Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case

Sigurd S. Pettersen[a], Carl F. Rehn[a], Jose J. Garcia[a,c], Stein O. Erikstad[a], Per O. Brett[a,c], Bjørn E. Asbjørnslett[a], Adam M. Ross[b], Donna H. Rhodes[b]

[a] *Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway*
[b] *Systems Engineering Advancement Research Initiative (SEAri), Massachusetts Institute of Technology, Cambridge MA, USA*
[c] *Ulstein International AS, Ulsteinvik, Norway*

Abstract: *In this paper, we address difficulties in ill-structured ship design problems. We focus on issues related to evaluation of commercial system performance, involving perceptions of value, risk and time, to better understand trade-offs at the early design stages. Further, this paper presents a two-stakeholder offshore ship design problem. The Responsive Systems Comparison (RSC) method is applied to the case to untangle complexity, and to address how one can structure the problem of handling future contextual uncertainty to ensure value robustness. Focus is on alignment of business strategies of the two stakeholders with design decisions through exploration and evaluation of the design space. Uncertainties potentially jeopardizing the value propositions are explicitly considered using epoch-era analysis. The case study demonstrates the usefulness of the RSC method for structuring ill-structured design problems.*

Key words: Systems Design, Naval Architecture, Multi-Attribute Utility Theory (MAUT), Uncertainty, Complexity

1. Introduction

In a competitive maritime industry, there is a need to design, develop and deliver systems able to sustain value throughout a multi-decade lifetime. However, design of ocean engineering systems remains a difficult task, mainly due to the complexity and uncertainty governing these systems and their sociotechnical contexts. Even a clear definition of what is a better ship is ambiguous (Ulstein and Brett 2015) - it all depends. Understanding the relation between business strategies and corresponding marine design decisions, is not straight-forward, and the ship design task could be considered a wicked problem (Andrews 2012), or an ill-structured problem (Simon 1973). An ill-structured problem lacks a specified beginning and goal states, and the relation between these are unknown. More information must be gathered to enrich the problem definition and take informed decisions. A differentiation can hence be made between the problem of defining the problem to solve, and the problem of solving this problem. In this paper we stress the importance of understanding both of these aspects when it comes to design of complex systems.

The driving forces behind ocean engineering systems are often commercially oriented, introducing risks due to high market volatility. High oil prices and large ultra-deepwater discoveries have spurred the development of offshore oil and gas fields. Offshore construction vessels (OCVs) have taken part in this arena, particularly in the development of marginally profitable fields. More recently, the oil price collapse has had significant impact on this industry, rendering recent large multi-functional, *gold-plated* design solutions unprofitable. However, there are multiple other sources of contextual uncertainty that can affect the initial value propositions, and hence need to be considered in ship design, including technical, regulatory and operational factors. Risk and uncertainty are usually associated with negative consequences, but it is also important to acknowledge the upside opportunities uncertainty can introduce (McManus and Hastings 2006). Actively considering uncertainty in the design process can result in solutions that reduce downside risk and increase upside exposure, hence increasing the expected system performance over its lifetime. Design solutions that continue to provide value in a variety of contexts are known as *value robust* solutions, which can be achieved by either active or passive value robustness strategies, relating to whether the system actively can change in response to uncertainty or not. Active change involves implementation of changeability, characterized by the ability of a system to alter its form and function for the future. This involves system properties such as robustness, flexibility, agility, scalability and upgradeability, often also referred to as *ilities* (Fricke and Schulz 2005; Ross, Rhodes, and Hastings 2008; Niese and Singer 2014; Chalupnik, Wynn, and Clarkson 2013). The current situation in the offshore industry serves as a perfect example of the importance of focusing on value robustness and flexibility as key factors for success in a volatile industry.

Research on design of complex offshore engineering systems under uncertainty has recently gained momentum, as researchers have called for taking a broader view to engineering systems design processes (de Weck, Roos, and Magee 2011; Fet, Aspen, and Ellingsen 2013). With the current state of the offshore market, Erikstad and Rehn (2015) address the need for approaches for handling uncertainty in ship design. As a response to such calls, recent research within marine design focuses on novel methods, including methods from operations research and systems engineering (Garcia et al. 2016). Operations research methods include stochastic programming applied to issues in ship design like machinery selection under uncertainty (Balland et al. 2013; Patricksson and Erikstad 2016). Another recent approach uses Markov decision processes for evaluating ship design performance under uncertainty (Kana and Harrison 2017).

In this paper, we use the Responsive Systems Comparison (RSC) method to understand the decision making process in ship design. The RSC method is based on two systems engineering methods; i) multi-attribute tradespace exploration and ii) epoch-era analysis (Ross et al. 2009; Ross et al. 2008). Specific RSC applications include the design of an anchor handler tug and supply vessel (Gaspar et al. 2012), environmental regulation compliance in a lifecycle perspective (Gaspar et al. 2015), ship design for naval acquisition affordability (Schaffner, Ross, and Rhodes 2014), and a simplified offshore construction vessel (OCV) case (Keane, Brett, and Gaspar 2015).

The current paper explores the ship design process using the RSC method based on a real industrial case. It represents an analysis of the design of an offshore construction vessel for a joint venture of two stakeholders with different preferences. Following this, the most significant contribution are the theoretical insights to ill-structured design problems, and its formulation as a two-stage abduction process.

2. Evaluation of Commercial System Performance

Commercial engineering systems are typically selected on basis of economic decision criteria like net present value (NPV), or based on decision models allowing managerial flexibility, such as real options. A shortcoming of economic approaches is the number of assumptions one has to make. What are the future revenue streams? What are future market conditions? What discount rate should we choose? Microeconomic theory separates between risk averse, risk neutral and risk seeking behavior, normally assuming a risk averse attitude among stakeholders. This is not reflected in the use of NPV, or other economic measures of merit alone (Erichsen 1989; Benford 1970). Prospect theory (Kahneman and Tversky 1979) goes further, proposing that decision makers are loss aversive, and value losses as more negative than an equivalent win positively.

Value may vary over time, hence there are differences between the perceived value at the time of a decision and the value of that decision as actually experienced (Ross and Rhodes 2008). Investments in the commercial shipping industry are made in order to receive expected future benefits. Do we really know how to discount such perceived value? Empirical research in behavioral economics show that time inconsistent discount models, such as hyperbolic discounting, often account better for the preferences of stakeholders than the common assumption of time consistent discounting, as in financial NPV calculations (Frederick, Loewenstein, and O'Donoghue 2002). If we do not know which discounting model that best represents stakeholder perception of value, how can we then discount?

Taking future uncertainty into account in the cash flows by simulation based on historical data and extracting measures like value-at-risk, may help mitigate going into the *flaw of averages* (Savage 2009), but still does not take into account situations where a ship owner competes against other agents for different contracts, i.e. alternative, uncertain cash flows. Game theory may guide us some of the way, but it assumes that other agents act rationally. If agents are not rational, what is then the probability of winning a contract? What do the customers offering a contract actually care about when they select a specific bid among several? For complex systems facing uncertainty in their future operating context and in their perceived value to the stakeholder, economic decision criteria should be amended with other value attributes that better capture the things that stakeholders actually care about.

