of the computational complexity in the model. Relates to transparency and intuition in aggregation/exploitation
	Modeling requirements	Requirements for preference modeling. Based on preference information necessary to induce an order on the set of alternatives

Montis et al. 2005). The further processing of this information along with additional information may create a distance between the decision maker and data. An important practical goal is therefore to ensure that decision makers are able to understand and accept data processing (De Montis et al. 2005; Sen and Yang 1998; Stewart 2005), which motivates the consideration of computational complexity of methods as another practical property in our method evaluation.

3 Results and discussion

In this section, method properties defined in Table 4 are evaluated based on examination of method algorithms and supporting literature. These results are summarized in Table 5 and further used for discussing and recommending methods for ship acquisition.

3.1 Evaluation of technical properties

When evaluating the property *ranking of alternatives*, we focus on the restrictions methods put on criteria with regard to measurement scales. This is related to how the information is utilized, often together with preference statements, to induce an order on the set of alternatives.

Both elementary methods included in this review permit ordinal ranking of alternatives as this is the only performance information necessary to produce an order. The outranking methods ORESTE and Regime also share this property. Ordinal criteria may also be used in ELECTRE II, provided that decision makers are able to define veto thresholds to be utilized in determining the discordance index. This requires that ordinal criteria have a sufficient amount of evaluation grades to support a meaningful modeling of these thresholds. The same applies to MELCHIOR, which requires both performance and indifference thresholds for criteria. ELECTRE III is better suited for

problems with cardinal criteria scales (Belton and Stewart 2002; De Montis et al. 2005; Moffett and Sarkar 2006) as concordance and discordance indices are cardinal. In PROMETHEE I and II, six preference functions are provided to model preference intensity on deviations along criteria scales, several of which are compatible with criteria on ordinal scales. Value function methods may be considered entirely cardinal with regard to ranking of alternatives. The basic approach of aggregating preference and performance information into an overall value is impossible with an ordinal scale where distances between points are undetermined.

If we consider scales for preference information in the form of *ranking of criteria*, a main distinction can be made between those methods that require determination of weights and those which do not. Maximax/Maximin does not require any such information as it implicitly allocates all importance to the criterion along which an alternative has its best or worst performance. Next, we have methods that only require an ordinal ranking of criteria such as the Lexicographic method, ORESTE, Regime and MELCHIOR. All other methods belonging to either the outranking or the value function class utilize cardinal ranking of criteria in the form of weights.

Degree of *compensation* is a property of the preference structure, and we may distinguish between no, partial or complete compensation in methods. In general, value function methods that aggregate overall value of alternatives utilizing weights that are interpreted as scaling constants are highly compensatory (Roy and Słowiński 2013). TOPSIS and UTA may be considered fully compensatory as they assume linear preferences (Guitouni and Martel 1998; Sen and Yang 1998). In our review, MAVT and AHP will also be considered fully compensatory since there is a complete trade-off between alternatives with regard to the weighted value of alternatives across criteria. Elementary methods are non-compensatory as there are no trade-offs between good and poor performance. Outranking methods

Table 5 Method properties

Class	Method	Technical aspects			Practical aspects	
		Ranking of alternatives	Ranking of criteria	Degree of compensation	Complexity	Modeling requirements
Elementary	Maximax/Maximin	Ordinal	None	None	Low	Low
	Lexicographic	Ordinal	Ordinal	None	Low	Low
Outranking	ORESTE	Ordinal	Ordinal	Partial	Medium	Medium
	Regime	Ordinal	Ordinal	Partial	High	Low
	ELECTRE II	Ordinal	Cardinal	Partial	High	Medium
	ELECTRE III	Cardinal	Cardinal	Partial	High	High
	MELCHIOR	Ordinal	Ordinal	Partial	High	High
	PROMETHEE (I and II)	Ordinal	Cardinal	Partial	Medium	Medium
Value function	TOPSIS	Cardinal	Cardinal	Full	Low	Low
	MAVT	Cardinal	Cardinal	Full	Low	High
	AHP	Cardinal	Cardinal	Full	Low	High
	UTA	Cardinal	Cardinal	Full	Medium	Low

building on concepts of concordance and discordance may be regarded only partially compensatory (Roy and Słowiński 2013).

