Application of systems engineering to structuring acquisition decisions for marine emission reduction technologies

Problem structuring for marine emission reduction technologies

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Abstract

Due to increasingly strict environmental regulation of marine transportation, vessel operators and other stakeholders are required to evaluate feasible compliance measures in the face of multiple criteria and with attention to uncertainties and risks. Several methods and models within operations research have been applied to explore such decision contexts, but little is reported on the problem structure itself and the key values, concerns and uncertainties that apply to them. The objective of the paper is to present a problem structure for acquisition of marine emission reduction technologies in the Norwegian ferry fleet drawing on methods from decision science and systems engineering. To attain this objective we utilize the SPADE methodology, which details five problem-solving activities covering stakeholders, problem formulation, alternatives, decisions and continuous evaluation. Each activity is informed by data collected through stakeholder interviews and literature analysis to establish an initial representation of acquisition decision issues. To keep a consistent and traceable problem structure, we provide a stakeholder diagram, value network, systemigram and decision hierarchy centered around stakeholders and their values. These models may serve to inform decision-makers in the development and appraisal of emission reduction technologies and strategies. The article demonstrates the application of systems engineering as a problem-structuring framework for complex, multi-dimensional marine technology acquisition decisions.

Keywords: decision analysis, SPADE, sustainability appraisal

1. Introduction

Air emissions from marine transportation pose a significant threat to global and regional environmental quality and human health. Of particular concern are emissions of greenhouse gases (GHGs), sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) that contribute to harmful effects such as climate change, acidification, eutrophication and ground-level ozone formation [1-6]. Meanwhile, waterborne movement of passengers and cargo is expected to increase in the decades to come in order to fulfill the rapidly growing demand for marine-based transportation services [7]. Mitigating adverse environmental effects through emission reductions has therefore become a priority area for the maritime community.

The International Maritime Organization (IMO) and the European Union (EU) have set ambitious reduction targets for air emissions. The International Convention for the Prevention of Pollution from Ships (MAPROL 73/78) Annex VI was introduced in 2005 with NO_x-emission standards for marine engines. This has since been revised to cover more ambitious emission levels, fuel quality requirements, introduction of global and regional emission control areas (ECAs) and mandatory measures to reduce GHG emissions [8]. IMO also recently adopted an initial strategy for GHG emission reductions, with an ambition of 50 percent reduction of annual GHG emissions by 2050 from the reference year 2008 [9]. Complimentary regulation such as the EU directive on the sulfur content in marine fuels [10], and regulation on monitoring, reporting and verification (MRV) of CO_2-emissions from maritime transportation [11] further introduce more ambitious targets and measures for EU member states.

In Norway, significant attention has been dedicated to technical and operational measures to reduce emissions in the ferry segment. Fleet renewal is overdue as the average vessel age approaches 24 years. The fleet is also the largest contributor of CO_2, SO_x, NO_x and PM emissions from domestic shipping [12]. Following up on its own political platform established in 2013 to promote deployment of alternative marine fuels in the maritime industry [13], the government instructed the Norwegian Public Road Administration (NPRA) to specify requirements for zero- and low-emission technologies on tenders for state road services whenever technology warrants such requirements. The same principle is currently also being explored for ferry concessions on county municipal road connections [14]. Concurrently, financial instruments have been introduced and are continuously being explored to incentivize installation of abatement technologies, alternative fuels and improved energy systems [15].

As a response to this, emission reduction technologies have been deployed to reduce operational emissions from ferries. As of March 2016, there were 25 LNG-fueled car and passenger ferries in operation worldwide, whereof 21 were in operation in Norway [16]. In 2015, the first fully electrically powered ferry “Ampere” was put in operation, with more to come on the same connection in 2018. This solution may become relevant for several ferry connections in Norway as between 60-70% of Norway’s 125 crossings may accommodate battery electric ferry operation [17, 18]. The technical and financial feasibility of biofuels has also been investigated [19, 20] and the first three ferries operating on biofuels alone were put in operation in 2016. The first bio-fueled hybrid electric plug-in ferry was also launched in 2017 [21]. Lastly, the Norwegian HYBRIDship project aims to launch the first ferry operating on hydrogen in combination with battery for propulsion within 2020 [22].