2.1. Profit as a subset of value

There are multiple examples of what may be perceived as value in commercial shipping today, in addition to profitability. Recently, there has been increased focus on environmentally friendliness. Several ship owners market themselves as "green". One may on the other hand, argue that for many profit-oriented players, green marketing is one way to increase profits further by making the product/service more attractive for customers and not because they care about the environment *per se*. However, it is difficult to reliably quantify the effect of this green marketing (Dahle and Kvalsvik 2016). It has also been proposed that the ultimate goal of some ship owners may be *prestige*, rather than pure profit. This may be signified by actions that drive costs, without really adding any "value" in economic terms. For example, 40% of platform supply vessels (PSVs) in the North Sea has been built with Ice Class, without really needing it (Garcia, Brandt, and Brett 2016). Again, it is possible to argue that ship owners believe this design choice will drive long-term profitability of their operation, as the vessel becomes more *versatile* with respect to operating region. These attitudes separate owners with a strong relation to the technical and operational aspects from ship owners with a purely commercial mind-set.

For commercial applications, in which profitability is the only objective, one may rephrase and say that profitability then is the (only) element of what the stakeholders perceive as value and success. Therefore, *value-focused thinking* (Keeney 1992) remains central, and value can hence be seen as a superset of profitability. If the preferred value attributes replicate profit-seeking stakeholders, this disaggregated approach nevertheless helps us untangle the complexity of the profit dynamics, which enables a better understanding of value trade-offs in various contextual settings.

2.2. Multi-attribute utility theory

Several methods for making decisions based on multiple value attributes exist (Ross et al. 2010; Papageorgiou, Eres, and Scanlan 2016). In this paper, we use multi-attribute utility theory, as presented by Keeney and Raiffa (1993). The attributes must adhere with the following criteria; i) *completeness*, representing all important aspects of decision making, ii) *operational*, possible to measure, iii) *decomposable*, so that they can be broken into parts for easier evaluation, iv) *non-redundant*, so that the same attributes are not counted twice, and v) *minimal*, so that the dimensionality of the problem is kept as small as possible. We here use an additive multi-attribute utility function, on the following form:

$$U(X) = \sum_{i=1}^{I} k_i U_i(X_i) \tag{1}$$

U here refers to the overall utility over all attributes. k_i are the weights for each attribute i, with an attribute value X_i. The value attributes selected for the model should be the things the stakeholders really care about, limited by short-term memory to seven, plus minus two (Miller 1956). Additional complexities can be handled by decomposition, making a value hierarchy adding structure to the utility function (Keeney 1992).

3. Methodology

The Responsive Systems Comparison (RSC) method is used in this paper. The RSC method was originally presented in Ross et al. (2009) and Ross, McManus, et al. (2008), but evolved to its current form in later papers, a recent reference being Schaffner et al. (2014). The stated purpose of the RSC method is "to take a designer or system analyst (RSC practitioner) through a step-by-step process of designing and evaluating dynamically relevant system concepts" (Ross et al. 2009). To fulfil this, the framework uses several other methods such as multi-attribute tradespace exploration (MATE) and epoch-era analysis (EEA). The RSC method is a generic approach to design decision making. A key heuristic for the method is to reduce the number of assumptions to a minimum. This makes it suited for combination with other tools and methods. Figure 1 illustrates the current layout of the RSC method, consisting of 9 steps clustered into 3 modules. Note that several feedback loops exist between the steps. As the understanding of the system increases, the stakeholders may perceive the system differently from their initial perspective.

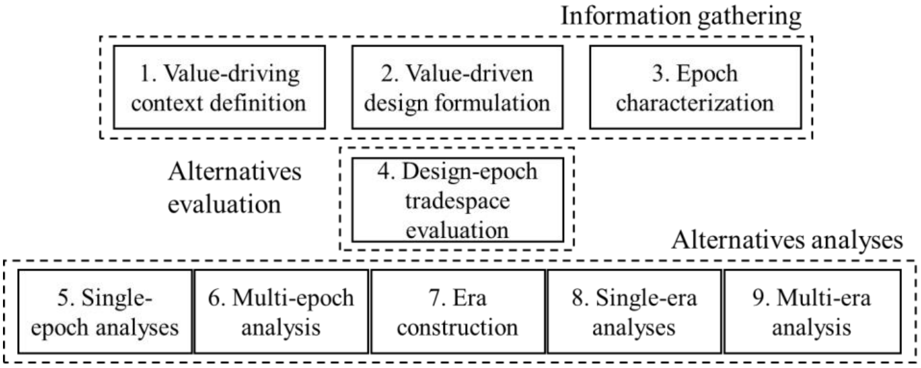


Figure 1: The Responsive System Comparison (RSC) method (adapted from Schaffner et al. (2014)).

The RSC method has been considered for implementation in this offshore case study due to its suitability to consider system design cases with changes in user needs and expectations, context and the system itself (Ross et al. 2009).

3.1. Information gathering

The initial steps of the RSC method collect the information used throughout the analysis. These steps should be supported by interviews with the decision-makers and other stakeholders in the project (Ross et al. 2009). First, in the "Value-driving context definition" the context of the system must be defined, in terms of how the context drives value. The "problem" in the environment is recast into an "opportunity", where an initial state can be turned into a desired state (Simon 1996). The outcome of the "Value-driving context definition" can be a value proposition. The value proposition will thus provide the link between the scope of the system design process and the business strategy of the stakeholders.

In the second step, "Value-driven design formulation", a set of value attributes are extracted from the value proposition. The attributes should be narrowed to the factors that stakeholders really care about. Having specified value attributes, the process of mapping from objectives and overall value statements to design descriptions can start. By abducting specific design instances and generalizing them into design variables that matter for system value, we map from the value space to the physical space driving costs (Ross, Rhodes, and Hastings 2008).

"Epoch characterization" is the final information gathering process where exogenous uncertainties are encapsulated within well-defined epoch variables. Every combination of epoch variables represents an epoch, a static short-run scenario. An epoch can be described as "a period of time for which the system has fixed context and fixed value expectations" (Ross and Rhodes 2008). Typically, epoch variables are technology or infrastructure changes, economic and market forces, policy and regulation, and resources and budgetary constraints.

3.2. Alternatives evaluation

The "Alternatives evaluation" defines the tradespace model upon which the designs are evaluated. The exact model which maps the connection between the value space, possibly via a performance space, to design and epoch spaces, is defined in this step. The modelling in this step relates to the causal mechanisms that were seen as "black box" in the information gathering. The aim of this evaluation process is to gain insight in how possible system architectures provide value, given important contextual uncertainties (Ross et al. 2009). The outcome of this stage are utility measures and costs for all design alternatives in all epochs. The required mapping between the value and design spaces is shown in Figure 2. In the figure, MAU refers to multi-attribute utility, while MAE refers to multi-attribute expense, a generalized cost representation.