3.2 Evaluation of practical properties

Computational complexity of methods concerns how input data in the form of preferences and scoring of alternatives are transformed to a final rank order. Some algorithms are seemingly intuitive in the sense that non-analysts may understand their underlying principles. Elementary methods are generally straightforward and easy to understand for non-analysts. The same can be said for value function methods, where aggregation of preferences and performance into a single overall value or utility is a rather transparent procedure (De Montis et al. 2005). MAVT, AHP and TOPSIS may all be categorized as having low computational complexity. UTA follows the opposite strategy by disaggregating values. The ordinal regression procedure by which partial value functions are obtained may be considered mathematically complex, but the concept of preference regression should be possible to communicate to decision makers lacking experience or knowledge of such methods. Outranking methods are generally considered more complex than value function methods. The exploitation procedure in ELECTRE methods is rather opaque and may be difficult to understand for decision makers without experience or knowledge of the method (Belton and Stewart 2002; De Montis et al. 2005; Moghaddam et al. 2011). The same applies to MELCHIOR which exploits outranking relations in a similar manner to

ELECTRE III. The concept of concordance utilized to build a rank order in Regime is straightforward if weights are known cardinally. If not, a cumbersome regime analysis must be undertaken to identify weights, which reduces the transparency of the decision-making procedure (De Montis et al. 2005). The first phase of ORESTE, where a complete preorder (global ranks) is built, rankings of criteria and alternatives are aggregated in a transparent manner. However, the meaning of threshold levels is more abstract in ORESTE than in ELECTRE and MELCHIOR methods, as they are defined on preference intensities as opposed to criteria. The following procedure whereby preference intensities and threshold levels are used to arrive at a final order may also be considered unintuitive. However, the representation of the procedure by if-then rules at least illustrates the traceability between the global ranks and the final order. PROMETHEE may be an exception from other outranking methods as it is usually considered a rather intuitive approach. In PROMETHEE II where a complete ranking is provided, the net flow is comparable with a utility function (Brans and Mareschal 2005).

Elementary methods are considered among the simplest along the properties of *modeling requirements*. Maximax/Maximin requires no information at all, and the Lexicographic method only requires an ordinal rank of criteria. The same applies to Regime, which only requires ordinal ranks of criteria. Next, we find methods that only require cardinal weights, such as TOPSIS, and an ordinal rank of alternatives, such as UTA. These may also be considered low on modeling requirements when compared to other

MCDM methods. More cumbersome are those that require ordinal/cardinal ranking of criteria in addition to determination of thresholds. In this group, we find ELECTRE II and III, PROMETHEE, MELCHIOR and ORESTE. The use of quasi-criteria in ELECTRE III is on the one hand a very useful approach to dealing with uncertainty and ambiguity (Figueira et al. 2005), but may on the other hand also induce a heavy cognitive burden on decision makers as they must be defined for all criteria. The meaning of these thresholds is unclear, and guidance on how to define them is missing (Belton and Stewart 2002). MELCHIOR suffers from the same as both indifference and preference thresholds must be defined on each criterion. ELECTRE II may be considered less time-consuming as it does not require defining preference and indifference thresholds for criteria. ORESTE also requires determining thresholds for preference, indifference and incomparability, but unlike ELECTRE III and MELCHIOR, these thresholds are defined on preference intensities and not for each criterion. In PROMETHEE, the modeling time is dependent on the preference function defined on each criterion. Modeling requirements are also considered high in MAVT/MAUT and AHP. In MAVT/MAUT, the determination of partial value/utility functions and trade-off constants makes preference elicitation an extensive procedure (De Montis et al. 2005; Moffett and Sarkar 2006). The same applies to AHP, which requires pairwise comparisons of criteria and alternatives (Polatidis et al. 2006).

3.3 Recommendation for use

As shown in Table 5, there is a great diversity among methods with respect to the selected properties. In the following paragraphs, we will critically discuss the operational value of methods for some decision contexts where ship design is being appraised, by examining problem characteristics with these method properties.