Ship owners bidding for public road ferry connections are currently faced with selection decisions, having to evaluate various concepts utilizing new power systems, fuels and abatement technologies to meet emission targets. The performance appraisal and risk evaluation of alternative courses of action and further propagation of this information in associated decisions should be done in a systematic manner. Several authors have approached marine emission reduction technology selection using multi-criteria decision aid to help distinguish important values, feasible alternatives and possible solutions to various decision problems. Schinas and Stefanakos [23] explored technology selection for MARPOL Annex VI compliance from the perspective of operators utilizing the analytic network process. MARPOL compliance is also analyzed in [24] where options for SO_x and NO_x emission reductions are evaluated. As uncertainty is a key feature of these decision contexts, several contributions have also addressed this. In [25] a fuzzy multi-criteria decision-making method is devised for shipping emission reduction addressing technological, economic, environmental and socio-political objectives. In [26], this approach is extended to accommodate situations where multiple decision-makers with potentially conflicting opinions and preferences need to be consulted. This is also addressed in [27] where alternative energy carriers for shipping are evaluated across a wide range of sustainability criteria.

While the key contribution of these works are the computational approaches offered, little is reported on the underlying values and concerns that underpin the resulting problem frames. Naturally, the approach by which they are produced are also omitted. In order to compliment this body of literature and facilitate future decision-analytical interventions, this article elaborates on both the process and outputs from problem structuring of these decision contexts. We present a problem structure based on systems engineering to develop an unbiased approach for emission reduction technology appraisals in acquisitions of car- and passenger ferries for Norwegian public road connections. The SPADE methodology is applied to decision analytical problem structuring as briefly described in section 2. The problem structuring activities are applied in section 3, which also reports on literature perspectives and a synopsis of the interviews with 16 industry stakeholders. The framework and application is discussed in section 4. The resulting model aims to assist decision-makers and other stakeholders as they critically appraise alternative technologies and strategies in tendering. The general approach may also be further adapted to evaluate other emerging technologies than those explored here.

2. Deriving a problem-structuring framework

Decision analysis is a process whereby formal models and tools based on utility and probability theory are utilized to improve decision-making [28]. The process involves problem structuring, problem analysis and problem resolution [29]. Problem structuring may be considered a *description problematique*, where the problem and potential courses of action are defined with sufficient detail to develop numerical models representing the problem at hand [30]. In order to arrive at a detailed analysis structure, the analyst must come to grips with stakeholders, their problems, values, constraints, uncertainties and key issues [31].

For this purpose, we will utilize a generic systems engineering approach. According to the International Council on Systems Engineering (INCOSE), systems engineering may be defined as "an interdisciplinary approach and means to enable the realization of successful systems" [32]. Systems engineering is both a discipline and a process: the discipline of seeing the whole and interactions between different parts, as well as the process of reaching a solution that is iteratively evaluated in relation to the needs and requirements of stakeholders [33]. Several systems engineering problem-solving models have been devised, such as [34, 35].

The SPADE methodology was derived from the essential systems engineering processes, which include in all instances the verification of results and the validation of assumptions [34]. In structuring acquisition decision problems concerning marine emission reduction technologies, we utilize SPADE originally developed as a "… streamlined methodology that is visually representative of the intrinsically iterative nature of systems engineering and at the same time free of jargon" [36]. Due to its simplicity it has been used to support problem-solving in multiple domains, such as product design [37] and organization design [38].

Although SPADE may be entered and exited at any activity, it is advised to initiate the cycle by identifying *stakeholders*, as shown in Figure 1. Stakeholders are individuals or groups that may have interests in a corporation and its activities [39]. When identifying stakeholders in a decision context, we aim to target those who may influence or be influenced by the outcome of the selected course(s) of action. Stakeholders may be classified according to their attributes relative to the decision at hand, such as their influence [40] or others [see 41]. In a decision-analytical context it is useful to distinguish stakeholders based on their involvement in the decision to be made, i.e. the individuals or groups whose values, concerns and expertise should be consulted to arrive at feasible and preferable courses of action. The typology developed by Clarkson [39] offers a simple distinction between *primary* and *secondary* stakeholders. In this study, we define a primary stakeholder as any individual or group that directly may influence the course of action due to their involvement in the acquisition process. Secondary stakeholders may influence the decision to be made through advocating their values and preferences indirectly.

Once primary stakeholders are identified, we need to elicit their needs and *formulate a problem* statement by distinguishing decision problems, values and uncertainties. Values encompass the objectives of stakeholders and the criteria that may be used to measure their attainment. A value hierarchy or network of objectives and criteria helps distinguish key performance metrics. In addition, constraints must be identified to properly qualify feasible alternatives.

Identifying uncertainties is also essential to understanding stakeholder problems. In a multi-criteria decision context, uncertainty implies the lack of information to describe, prescribe or predict a system, its behavior or other characteristics deterministically and numerically [42]. This uncertainty may be distinguished based on its *nature* depending on whether it is due to intrinsic variability in the system (aleatoric), lack of knowledge (epistemic) or competing interpretations (ambiguity) [43]. In exploring uncertainties related to emission reduction technologies, we will focus on the origins, pathways and modeling approaches to deal with various forms of uncertainties.