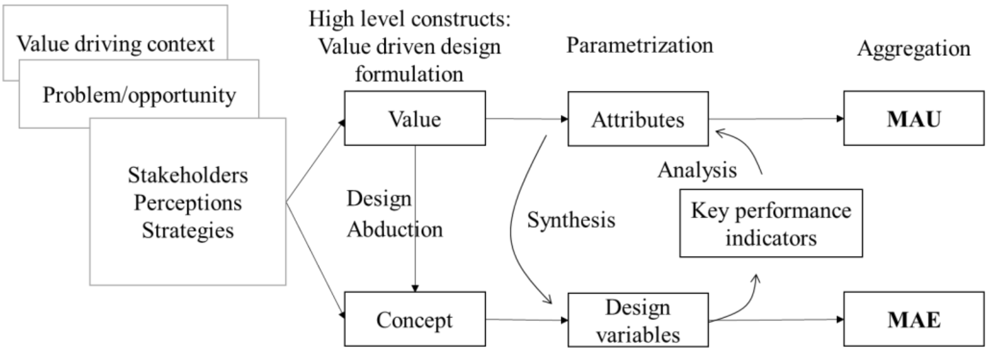


Figure 2: Relating value and design concept to the tradespace.

3.3. Alternatives analyses

“Alternatives analyses” consists of five steps concerned with producing metrics that let us compare and get insight of alternative designs in and across epochs and eras. In “Single-epoch analyses” tradespaces are explored with the Pareto efficient frontier of non-dominated solutions as the criteria of design goodness of fit (Keeney and Raiffa 1993). For the “Multi-epoch analysis”, Fitzgerald and Ross (2012) propose additional metrics to identify value robust designs across changing contexts and needs. These measures can be extended to consider active value robustness and changeability.

To be able to analyse design performance in a lifetime perspective, eras are constructed. Eras are scenarios representing the long run system context, consisting of sequences of epochs assembled along a timeline (Ross and Rhodes 2008). In accordance with microeconomics, the long run is signified by holding no factors constant (Varian, 2006). Era construction is an example of scenario planning, allowing for strategic planning for the medium to long-term, as they seek to answer from the stakeholder’s perspectives “What can conceivably happen?” and “What would happen if…?” (Lindgren and Bandhold 2003). Eras thus enable assessment of the lifecycle performance of various designs in different contextual operating conditions.

“Single-era analyses” and “Multi-era analysis” are the two final steps of the RSC method. In the “Single-era analyses” time-dependent effects of unfolding eras are investigated for interesting design alternatives (Schaffner, Ross, and Rhodes 2014). “Multi-era analysis” explores dynamic system properties by identification of patterns across multiple eras, exploring design-strategy pairs, to understand how we for example can implement changeability to ensure value robustness.

4. Case study

The case study centres on the design of an offshore construction vessel, following the RSC method. The information gathering phase was informed by interviews with decision-makers from a real ship design project, and a retrospective Accelerated Business Development (ABD) process. This process is described by Brett et al. (2006).

4.1. Step 1: Value-driving context definition

The business opportunity for a new offshore ship design emerges from a set of trends in the oil and gas industry. Increasing world population and economic growth is believed to lead to an increased demand for energy. While there are alternatives to oil and gas emerging, both due to the depletion of most easy-access resources and the threat of global warming, the offshore oil and gas markets are expected to be strong for a long time despite a characteristic high short-term volatility.

Two shipping companies form a joint venture to introduce novel offshore technologies to a new operational region. Their strategies and goals are different, while one provides a wide range of services within the Gulf of Mexico, the other is a world-wide operator with principal focus on light well intervention (LWI) services. The involvement of more than one key stakeholder increases intrinsically the difficulty of selecting a single design to build (Fitzgerald and Ross 2013). The merger of shared and competing goals into one system concept, calls for a collaborative engineering approach combining coordination, cooperation and collaboration between stakeholders. The intention of this approach is to attain more together than what would be possible apart. While the ship design project that results from the business opportunity is to be done by a joint venture between the two stakeholders, the preferences of each ship owner should be kept separate. This strategy makes it easier to understand which trade-offs and compromises are made through the decision-making process. For this reason, we keep the value propositions of each main stakeholder separate. The outcome of Step 1 is thus the two following value propositions:

> **Stakeholder 1:** *"Being the first subsea contractor in the Gulf of Mexico by building and operating a fleet of profitable OCVs."*
>
> **Stakeholder 2:** *"Being the leading provider of high quality solutions for the offshore oil industry, by adding advanced, environmentally friendly and profitable OCVs to the existing fleet."*

4.2. Step 2: Value-driven design formulation

Once the value-driving context has been defined, which helps us outline the problem to be solved, we can start formulating the value-driven design. The value attributes are derived from the value propositions, and therefore align with the business opportunity that was identified in Step 1. Interviews with key decision makers are an important ingredient when collecting the appropriate statements of needs, and expressing them in terms of objectives (Ross et al. 2009). We separate between monetary and non-monetary aspects of value, which are assessed independently in the model, due to their temporal differences. Profitability is incorporated indirectly in the model, through cost minimization for feasible designs for a mission with a given rate, and is considered a value attribute at the era level. See Chapter 4.4 and Chapter 5.2 for further information and discussions on profitability. The non-monetary value attributes of the two key decision-makers are at the epoch level, and are summarized in Table 1. The associated single-attribute utility functions for the non-monetary value attributes of each stakeholder are given in Figure 3.

Table 1: Stakeholder value attributes.

Stakeholder	Value att.	Level	Units	Worst	Best	Description
1	Originality	Epoch	[-]	0	10	First mover with advanced equipment in GoM.
1	Replicability	Epoch	[-]	0	10	Easiness to replicate at different yards.
1	Profitability	Era	[$]	-	-	Net cash flow from the investment.
2	Eco-friendliness	Epoch	[-]	0	10	Environmental friendly transit and operations.
2	Fleet integrability	Epoch	[-]	0	10	Integrability with current advanced fleet.
2	Profitability	Era	[$]	-	-	Net cash flow from the investment.

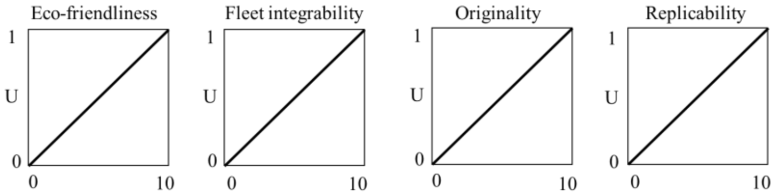


Figure 3: Single-attribute utility functions.

Originality represents the ability of being the first mover with advanced equipment into the Gulf of Mexico (GoM) market. Originality is a measure of how technically advanced a vessel is compared with the current operational fleet in this area, physically operationalized through the crane lifting and light well intervention capability on a scale from 0 to 10 where higher is better. Replicability represents a measure on the simplicity to which a design can be reproduced by another yard. It reflects the building complexity, in this maritime context operationalized by the gross tonnage (GT) on a defined 0 to 10 scale, where a lower GT represents a higher number on the scale. Complex ships are assumed to be more difficult to copy and reproduce compared to simpler ones, as more information is needed to describe complex systems. Eco-friendliness represents the ability of a design to perform with as low environmental footprint as possible. This is defined on a scale from 0 to 10, dependent on aspects of eco-friendliness of a design in transit and operation operationalized through the water resistance of the design and the fuel type used. Fleet integrability represents the degree to which the design integrates into the current advanced light well intervention fleet of stakeholder 2. The attribute is defined on a scale from 0 to 10 based on the LWI capability of the current fleet of stakeholder 2.