If we consider concept design, where primarily technological criteria measured on a cardinal scale are available and owners are not involved, UTA exhibits technical and practical properties useful in assessing a set of candidate design solutions. It is especially useful in a situation where an optimization routine has been applied, generating an extensive set of Pareto optimal design solutions, as seen, for example, in Xuebin (2009). Although UTA implies a cardinal interpretation of ranking of criteria, designers are not required to make explicit quantitative judgements about the relative importance of criteria. The ordinal ranking of a subset of alternatives should be given to experienced designers that are able to make an aggregated judgement considering all aspects of design simultaneously. We emphasize that this method generally should only be applied when trade-offs between good and poor

performance along criteria are permitted. This is usually the case when only technical and economic considerations are made of acceptable candidate solutions. As it is an additive value method, it also follows that criteria must be preferentially independent in the mind of decision makers, i.e., they are able to consider the relative importance between any two criteria without concern of the state of any other criteria, provided that their levels are fixed (Keeney and Raiffa 1993).

If we further imagine a situation where owners participate in the design decision-making process at early phases, TOPSIS is a promising method as it utilizes cardinal criteria and cardinal ranking of criteria. In addition, it is considered very practical with minimum requirements to preference information in addition to offering an intuitive data processing procedure. In addition to weights, owners and designers must determine positive and negative ideal points to produce the rank. A simple approach to this could be to define ideal points based on extreme criteria values of alternatives in the setup for consideration, but care must then be given to potential problems with rank reversals if the initial set of alternatives considered is altered (García-Cascales and Lamata 2012). This rearrangement of an order based on the introduction or elimination of a non-optimal alternative is a rather counterintuitive phenomenon from a decision maker perspective. Determining thresholds not dependent on the set of alternatives considered could reduce the likelihood of this problem occurring, as well as adopting more robust variants of the methods (García-Cascales and Lamata 2012). Since the method is rather sensitive to weights (Sen and Yang 1998), the determination of these should also follow a rather rigorous process with regard to elicitation and validation. We also mention ELECTRE III as a potential method in these situations if compensation is not allowed. It may be considered rather unpractical, but is the only approach considered in this review that utilizes cardinal ranking of criteria and alternatives without allowing full compensation.

Moving on to situations where design descriptions are more mature and rich, allowing problem definitions with criteria on both ordinal and cardinal scales, a new set of methods comes to attention. Particularly outranking methods offers interesting properties in situations where criteria scales are mixed and only limited compensation is permitted. If we again are faced with the lack of precise preference information from owners or other parties considered problem holders, ORESTE may be a useful method. Designers with expert knowledge and experience could provide an ordinal rank of criteria reflecting a perceived importance rank owners might have. The main drawback of this method is that it requires determining thresholds of indifference and preference, which is particularly difficult as they are defined on preference intensities