Identifying and evaluating an initial set of *alternatives* where feasible courses of action are shortlisted and described is the third activity. Keeney [44] suggests several approaches to identify and eliminate alternatives based on values, such as beginning with alternatives that satisfy the defined objectives and criteria. One such strategy is to identify alternatives that are expected to perform well along one or several fundamental objectives. In addition, alternatives that might influence means objectives, and thereby indirectly fundamental objectives, should also be considered. Note that briefly considering 'improbable alternatives' often leads to innovation [45].

Once a set of alternatives are defined, it is possible to construct multi-criteria models that support *decisions*. Any calculus may be applied in an effort to discriminate between candidate alternatives as long as the available data is sufficient to accommodate the selected approach. However, the analyst must be aware of the technical and practical properties associated with various modeling approaches, as elaborated in [46, 47].

Evaluating the information developed in the outer-ring activities should be done continuously to ensure that the problem structure adequately captures all critical elements to be addressed in the subsequent modeling and analysis.

Once an initial SPADE cycle has been completed, additional iterations are necessary to refine the problem structure and initiate the problem analysis phase using formal model representations.

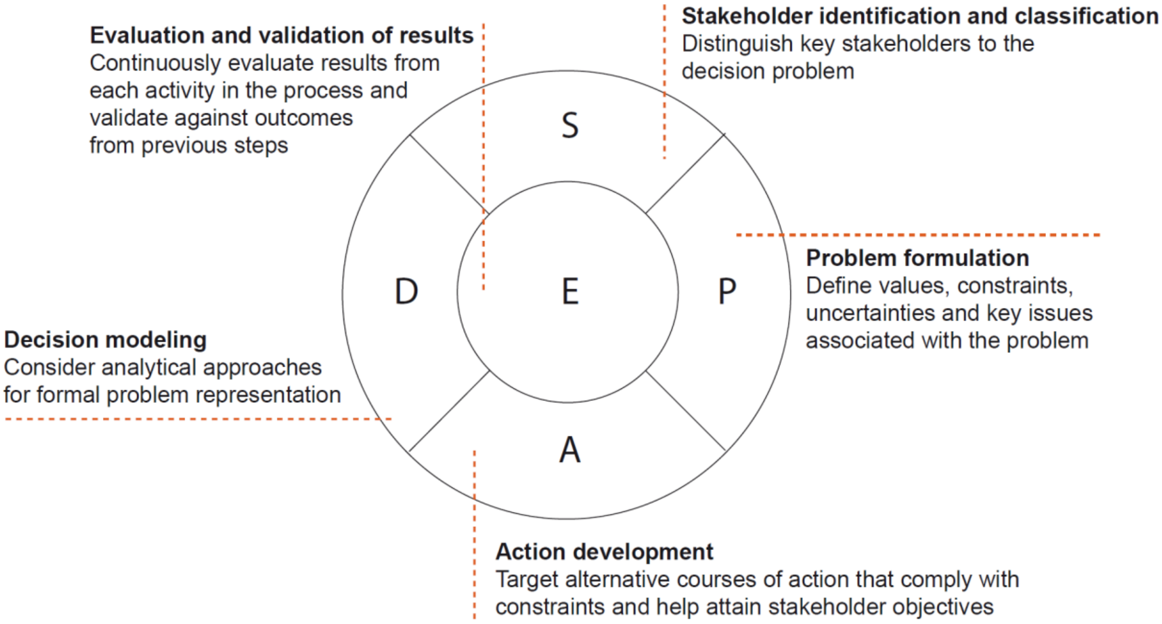

Figure 1: SPADE methodology used for problem structuring

3. Applying SPADE

3.1 Stakeholder identification and classification

In order to identify and classify stakeholders, it is necessary to define the decision context in question. Ship acquisition is the process of introducing new tonnage or converting existing tonnage in a ship company [48]. During this process the requirements, functions and architecture of the ship is defined alongside other managerial activities to support its physical realization. New ship development may be viewed as a decision-making process where multiple stakeholders contribute to inform, influence and ultimately make decisions pertaining to the ship and its systems [49]. Figure 2 shows a classification of stakeholders in the acquisition decision-making context based on level of involvement in the acquisition process.