Table 2 presents the design variables generalized from common parametrizations of offshore vessel designs. The design variables represent the aspects of the physical design concepts with stronger influence on the value attributes. To avoid disregarding a-priori designs of high potential value, we do not check for basic feasibility requirements at this stage, like stability or minimum freeboard.

Table 2: Design variables.

Design variable	**Units**	**Values**
Length	m	[120, 140, 160, 180]
Beam	m	[20, 25, 30, 35]
Depth	m	[8, 11, 14]
Installed power	MW	[5, 10, 15, 20, 25]
Accommodation	persons	[50, 150, 250, 350]
Main crane capacity	tonnes	[0, 200, 400, 600, 800]
Light well intervention	tonnes	[0, 300, 600]
Moonpool	[-]	[No, Yes]
Fuel type	[-]	[MGO, Dual Fuel (DF)]
Dynamic positioning	[-]	[DP2, DP3]
Remotely operated vehicle	[-]	[No, Yes]

4.3. Step 3: Epoch characterization

The epoch characterization phase elicits exogenous uncertainties perceived by the stakeholders as potentially impacting the value of the system. For the offshore vessel in this case study, we define the system boundary around the ship itself, and hence eight epoch variables are predicted to affect the vessel, as illustrated in Figure 4.

Figure 4: Ship system boundaries and epoch variables.

The eight epoch variables, classified in contract parameters and technical requirements are presented in Table 3. Additionally, we define each of the four operational areas as a combination of water depth and sea state, represented by the significant wave height (Hs), as described in Table 4. Further, the possibility that the ship is in lay-up is also included.

Table 3: Epoch variables representing important sources of exogenous uncertainty.

	Epoch variable	**Unit**	**Values**
Contract parameters	Contract rate	k$/day	[50, 70, 120, 170, 220]
	Operational area	[-]	[1, 2, 3, 4]
Technical requirements	Light well intervention req.	tonnes	[0, 300, 600]
	Module weight req.	tonnes	[0, 200, 400, 600]
	Accommodation req.	POB	[50, 150, 250, 350]
	ROV req.	[-]	[0, 1]
	Dynamic positioning req.	[-]	[0, 1]
	Deck area req.	m^2	[0, 1000]

Table 4: Characteristics of depth and sea state (Hs) for the four operational areas.

Operational area	Epoch var. value	Depth [m]	Hs [m]
Gulf of Mexico	1	1600	2.0
Brazil	2	2500	2.5
North Sea	3	200	3.0
West Africa	4	1800	1.0

4.4. Step 4: Design-epoch tradespace evaluation

This step enables the representation of all designs from the design space in terms of utility and costs in the tradespace, to gain an understanding of how system concepts provide value given important contextual uncertainties (Ross et al. 2009). At this stage, we model the mapping between the value space and the design space. Some of this mapping takes place by going through modelling of physics and economics, via “key performance indicators” (KPIs). The outcome of Step 4 is a measure of multi-attribute utility (MAU), and a cost measure, multi-attribute expense (MAE).

There are various intermediate performance indicators in the model, which are central in the mapping between value and physical design. At an early design stage, we want to evaluate multiple designs in different epochs, hence the models need to be low fidelity in order to make it computationally feasible. Therefore, in absolute terms, the estimated properties may not be correct, but for comparisons in relative terms indicate the main relationships between the relevant parameters. The physical calculations include lightweight, deadweight, deck area, speed, acquisitional and operational costs.

This paper focuses on design of commercial systems, where profitability is central. It is important to understand that even though profitability is not assessed as a value attribute in a particular epoch, it is incorporated indirectly because we want to minimize the costs in a mission with a given day rate. Hence, when we seek Pareto optimal designs, we also find the designs that maximize the profitability for each epoch, and this way of structuring the problem opens up for easy exploration of the trade-off between profitability and other value attributes such as eco-friendliness. In order to assess profitability, a financial model is used to calculate the cash flows. The financial system boundary is around the ship itself, and hence we do not include financial details on the fleet level for the ship owners. Fuel costs are not included in this model, since they are assumed paid by the charterer. The system boundary in this analysis does not include specific aspects of the market, such as supply and demand, and we hence just work with contracts, with their rates and requirements. Assessment of these underlying dynamics remains outside the scope of this analysis.

Figure 5 illustrates the architecture of the methodological approach in this paper, comprising mainly four elements: the design space, the system modelling, the epoch space and the resulting evaluation criteria: value and cost. What is particularly important to consider, is how an epoch can be decomposed into information regarding the context and needs. Both, context and needs may change over time, randomly, or one may see more casual relationships. Proper investigation of these dynamics is important in order to make value robust design decisions, for example through interviews with the stakeholders. In this analysis, we assume that the set of value attributes remains constant in different epochs. Further, in the process of calculating the MAU, we assume that the weights remain static at 0.5 for each of the two value attributes for each of the two stakeholders. The different costs components are aggregated to a multi-attribute expense (MAE) function for each stakeholder, where acquisition costs and operational costs are weighted equally. When a design does not satisfy the requested technical requirements in an epoch, it is considered infeasible. No direct limitations are imposed on the newbuilding price.

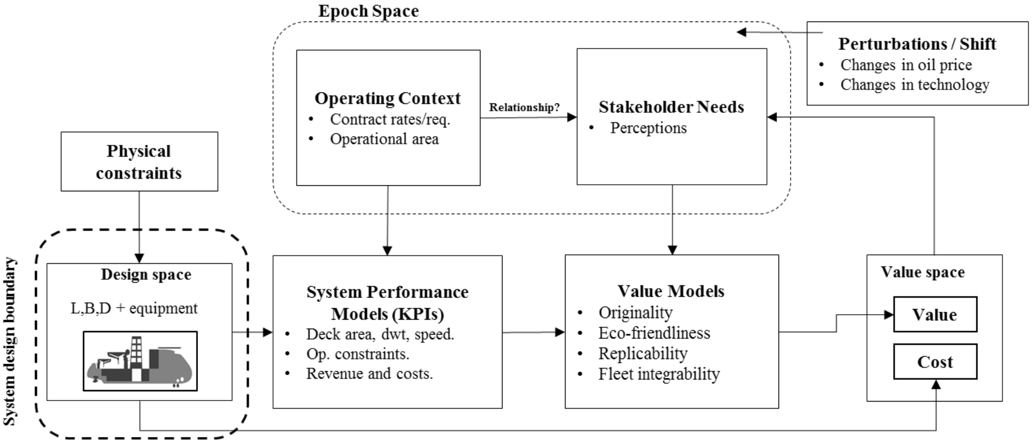


Figure 5: Illustrating the design-value mapping model.

Once the value-epoch model is defined, all design solutions can be plotted in terms of MAU versus MAE, creating a tradespace for a given epoch. Taking the view that we investigate a trade-off between utility and cost, the non-dominated solutions become those designs that for each possible budgetary constraint maximizes utility. Since we maximize utility and minimize costs for a given contract with a given day rate, we indirectly find the designs that maximize the profit for that particular epoch and contract.

Table 5: Sample designs for further assessment.