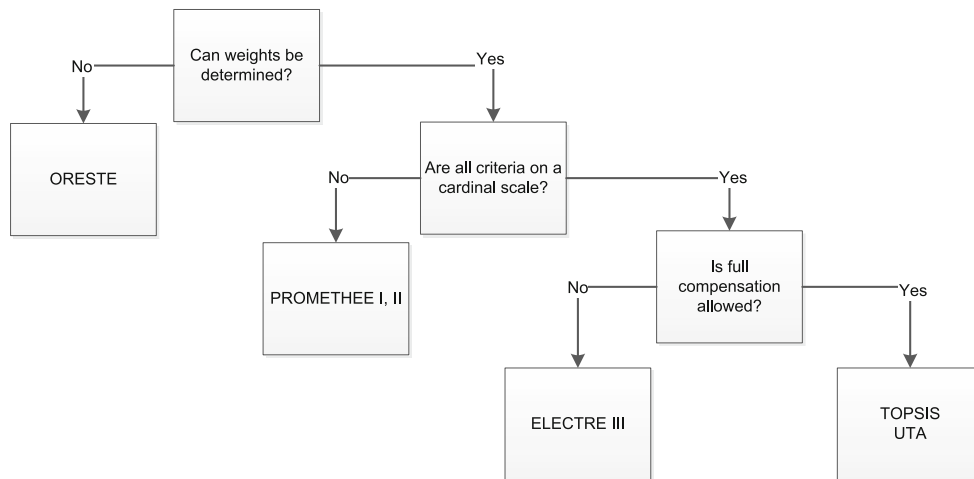


Fig. 1 Recommendation of methods for ship design appraisals

and not criteria themselves (as in, for example, ELECTRE III or MELCHIOR). If a decision support software or analysts with MCDM-capacities are available, this elicitation could be well facilitated. Since ORESTE ranks all alternatives on an ordinal scale across criteria, some information may be considered “lost” as the information utilized is weaker than the original cardinal nature of some criteria provided allow for. MELCHIOR also offers many of the same properties. Interpretation of threshold levels is more intuitive as they are defined on criteria, but this process can be rather time-consuming if the set of criteria is large. Data processing is also more complex than in ORESTE.

Finally, we consider a decision context, either in design or at the point of investment, where owners are involved and design descriptions are complete. This turns our attention to PROMETHEE I and II, which combine ordinal ranking of alternatives with cardinal ranking of criteria. In addition to being intuitive and moderately time-consuming, decision support software offering graphical illustrations of alternatives and criteria in the GAIA plane helps explore the decision structure further. Projection by means of principal component analysis helps preserve as much information as possible in this illustration where the similarity of criteria, their discriminant power and differences between alternatives relative to criteria may be interpreted visually (Brans and Mareschal 2005). This feature is useful in exploring the problem and possible alternatives prior to making long-term economic and organizational commitments of the magnitude that ship acquisition entails. As PROMETHEE I and PROMETHEE II primarily differ with regard to what preference structure is obtained, we recommend evaluating whether the incomparability relation is of interest in the decision process. This concept may be

somewhat difficult to grasp at first hand for decision makers, and if so, PROMETHEE II may be used.

4 Summary and conclusion

Our review has compared 12 MCDM methods with regard to their technical and practical properties and further evaluated their applicability in multi-criteria appraisals in ship acquisition. Results show that several methods not applied before offer promising properties to common decision contexts occurring throughout the ship acquisition process. Our discussion has illuminated some typical decision contexts and suggested appropriate methods based on the characteristics of the problem environment and properties of methods.

We further summarize our reasoning in Fig. 1 to provide a more generic method selection procedure applicable to all decision contexts for sustainability appraisal in ship acquisition. This procedure may not be considered exhaustive, as decision contexts might be highly diverse.

If we compare our results to previous applications of MCDM methods for ship design appraisals, we see that TOPSIS is the only method both previously applied and currently recommended. The widely recognized and applied method AHP is for instance not recommended. This deviance stems from the fact that it is penalized for its cumbersome preference modeling requirements. Since TOPSIS is equally transparent and less time-consuming, it should be considered a good replacement in any situation AHP has previously been applied. This review has furthermore not rewarded AHP for its preference elicitation technique, which allows deriving weights and scoring alternatives by the assistance of verbal scales. In these

situations, we refer to methods that keep intact this ordinal nature of information, such as ORESTE or even MELCHIOR. We also acknowledge that MAVT may map ordinal information onto a cardinal scale in a rather elegant, though time-consuming manner. This actually makes MAVT suitable in both situations where alternatives are ranked on mixed scales or entirely on cardinal scales. Our review shows that for the first situation, PROMETHEE is considered a better and less time-consuming method (unless full compensation is explicitly desired). In the second situation, the simple methods TOPSIS and UTA have the same technical properties as MAVT. In this data situation, we also recommend ELECTRE III if full compensation is not allowed.

Our assessment does not find any of the elementary methods to be suitable for appraisals in ship acquisition. This is mainly due to their tendency to produce a final order based on only one or a very limited amount of criteria. Considering the complexity and diversity of criteria and the magnitude of commitments made in an acquisition, these approaches are considered too simplistic.

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