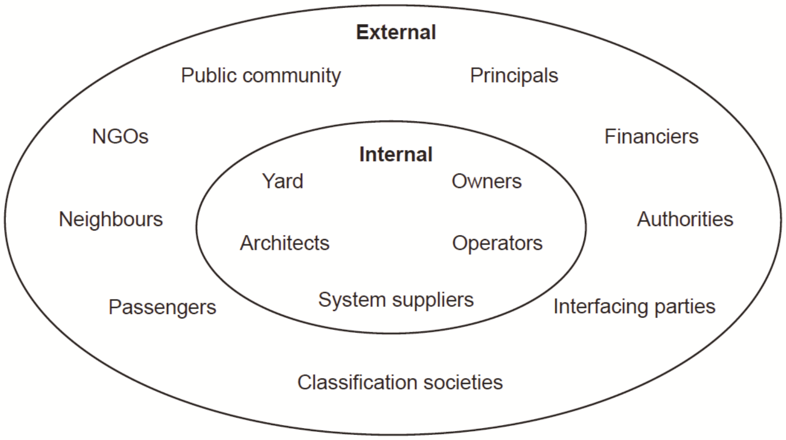

Figure 2: Stakeholder diagram distinguishing internal and external stakeholders to the acquisition decision-making context

We distinguish directly involved stakeholders as those whose knowledge, expertise and judgement is consulted during acquisition decision-making. These are the industrial partners dealing with managerial, technical and project activities of the acquisition process, found at the core of the figure. From this grouping, we have interviewed 16 stakeholders to inform the problem structure. Table 1 details positions of the interviewees in the study. Indirect stakeholders, such as principals, regulators, financiers, passengers and the like may impose requirements that strongly influence the final solution and physical embodiment of the ship, but are not considered direct as they do not have direct decision-making roles in the acquisition process.

Table 1: Stakeholders interviewed in the study

Department	Role	Ship owner / operator	Supplier	Yard
Management	Chief executive officer	✓		✓
	Chief financial officer			✓
	Chief technology officer	✓		
Technical	Technical director	✓ ✓	✓	✓
	Design manager			✓
	Production manager			✓
	Engineering manager		✓	✓
Project & sales	Project manager	✓		✓
	Sales director		✓	✓

3.2 Problem formulation

Decision problems

We identify three nested decision problems with regard to emission-reduction technology acquisitions based on the interviews in this study. These encompass the development, appraisal and selection of

i) technology solution concepts
ii) competitive tenders
iii) long-term technology strategies

In order to evaluate and further select preferable technologies and strategies, the operator must be able to discern those whose benefits and costs are balanced in an acceptable manner. In appraising *technology solution concepts*, key objectives and criteria for vessel performance must be established to identify and evaluate utilities associated with alternative courses of action. Operators furthermore have to tune contract price and technology ambition level to develop *competitive tenders* they are able to conform to during the contract period. This also requires attention to potential offers competitors might submit as well as any scoring system the principal may use. Finally, operators may benefit from developing *long-term technology strategies* to properly build capabilities and allocate resources to the right technologies at the right time.

Decision values – objectives and criteria

Objectives are goals to be attained by stakeholders of primary interest relative to the decision at hand. Figure 3 shows a value network for marine emission reduction technology selection developed from stakeholder interviews and literature. The core of the model shows high-level objectives organized according to economic, environmental and social performance, while lower level nodes illustrate criteria to help support attainment of these objectives. This list is not exhaustive and criteria are not exclusive, but the model is useful to understand some key values underpinning decision-making in ship and emission reduction technology acquisition processes.

Performance values for alternative technologies are subject to both epistemic and aleatoric uncertainty as i) there is little historical data to rely on and ii) conditions outside the control of decision-makers may change over a contract or vessel lifecycle which might also impact the long-term outcome of the decisions made [50]. This uncertainty permeates all decision problems listed above, and should be explicitly accounted for. Although each of these challenges warrant separate *formal* decision-model representations, we will view them as embedded from a *problem structure* modeling perspective.

Economic performance is critical to ensure competitive bids and profitability throughout the investment lifecycle for ferry operators. A range of criteria might be associated to this objective, depending on the specific properties of the contract at hand. Relevant examples may be found in [51-58]. *Environmental performance* may be linked to upstream as well as operational impacts and as has been seen for studies of alternative fuels, a life cycle perspective is necessary to avoid problem-shifting [1-3, 6]. Environmental performance may also be associated with regulatory and contractual compliance as well as social acceptance, so the analyst must detangle unique environmental concerns from other objectives in modeling environmental values. Additional environmental criteria may be found in [54, 55, 58-60]. *Social performance* may encompass physical hazards and discomfort of crew and passengers due to conditions onboard the ferry, as exemplified in [61]. Social performance from a wider perspective may also encompass conformance to expectations from society at large, as seen in [27].