Design name		**I**	**II**	**III**	**IV**	**V**	**VI**
Design ID	[-]	116454	114843	110835	128020	111081	128356
L, B, D	[m]	140,25,8	160,30,11	160,20,8	180,20,8	120,30,8	180,20,8
Main crane	[tonnes]	200	400	800	400	800	800
Accommodation	[POB]	150	250	150	150	250	250
Engine power	[MW]	15	25	15	15	15	15
Light well intervention	[tonnes]	300	0	600	600	600	600
Moonpool	[-]	Yes	Yes	No	No	No	No
Fuel type	[-]	Diesel	Diesel	Diesel	DF	Diesel	DF
Remotely operated vehicle	[-]	Yes	Yes	Yes	Yes	Yes	Yes
Dynamic positioning	[-]	DP3	DP3	DP3	DP3	DP3	DP3
Deck area	[m^2]	1200	2000	1000	1300	1000	1000
Dwt	[tonnes]	7300	19000	4500	6700	5400	5400
Max speed	[knot]	18	20	18	18	17	18
Acquisition cost	[m$]	164	210	215	236	223	247

To gain better insight in this design problem, six designs are studied more in detail in the following analyses, as illustrated in Table 5. Since we do not check for technical feasibility on the design variables, to reduce the number of assumptions, we may get solutions that seem unrealistic to ship designers. This is especially true for designs III and IV.

4.5. Step 5: Single-epoch analyses

In this step, we analyze and explore the tradespaces for each stakeholder in different epochs, gaining insight into the trade-offs among alternative designs. This process is carried out with the means of learning about the complex system behavior in different static contexts. Tradespace yield is a useful metric for evaluating single epochs, which takes the feasible designs within the epoch, as the percentage of the total number of enumerated designs (Ross et al. 2009). This also gives a hint of whether the attribute ranges should be redefined to make it easier for designs to fulfil requirements. For illustration, we assess the system behavior under three epochs, represented in Table 6.

Table 6: Three relevant example epochs for the Gulf of Mexico.

	Low case	**Base case**	**High case**
Epoch ID	981	6813	6889
Contract rate	$70 000/day	$170 000/day	$220 000/day
Operational area	Gulf of Mexico	Gulf of Mexico	Gulf of Mexico
LWI	0 tonnes	600 tonnes	600 tonnes
Module weight	200 tonnes	200 tonnes	400 tonnes
Accommodation	50 people	150 people	250 people
ROV req.	Yes	Yes	Yes
Dynamic positioning	DP2	DP3	DP3
Deck area req.	0	1000	1000
Tradespace yield	0.20	0.02	0.01

The tradespace yield measures are in this case identical for the two stakeholders. Only the designs that have the technical equipment to satisfy the requirements in an epoch are defined as feasible. Due to the structure of the model, and the high number of designs generated, the tradespace yield measures becomes relatively low.

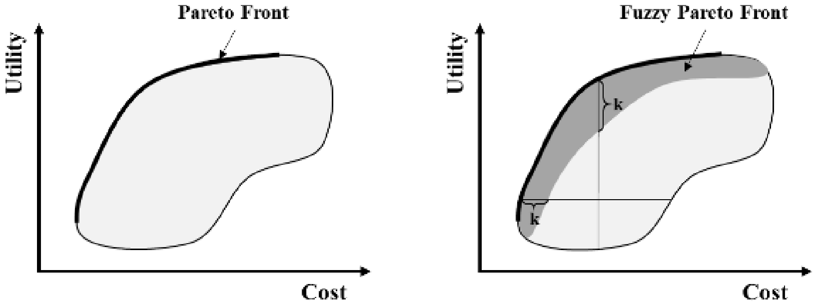


Figure 6: Pareto optimality and Fuzzy Pareto optimality with k% fuzziness, for a tradespace defined by utility and cost.

There exist multiple metrics to measure the performance, mostly based on Pareto efficiency. Figure 6 demonstrates the concept of the Pareto efficient frontier, with and without fuzziness, as introduced by Smaling and Weck (2004). The Fuzzy Pareto Number (FPN) is a metric that can be used to quantify the distance to the Pareto front for each design. FPN is defined as the smallest fuzziness percentage for which a design is in the fuzzy Pareto set (Fitzgerald and Ross, 2012). The FPN of the six designs followed in this analysis for both stakeholders are illustrated in Table 7. FPN of 101 represents infeasibility, while FPN of 0 stands for Pareto optimality.

Table 7: Fuzzy Pareto Number (FPN) for the six designs in three considered epochs for stakeholder 1 and 2.

	Stakeholder 1			Stakeholder 2		
Design	Low case	Base case	High case	Low case	Base case	High case
I	101	101	101	101	101	101
II	22	101	101	16	101	101
III	3	0	101	4	1	101
IV	8	8	101	0	0	101
V	5	3	0	9	6	2
VI	7	3	0	0	0	0

4.6. Step 6: Multi-epoch analysis

The purpose of multi-epoch analysis is to find value robust systems across changing contexts and needs, by measuring system value across multiple epochs. A separation can be made between actively and passively value robust systems (Ross, Rhodes, and Hastings 2008):

- **Passively value robust** systems are relatively insensitive to changing conditions, and continue to deliver value above an acceptable level, while maintaining the initial design configuration.
- **Actively value robust** systems can benefit from dynamically taking actions in response to changing conditions that may deteriorate the system performance, such as implementation of changeability.

In this analysis, we only consider passive value robustness. An overview of metrics for assessing design performance across multiple epochs is presented by Fitzgerald and Ross (2012). The Fuzzy Normalized Pareto Trace (fNPT) identifies passively value robust designs. In its “unfuzzy” form (0% fuzziness), it is simply the fraction of epochs in which a design is located on the Pareto front. With a fuzziness above 0, it represents the fraction of epochs in which the design is within the fuzzy Pareto set. If active value robustness is achieved through changeability, *effective* fNPT may be used as a measure of improved performance. The feasible design space is changing in size for each epoch. The fNPT metric is assumed only based on the feasible designs in an epoch.

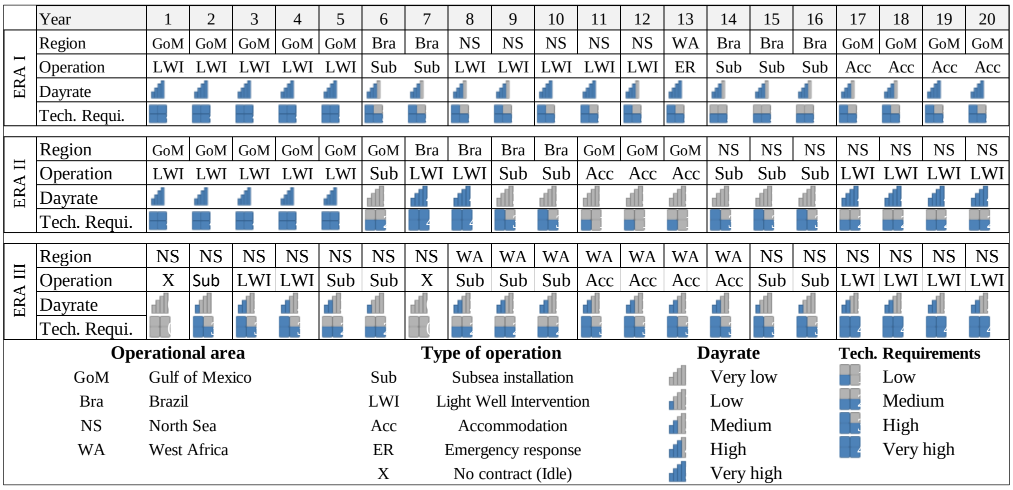
Table 8: NPT and k% fNPT for the six designs for stakeholder 1 and 2.