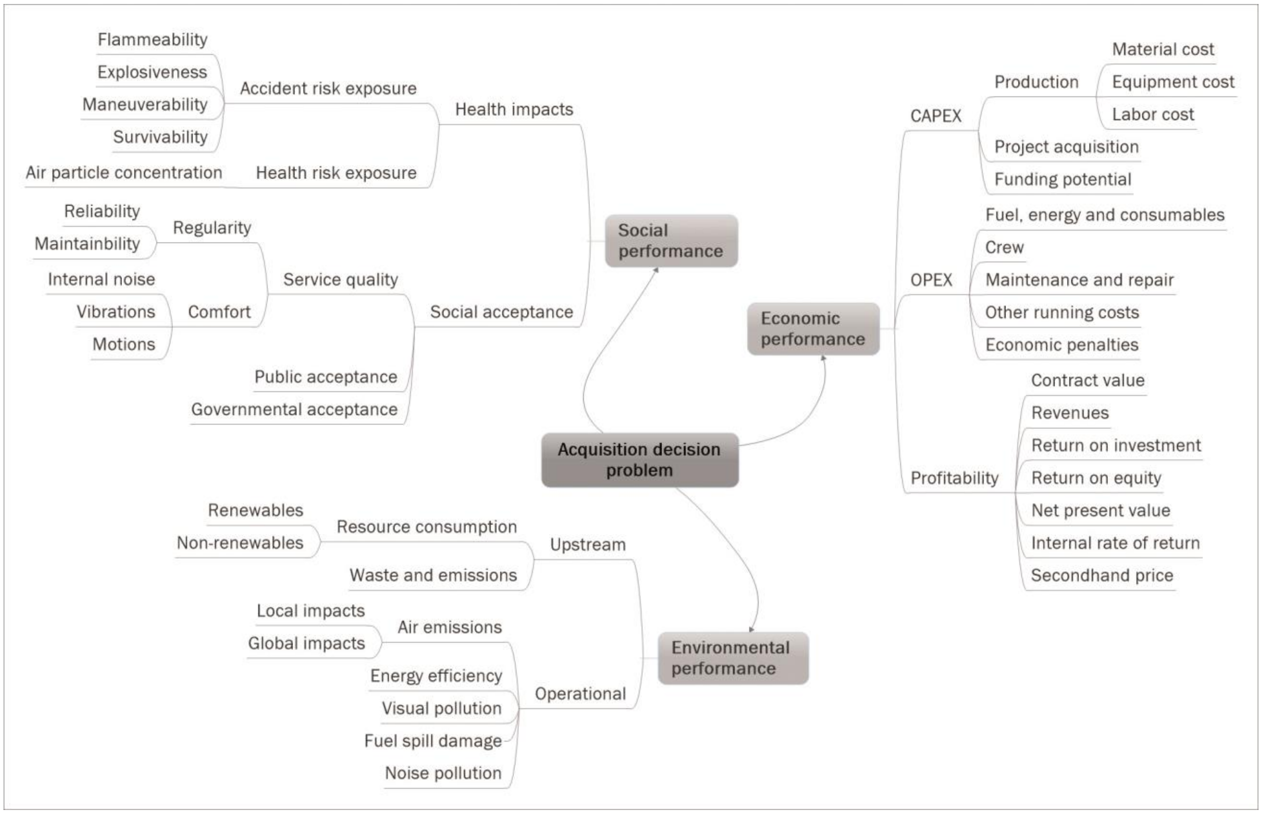

Figure 3: Value network for marine emission reduction acquisitions based on interviewee statements and literature

Decision uncertainties

Identifying key concerns of decision-makers is necessary to distinguish elements of uncertainty and risk in the decision context. Although uncertainties may manifest themselves on many levels of the model complex, we focus on those factors outside the control of decision-makers that may change after the decision has been made and consequently alter the expected outcome of the selected course of action. For this purpose, we utilize a *systemigram* to capture the origins, pathways and ultimately impact on values from the perspective of decision-makers. The diagram is an illustration of significant elements and interrelationships within a system of interest [62]. Figure 4 shows a systemigram developed from stakeholder interviews, and displays risk factors originating from the operating environment during a ferry concession period as well as the pathways to a potential impact on environmental, social and economic performance. The illustration is not exhaustive, but includes critical parameters and sources of concern to ferry operators during evaluation of emission reduction technologies. In elaborating on the diagram, we resort to Blanchard's [33] key trends in the external environment that must be addressed during system development and acquisition.

Firstly, requirements constantly change over the system lifecycle due to dynamic conditions worldwide [33]. For emission reduction technologies, regulatory changes might not only alter the comparative performance of the set of alternatives evaluated at the point of investment, but also compromise the potential to attain future contracts as exemplified in [50]. For instance, introduction of new ECAs or stricter emission limits could lead to loss of contracts in the investment period. The same applies to requirements specifying permissible fuels, technologies or emission limits for a given contract. As this has been an emerging trend in Norway [see 13, 14, 15], operators must carefully evaluate solutions that can retain value throughout the contract lifecycle.

Secondly, overall lifecycle costs tend to increase which calls for more attention to costs of system operation and support [33]. For emission reduction technologies, energy costs is an important variable in the total cost analysis. They are also difficult to estimate as fuels are related to agricultural, oil and other energy markets which generates a wide bandwidth of forecasts for fuel production cost [63-65]. Subsidies to support specific energy carriers and technologies will also directly influence energy price fluctuations. Further distribution and bunkering capabilities depends on global demand [60] which is linked to both technology and market development.

A third observation is that system lifecycles tend to extend while technology life cycles become shorter [33]. While the investment horizon for a vessel spans several decades, installed emission reduction technologies may have much shorter lifecycles. The extent to which development and support for technologies is sustained over time influence availability of spare parts as well as access to repair and maintenance services. For this reason, technology maturity is considered an important parameter in evaluating emerging energy technologies [see 26, 66] This might affect both technical reliability and secondhand value of the ferry. Regularity is critical for operators as their license to operate and ability to gain new contracts depends partly on their reputation and consistency. Failure to meet schedule regularity may also induce financial penalties for the operator. The same applies to violation of contractual air emission limits [see 67].

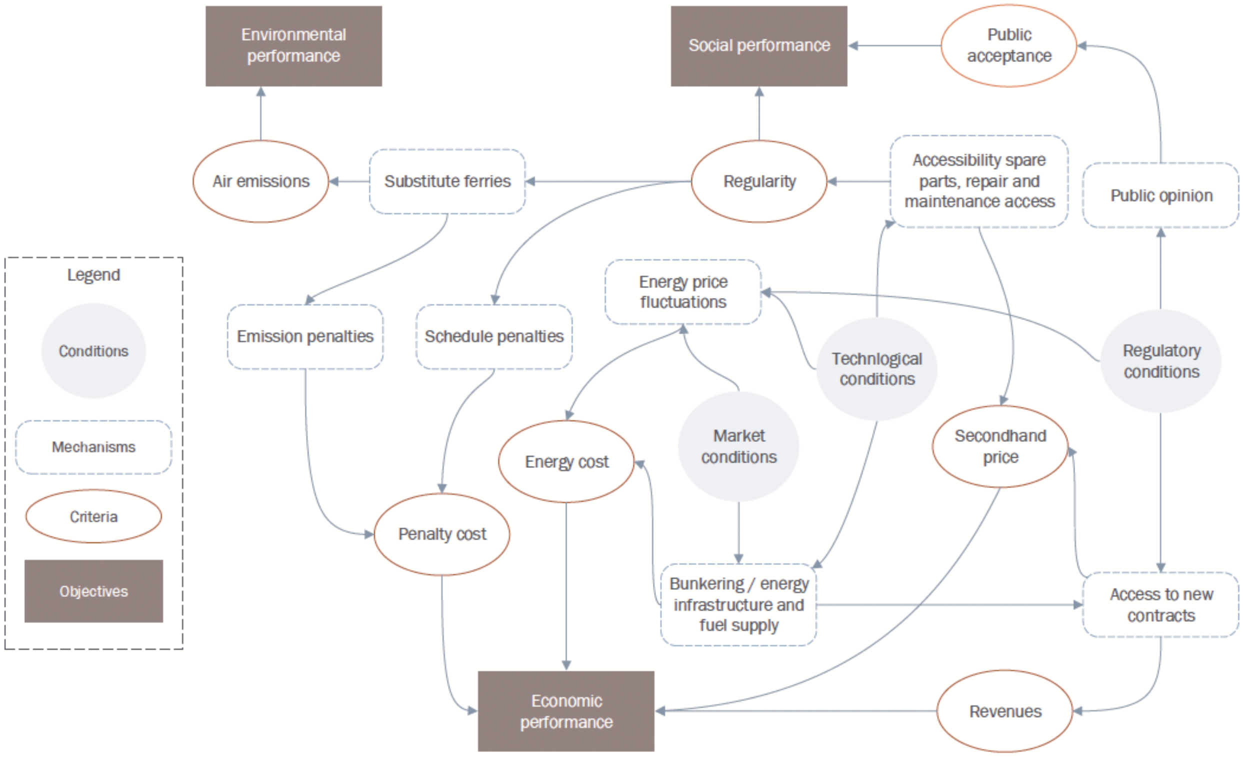

Figure 4: Systemigram of uncertainties related to objectives in marine emission reduction technology selection

3.3 Action development

For technology selection problems, specific regulatory, tender, and class requirements relevant for the connection and contract at hand should be used to identify permissible solutions. Even within these boundaries, the combination of power systems, fuels and abatement technologies could be quite extensive so decision-makers and analysts should focus on key stakeholder values and constraints to identify promising configurations. Figure 5 shows an example of a decision hierarchy to encapsulate pertinent information from the first three activities relative to concept selection. This representation along with others derived up to this point should be used to evaluate adequate decision support techniques and methods.