		Stakeholder 1			Stakeholder 2		
Design	Feasible	NPT	10% fNPT	20% fNPT	NPT	10% fNPT	20% fNPT
I	0.06	0.00	0.02	0.06	0.00	0.03	0.06
II	0.07	0.00	0.00	0.00	0.00	0.00	0.00
III	0.35	0.01	0.34	0.35	0.00	0.27	0.35
IV	0.17	0.00	0.01	0.14	0.00	0.17	0.17
V	0.45	0.00	0.31	0.44	0.00	0.04	0.33
VI	0.45	0.00	0.27	0.44	0.00	0.44	0.45

The passively value robust metrics are relatively low due to the structure of the problem. There are no static designs that perform well over all the epochs considered. Large multi-functional vessels will be able to take different missions, but require higher rates to be profitable than smaller designs that are optimized for single missions. This reasoning indicates that changeability could be valuable. For a proper assessment of the active value robustness of the designs, weighting and filtering based on probability may be considered.

4.7. Step 7: Era construction

The entire era space for this problem would be extremely large, considering the sizeable epoch space. While simulation methods could be applied to sample eras based on historical data following simple logical rules, a narrative approach is here used to represent likely system lifecycle scenarios. This enables simple “what if”-analyses that are easily communicated among stakeholders. Epoch durations through an era could be dynamic, but in this case we simplify and assume a static time span of 1 year per epoch. This intends to capture the volatility of the oil and gas industry, and to include the possibility for shorter "accident-driven" missions. For the case, the following three eras are specified for a 20-year system lifecycle, encapsulating stakeholder beliefs. The three eras are presented in Figure 7, in terms of operational areas, types of operation, day rates and technical requirements. Era I represents a baseline scenario, with an initially targeted tender contract and a strong offshore market continuation. Era II represents a similar start with the targeted tender contract, followed by a weakened market ending with offshore decommissioning in later years. Era III represents a market collapse where the initial targeted tender contract is not won.



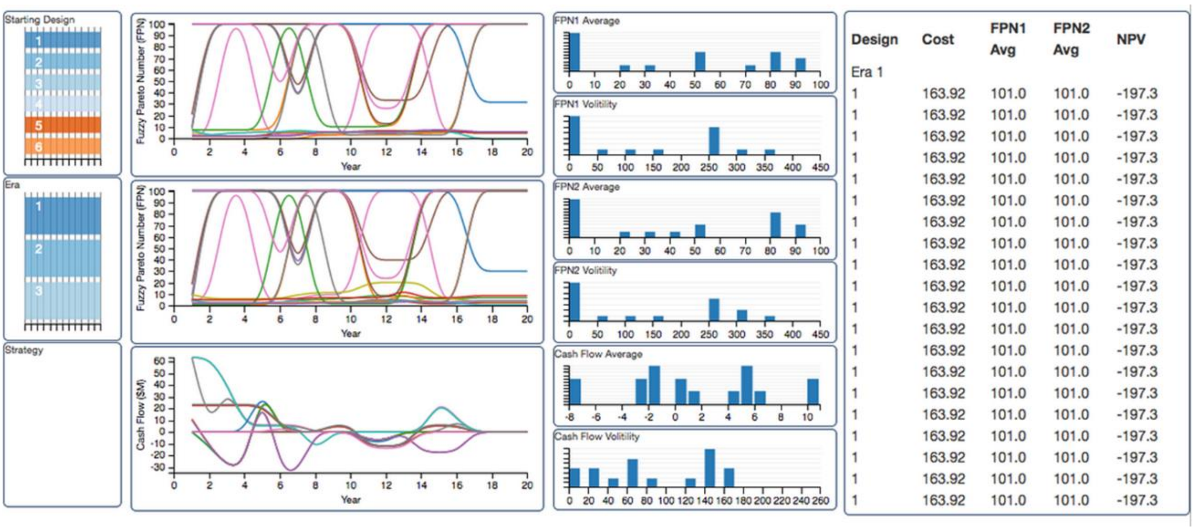
	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
ERA I	Region	GoM	GoM	GoM	GoM	GoM	Bra	Bra	NS	NS	NS	NS	NS	WA	Bra	Bra	Bra	GoM	GoM	GoM	GoM
	Operation	LWI	LWI	LWI	LWI	LWI	Sub	Sub	LWI	LWI	LWI	LWI	LWI	ER	Sub	Sub	Sub	Acc	Acc	Acc	Acc
	Dayrate																				
	Tech. Requi.																				
ERA II	Region	GoM	GoM	GoM	GoM	GoM	GoM	Bra	Bra	Bra	Bra	GoM	GoM	GoM	NS	NS	NS	NS	NS	NS	NS
	Operation	LWI	LWI	LWI	LWI	LWI	Sub	LWI	LWI	Sub	Sub	Acc	Acc	Acc	Sub	Sub	Sub	LWI	LWI	LWI	LWI
	Dayrate																				
	Tech. Requi.																				
ERA III	Region	NS	NS	NS	NS	NS	NS	NS	WA	WA	WA	WA	WA	WA	WA	NS	NS	NS	NS	NS	NS
	Operation	X	Sub	LWI	LWI	Sub	Sub	X	Sub	Sub	Sub	Acc	Acc	Acc	Acc	Sub	Sub	LWI	LWI	LWI	LWI
	Dayrate																				
	Tech. Requi.																				

Operational area		Type of operation		Dayrate	Tech. Requirements
GoM	Gulf of Mexico	Sub	Subsea installation	Very low	Low
Bra	Brazil	LWI	Light Well Intervention	Low	Medium
NS	North Sea	Acc	Accommodation	Medium	High
WA	West Africa	ER	Emergency response	High	Very high
		X	No contract (Idle)	Very high	

Figure 7: Description of three narrative eras.

4.8. Step 8: Single-era analyses

Single-era analyses focus on long-term value sustainment through dynamic scenarios with changing contexts and needs. Insight is gained through investigation of time-dependent effects that emerge through various sequences of epochs. For passively value robust designs, one can better identify strengths and weaknesses for different eras, and understand value trade-offs in various realizations of the future. For actively value robust designs, long run strategies can be examined as means to exercise changeability, and identify path dependencies. Visualization of these datasets remains difficult, but is an essential tool for gaining insights and communicating the results to stakeholders (Curry et al. 2017). Figure 8 illustrates an interactive map of the performance of various designs in the three narrative eras constructed in this case.



Design	Cost	FPN1 Avg	FPN2 Avg	NPV
Era 1				
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3

Figure 8: Illustration of candidate designs over different single eras with supporting metrics (adapted from Curry et al. (2017)).

Tracking of monetary performance metrics such as net present value and return on investment through each scenario, are particularly interesting to commercial system stakeholders. Monetary and non-monetary performance metrics can be concurrently illustrated in a lifecycle performance plot, as shown in Figure 8. Additionally, we are interested in evaluating the risk of defaults and the financial survivability of a design, which becomes visible the era level of the analysis. We may for example be willing to accept short periods of loss, in order to have higher overall probability of survival.

4.9. Step 9: Multi-era analysis

Multi-era analysis is a parallel process to the multi-epoch analysis. While multi-epoch analysis seeks to identify value-robust designs across the epoch space, the aim of multi-era analysis is to do the same in the era space.

Considering the magnitude of the era space, it is computationally infeasible to find metrics parallel to those found in multi-epoch analysis. Smarter search mechanisms are needed to perform viable multi-era analyses, including methods for sampling epochs to eras, for example based on strategic system management decisions. The propagation of the era will be dependent on the trajectory of system decisions, especially when considering active value robustness and changeability. In addition, perturbations creating a shift from one epoch to the next will create path dependencies. For this reason, rolling horizon heuristics could be of interest in further research. A rolling horizon approach would not consider a fully rolled out scenario tree from the beginning, but continuously update the scenario tree as future uncertainties are resolved and decisions are made.

5. Discussion

5.1. On problem structuring

Design of engineering systems involves simplification of an initial ill-structured problem. There is a significant difference between the task of defining the ill-structured problem in terms of well-structured representations, and the task of solving a well-structured representation of the design problem. The Responsive Systems Comparison (RSC) method facilitates the problem definition processes, in addition to laying out a structured approach for solving the subsequent well-structured design problem. Taking relatively abstract business propositions into a more well-structured problem space represents in itself a design problem, as many alternative well-structured problems can be formulated. Thereafter, the well-structured problem can be solved, and resulting recommendations can be communicated to decision makers. Hence, this can be considered a two-stage abductive reasoning process, as illustrated in Figure 9.

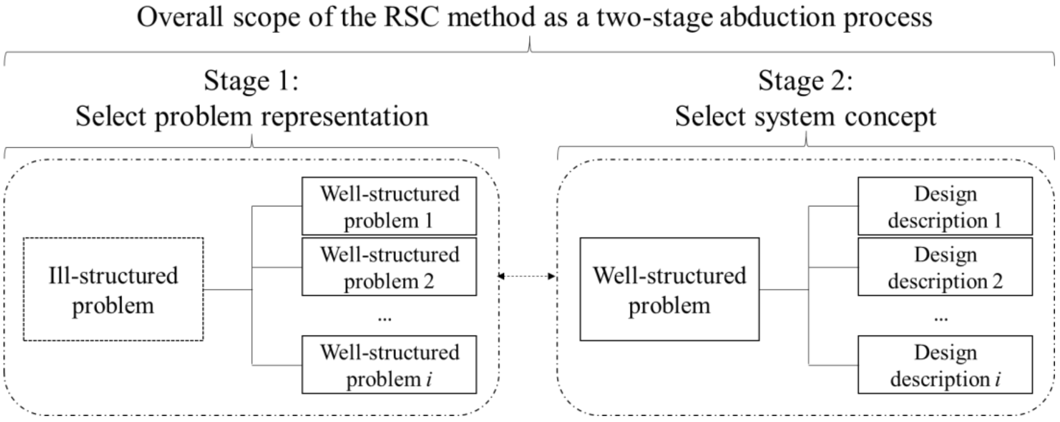


Figure 9: Making ill-structured problems well-structured, and solvable through two abductive stages.

Structuring an ill-structured problem represents in itself a result, as it reduces the ambiguities surrounding stakeholder preferences. For instance, the knowledge generated by explicitly relating a value proposition to the design space by producing a model, defines the design problem in such a way that it finally can be solved. The case study shows that the RSC method generates useful insights that will influence how design problems are framed, and thus how they are made solvable. Even incomplete RSC analyses provide value in early stage design problems, as they help structure the design process.

5.2. Profitability in a multi-attribute utility model

Evaluating commercial systems naturally require some attention given to monetary measures of value, beyond the trade-off between utility and cost. The model proposed in this case study incorporates profitability at the era-level, where non-dominated solutions are explored for a given contract with a fixed day rate. This enables identification of solutions that reduce costs for a given revenue, hence implicitly maximizing profitability. Two of the criteria of multi-attribute utility theory are violated when attempting to incorporate profitability as an epoch-level value attribute, namely non-redundancy and operationalization (Keeney and Raiffa 1993).

What generates value and what demands resources, or costs, should be kept separate according to the non-redundancy criteria. Since profitability already incorporates the costs, double counting becomes an issue when using profitability as an epoch-level value attribute. In the case of epochs with fixed revenue, attempting to use revenue alone as an epoch-level value attribute will not add differentiation among designs. However, use of an alternative well-structured problem representation, as illustrated in Stage 1 in Figure 9, may render revenue a meaningful epoch-level value attribute. Further, it is challenging to operationalize profitability as an epoch-level value attribute. One could argue that the perceived value of some profit depends on the size of the investment, rather than just the amount of money gained. A stakeholder would perhaps perceive the relative return on investment (ROI) as more important than the cash flows. However, issues with double counting again makes this approach troublesome. Additionally, running a loss is not easily modelled in a utility function, where contributions to utility are measured on a positive scale. A loss cannot be understood as adding positively to utility. Hence, a weakness when applying multi-attribute utility theory to commercial engineering systems design is that the profit cannot be rationally modelled within the framework.

In general, the value attributes selected depend on the location of system boundaries and level of abstraction, and not only on the stakeholder preferences. Inclusion of profitability at the era-level is found to be most meaningful for the case presented in this paper. This enables meaningful incorporation of short periods with negative profitability, with the aim of maximizing the overall profitability. Further, use of profitability as an era-level value attribute allows other interesting aspects of profitability to be considered, such as incorporation of constraints on losses and assessment of the effects of different stakeholder risk attitudes for the alternative designs.

6. Conclusion

In this paper, we show the applicability of the Responsive Systems Comparison method for structuring ill-structured design decision problems, making design problems more tangible. The strengths in the method with respect to the more well-structured design problem lie in the reduction of assumptions, supporting the decision-making process by communicating the trade-offs and compromises between multiple aspects of value. By applying the RSC method to a design case of an industrial offshore construction vessel, we show that commercial systems performance models can be integrated within the framework.

References

Andrews, David J. 2012. “Art and Science in the Design of Physically Large and Complex Systems.” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 468: 891–912.

Balland, O., Stein Ove Erikstad, K. Fagerholt, and Stein W. Wallace. 2013. “Planning Vessel Air Emission Regulations Compliance under Uncertainty.” *Journal of Marine Science and Technology* 18 (3): 349–57.

Benford, Harry. 1970. “Measures of Merit for Ship Design.” *Marine Technology*, no. October: 465–76.

Brett, Per Olaf, Evangelos Boulougouris, Richard Horgen, Dimitris Konovessis, Ivan Oestvik, George Mermiris, Apostolos D. Papanikolaou, and Dracos Vassalos. 2006. “A Methodology for Logistics-Based Ship Design.” In *IMDC 2006*. Ann Arbor, Michigan, USA.

Chalupnik, Marek J., David C. Wynn, and P. John Clarkson. 2013. “Comparison of Ilities for Protection Against Uncertainty in System Design.” *Journal of Engineering Design* 24 (12): 814–29.