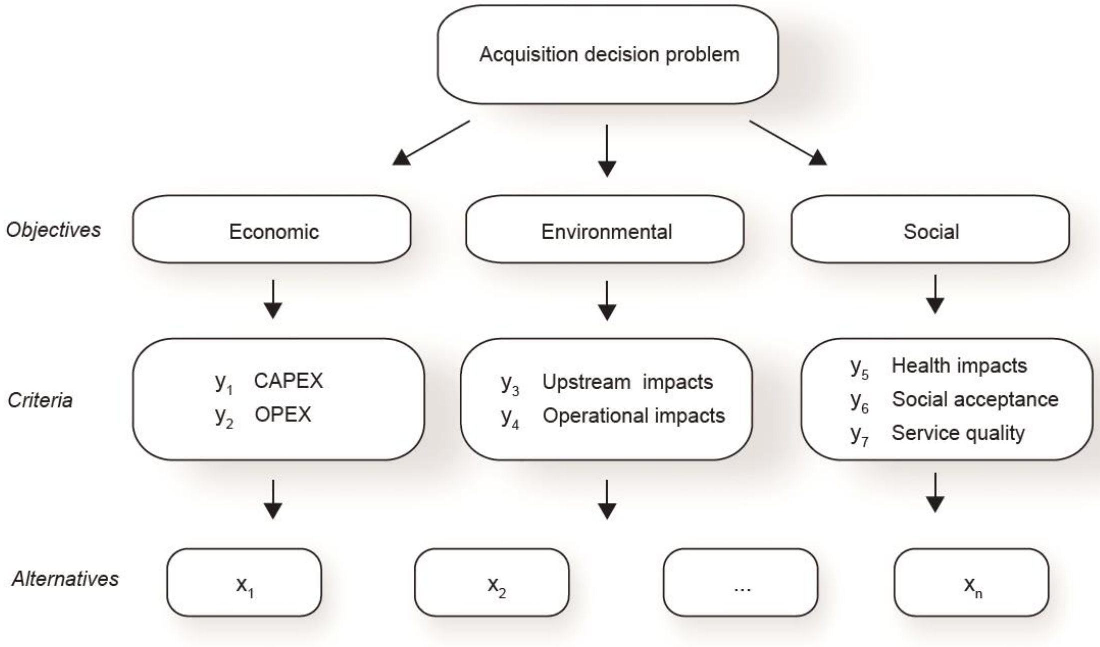

Figure 5: Decision hierarchy connecting high-level values and alternatives for technology selection problems

The generation or synthesis of alternatives depend on the specific decision problem to be resolved. Whereas technology selection problems generate alternatives based on requirements and further the configuration of existing or attainable solutions, higher-level strategic decision problems may be viewed as less constrained depending on the planning horizon. Other criteria would be relevant to include should the decision problem be selection of tender or technology strategies. This would generate other courses of action.

3.4 Decision modeling

Having identified key elements of the problem structure, analysts may move on to explore feasible methods, models and techniques to further analyze the problem at hand. For emission reduction technology selection, we consider the general problem formulation $Max\ \{y_1(x), \dots, y_m(x) | x \in X\}$ where X is a finite set of n design alternatives and F is a family of m criteria to be maximized. A wide range of utility aggregation methods could help explore such decision-problems depending on their technical and practical properties for dealing with data, tradeoffs as well as available resources in the decision-context. We will not elaborate on this here, but refer to considerations and suggestions for methods suitable in ship acquisition in [68].

As uncertainty is an important aspect of emission reduction technology acquisition decisions, techniques to explore variability in input parameters and their effect on output parameters should be used along with the selected utility aggregation methods. We may largely divide this into approaches based on probabilities, scenarios and fuzzy sets and numbers [see 69].