Curry, Michael D., Carl F. Rehn, Adam M. Ross, and Donna H. Rhodes. 2017. “Designing for System Value Sustainment Using Interactive Epoch-Era Analysis: A Case Study from Commercial Offshore Ships.” In *15th Annual Conference on Systems Engineering Research*. Redondo Beach, CA.

Dahle, Aleksander, and Daniel Jøsok Kvalsvik. 2016. “Freight Rate Determinants in the Offshore Market: Does Energy Efficiency Pay?” Norwegian School of Economics.

de Weck, Olivier L., Daniel Roos, and Christopher L. Magee. 2011. *Engineering Systems: Meeting Human Needs in a Complex Technological World*. Cambridge, MA: The MIT Press.

Erichsen, Stian. 1989. *Management of Marine Design*. London, UK: Butterworths.

Erikstad, Stein Ove, and Carl Fredrik Rehn. 2015. “Handling Uncertainty in Marine Systems Design - State-of-the-Art and Need for Research.” In *12th International Marine Design Conference*, 2:324–42.

Fet, Annik Magerholm, Dina Margrethe Aspen, and Harald Ellingsen. 2013. “Systems Engineering as a Holistic Approach to Life Cycle Designs.” *Ocean Engineering* 62: 1–9.

Fitzgerald, Matthew Edward, and Adam M. Ross. 2012. “Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain.” In *6th Annual IEEE Systems Conference*, 281–88. Vancouver, Canada.

———. 2013. “Guiding Cooperative Stakeholders to Compromise Solutions Using an Interactive Tradespace Exploration Accessed Guiding Cooperative Stakeholders to Compromise Solutions Using an Interactive Tradespace Exploration Process.” *Procedia Computer Science* 16. Elsevier B.V.: 343–52.

Frederick, Shane, George Loewenstein, and Ted O’Donoghue. 2002. “Time Discounting and Time Preference: A Critical Review.” *Journal of Economic Literature* 40 (2): 351–401.

Fricke, Ernst, and Armin P. Schulz. 2005. “Design for Changeability (DfC): Principles to Enable Changes in

Systems throughout Their Entire Lifecycle.” *Systems Engineering* 8 (4): 342–59.

Garcia, Jose Jorge, Ulrikke Brask Brandt, and Per Olaf Brett. 2016. “Unintentional Consequences of the Golden Era of the Offshore Oil & Gas Industry.” In *ICSOS 2016*.

Garcia, Jose Jorge, Sigurd Solheim Pettersen, Carl Fredrik Rehn, and Ali Ebrahimi. 2016. “Handling Commercial, Operational and Technical Uncertainty in Early Stage Offshore Ship Design.” In *11th System of Systems Engineering Conference (SoSE)*. Kongsberg, Norway.

Gaspar, Henrique M., Océane Balland, Dina Margrethe Aspen, Adam M. Ross, and Stein Ove Erikstad. 2015. “Assessing Air Emissions for Uncertain Lifecycle Scenarios via Responsive Systems Comparison Method.” *Proc IMechE Part M: J Engineering for the Maritime Environment* 229 (4): 350–64.

Gaspar, Henrique M., Donna H. Rhodes, Adam M. Ross, and Stein Ove Erikstad. 2012. “Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach.” *Journal of Ship Production and Design* 28 (4): 145–59.

Kahneman, Daniel, and Amos Tversky. 1979. “Prospect Theory: An Analysis of Decision under Risk.” *Econometrica* 47 (2): 263–91.

Kana, Austin A., and Brandon M. Harrison. 2017. “A Monte Carlo Approach to the Ship-Centric Markov Decision Process for Analyzing Decisions over Converting a Containership to LNG Power.” *Ocean Engineering* 130 (November 2016): 40–48.

Keane, André, Per Olaf Brett, and Henrique M. Gaspar. 2015. “Epoch Era Analysis in the Design of the Next Generation Offshore Subsea Construction Vessels.” In *10th System of Systems Engineering Conference (SoSE),* 322–27.

Keeney, Ralph L. 1992. *Value-Focused Thinking: A Path to Creative Decisionmaking*. Cambridge, MA: Harvard University Press.

Keeney, Ralph L., and Howard Raiffa. 1993. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. Cambridge, UK: Cambridge University Press.

Lindgren, Mats, and Hans Bandhold. 2003. *Scenario Planning: The Link between Hte Future and Strategy*. Palgrave Macmillan.

McManus, Hugh L., and Daniel E. Hastings. 2006. “A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems.” *IEEE Engineering Management Review* 34 (3): 81–94.

Miller, George. 1956. “The Magical Number Seven, plus or Minus Two: Some Limits on Our Capacity for Processing Information.” *Psychological Review* 101 (2): 343–52.

Niese, Nathan D., and David J. Singer. 2014. “Assessing Changeability under Uncertain Exogenous Disturbance.” *Research in Engineering Design* 25: 241–58.

Papageorgiou, Evangelos, Murat Hakki Eres, and James Scanlan. 2016. “Value Modelling for Multi-Stakeholder and Multi-Objective Optimisation in Engineering Design.” *Journal of Engineering Design* 27 (10): 697–724.

Patricksson, Øyvind S., and Stein Ove Erikstad. 2016. “A Two-Stage Optimization Approach for Sulphur Emission Regulation Compliance.” *Maritime Policy & Management*.

Ross, Adam M., H. L. McManus, A. Long, M G Richards, Donna H. Rhodes, and Daniel E. Hastings. 2008. “Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change.” *AIAA Space 2008*. San Diego, California.

Ross, Adam M., H. L. McManus, Donna H. Rhodes, Daniel E. Hastings, and A. Long. 2009. “Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System.” In *AIAA Space 2009*. Pasadena, CA.

Ross, Adam M., Gregory O’Neill, Daniel E. Hastings, and Donna H. Rhodes. 2010. “Aligning Perspectives and Methods for Value-Driven Design.” *AIAA Space 2010*, 1–30.

Ross, Adam M., and Donna H. Rhodes. 2008. “Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis.” In *INCOSE International Symposium*, 18:1186–1201. Utrecht, the Netherlands.

Ross, Adam M., Donna H. Rhodes, and Daniel E. Hastings. 2008. “Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value.” *Systems Engineering* 11 (3). Wiley Subscription Services, Inc., A Wiley Company: 246–62.

Savage, Sam L. 2009. *The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty*. *Wiley*.

Schaffner, Michael A., Adam M. Ross, and Donna H. Rhodes. 2014. “A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design.” *Procedia Computer Science* 28: 304–13.

Simon, Herbert A. 1973. “The Structure of Ill Structured Problems.” *Artificial Intelligence* 4: 181–201.

———. 1996. *The Sciences of the Artificial*. 3rd ed. Cambridge, MA: The MIT Press.

Smaling, Rudolf M., and Olivier L. de Weck. 2004. “Fuzzy Pareto Frontiers in Multidisciplinary System Architecture Analysis.” In *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 1–18. Albany, NY.

Ulstein, Tore, and Per Olaf Brett. 2015. “What Is a Better Ship ? – It All Depends...” In *IMDC 2015*, 1:49–69.