Probabilistic models treat uncertain inputs as random variables with associated probability distribution functions. This approach is useful to deal with both aleatoric and epistemic uncertainties. In this category we find multi-attribute utility theory (MAUT), stochastic models and belief functions [69]. We may also include stochastic sensitivity analysis approaches as means to explore uncertainties by evaluating how variability in performance values and criteria weights affect the ranking of alternatives. The systemigram may be utilized to target key uncertainty parameters to be included in such models as well as the assumptions and data necessary to quantify them. The systemigram could also be further developed, refined and specified to a Bayesian belief network, facilitating formal modeling of the probabilistic relationships between perturbations and objectives [70].

Scenario approaches are useful in situations where uncertainties are complex and interrelated to the point where other techniques become insufficient or incomprehensible. In scenario analysis, a smaller set of future narratives are developed wherein alternative courses of actions are evaluated [71]. Further global aggregation of scenario evaluations is also possible, e.g. through evaluating performance stability across scenarios [69, 71]. Such approaches could be useful in developing tendering strategies to assess potential courses of action in bidding scenarios. It may also serve as means to identify emission reduction technology strategies in the longer term to target a subset of technologies for which organizational capabilities and resources should be directed. Again, the systemigram may be used to inspire scenario generation within specific decision problems to be resolved.

Finally, fuzzy modeling may be used deal with information that is unquantifiable, incomplete or unobtainable. Fuzzy modeling permits (partial) membership of objects to multiple sets, in contrast to crisp modeling where this membership is binary. This is particularly useful for situations where precise boundaries for a set is difficult to define [69], such as the transition between values on a criteria measurement scale or preference statements. This form of uncertainty modeling may be utilized if criteria and uncertainties are best expressed in linguistic form. When quantitative data is inaccessible, expert judgement may still be utilized. This has been widely explored in ship design appraisals with examples found in [25-27, 46, 58, 59, 61, 72]

3.5 Continuous evaluation and validation

Checkland makes the point with soft-systems methodology about the importance of iteration and reflection with addressing problems with a human dimension [73]. The activities above have been evaluated continuously and iteratively in and between each step through coding, comparing and cross-validating results from interviews. Additional evaluation and validation is done by comparing these results with literature, which also complements and supports knowledge derived in each activity. In a decision analysis intervention, the analyst should reiterate activities until there is convergence or otherwise acceptable agreement about the results.

4 Reflections and conclusion

In this article, we have derived a problem structure to support marine emission technology acquisition in the Norwegian ferry fleet using systems engineering. By conducting a first iteration of the SPADE cycle informed by interviews and literature, we have identified three nested decision problems and further elaborated on values, concerns and modeling approaches that may lead to problem resolution. Further iterations of the SPADE cycle must be conducted to arrive at specific, quantitative problem representations. For each activity and cycle, analysts must validate assumptions and the importance of extracted information to ensure that a useful problem structure is developed and that the results are defensible and useful to the final decision-maker.

The article demonstrates the application of systems engineering as a problem-structuring framework for complex, multi-dimensional marine technology acquisition decisions. The application of SPADE for problem structuring has been model-based to help systematize, visualize and link key elements of the problem in a consistent and traceable manner. The stakeholder diagram, value network, systemigram and decision hierarchy allows the analyst to view the problem from different perspectives using values to map and navigate between these representations. The specific models may serve as a foundation in similar decision contexts to accelerate a systematic problem structuring process.

The suggested approach offers a sequence of steps to elicit, trace and model key components of a problem structure. As each decision-making context is unique, the exact intervention techniques need to be customized. For instance, eliciting values could be done in a number of different ways depending on the case to be explored. The case study offered was based on individual interviews of the selected stakeholders. While this allows each respondent to contemplate key problem characteristics based on their expertise and opinions, a group stakeholder approach would enhance both problem dialogue and refinement. The SPADE-based methodology offered here is not intended to provide a recipe for problem structuring elicitation. For this, we encourage analysts to consult techniques suitable to the case at hand.

Another important necessity not constrained in our methodology is the combination and negotiation of conflicting perspectives and objectives of individuals and groups of stakeholders. For instance, as part of the problem structuring case study, it became evident that consulted stakeholders had differing opinions on the merits of alternative decisions relative to key objectives and criteria. In addition, it might be possible for stakeholders to disagree on which objectives and criteria to include in a decision model. This could become a critical issue in the subsequent formal modeling where both criteria and their quantitative values for alternative courses of action must be determined. Including methods to accommodate such situations would help extend its applicability to decision problems where stakeholder negotiation is essential.

Finally, the methodology as applied here does not address how to move from qualitative models to quantitative problem representations. In this gap, analysts must work to interpret the models and form sensible approaches to solving specific decision-problems. As pointed out, multiple techniques align with the diagrams the SPADE approach produces, but examples of bridging these are left for future work. Innovative applications that connects the soft and hard domains of operations research could improve both these activities and improve decision analytical problem interventions.

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