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An evaluation of suitable methods to deal with deep uncertainty caused by the energy transition in ship design

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ABSTRACT

The maritime energy transition presents deep uncertainties that are difficult to deal with in the current ship design process. Even though other fields have stressed using adaptive strategies and explorative methods to deal with deep uncertainty, it is rarely included in ship design. Therefore, this paper compares three applicable methods to investigate how such aspects could support the design process. Each method is found to offer specific improvements to decision making, but no separate method meets the established criteria to the desired degree. The methods are found to be complementary, and by developing a combined method for ship design, ships can be better prepared to deal with deep uncertainty.

KEY WORDS

Ship Design; Uncertainty; Adaptability; Energy Transition, Sustainable Fuels

INTRODUCTION

The maritime industry is transitioning toward operations with zero emissions. The use of alternative fuels and technologies is required to achieve substantial emission reductions. However, even though many different options are under development, they all have different properties and challenges to take into account in ship design (Hoecke 2021, Bouman 2017). Furthermore, because research is ongoing, the performance and requirements of options in practice are still uncertain (Balcombe 2019). Additionally, regulatory ambitions are aiming for increasingly larger reductions in Green House Gases (GHG) and other harmful substances, but the details of future regulation are unknown and subject to ongoing scientific and societal discussions (Serra 2020). The level of uncertainty regarding regulation and technology for the energy transition can be defined as deeply uncertain, which means uncertainty cannot be ordered in terms of possibility or occurrence (Marchau 2019). Although uncertainty is not uncommon in ship design, ship owners and designers are faced with an unprecedented level of uncertainty and require new methods to deal with it.

The inevitable, but uncertain changes toward propulsion and machinery systems with lower emissions, should preferably be dealt with during the design process. However, as designers currently mainly reuse existing knowledge to establish assumptions and probability to deal with uncertainty, it is difficult to take higher levels of uncertainty into account. Nevertheless, within the ship design research field, several authors have introduced and investigated the effect of different sources of uncertainty in design decision making. For example, real options has been used to evaluate alternative designs for multiple sets of contracts (Pettersen 2017, Curry 2018) or to investigate when to invest in LNG to comply with environmental regulation (Acciaro 2014), and epoch era analysis has been used to take the effect of market changes into account (Gaspar 2012). However, these use a limited amount of scenarios and options, and probabilistic and parametric assumptions that are currently difficult to establish for the energy transition due to deep uncertainty.

Fortunately, much research has been done in other fields on how to deal with high levels of uncertainty in decision making (Marchau, 2019). This has resulted in methods that visualize and evaluate adaptive strategy as part of the decision-making process. Consequently, such methods could offer valuable insights for the maritime energy

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transition. However, besides experimental application (Keane 2015, Rehn 2016), such methods have, to the knowledge of the authors, not been applied to deal with the energy transition problem in the ship design process.

Several aspects of these methods could potentially benefit the ship design process to deal with deep uncertainty. First, the exploration of performance in different scenarios enables designers to identify the vulnerability of a design to uncertainty. Such an ability can provide insight into how a design can cope with external changes while remaining on track to meet its objectives (McDowall 2006). Furthermore, a visualization of sensitivity to parametric uncertainty allows designers to better understand and be cautious of deterministic pitfalls (Patricksson 2016). Second, besides identifying the vulnerabilities of a single design, the process would benefit from the ability to investigate multiple alternative designs. Moreover, assessing the ability to change between alternative designs to deal with uncertainty could also be valuable (Rehn 2019). Third, the preparation and adaptation of a design to changes is also recognized as an effective way to deal with deep uncertainty (Haasnoot 2013). Therefore, besides the analysis of vulnerability and design exploration, the design process would also benefit from developing strategies that can be used when other situations occur then the vessel is designed for. By continuously developing this adaptive strategy, the ship might be more proactive and better able to deal with uncertainties over time. Lastly, the use of a method should be supportive instead of exhaustive, so the focus of the designer can remain on designing.

Three promising methods that could be used to meet these aspects in the ship design process were identified in literature research. First, Dynamic Adaptive Policy Pathways (DAPP) evaluates alternative options and develops possible pathways to compliance (Haasnoot 2013). Second, Responsive Systems Comparison (RSC) determines the performance of a design in established scenarios (epochs & eras), also allowing evaluation including retrofit (changeability) (Ross 2009). Third, Robust Decision Making (RDM) explores the effect of uncertainties on a pre-specified design and analyses its vulnerability (Lempert 2019). The methods are compared on their ability to implement the aspects above in the ship design process to a desirable level. Each method is applied to a general cargo ship case to allow for a first comparison. The goal is to better understand the usability and potential of each method for the energy transition in shipping. The setup of comparison criteria, the case study and the data used is presented in the methodology section. Next, the setup and the results of each method are discussed. Lastly, the methods are compared and evaluated using the comparison criteria.

METHODOLOGY

A set of criteria and sub-criteria are used to compare the three methods. These are based on the aspects that could potentially improve the ability to deal with uncertainty during the design process that are identified in the introduction. The criteria are measured on a scale from 1 (worst) to 5 (best).

- Uncertain scenario vulnerability assessment
    - Scenario specific analysis
    - Uncertain parameter sensitivity
- Alternative design exploration
    - Initial design robustness
    - Evaluation adaptive design
- Evaluation of adaptable strategy
- Supportive method setup

In this paper, a supportive method is defined as being (partly) re-usable, with clear modules, input and output, that is easily applicable to new cases. Besides the criteria, the level of uncertainty that the method can deal with is compared as well. These levels go from complete determinism (0), clear enough (1), probabilistic representation (2), a few possibilities (level 3), many possibilities (4), to unknown (5) (Marchau 2019). Of these, levels 4 and up can be considered deep uncertainty, which is encountered by ship designers in the maritime energy transition.

Case study setup

This research aims to establish what insights the three methods provide by performing a case study into the effects of uncertainty on the performance of the general cargo vessel. The basis of each method is equal and includes a general cargo ship, alternative options a set of uncertainties. A general cargo vessel has been chosen because these cargo-type vessels present a large share of total maritime emissions, which has resulted in many energy transition studies. This specific vessel has been used for a case study into the application of ammonia and methanol, which is used as a reference for verification (Wijnand, 2020). The vessel parameters are presented in

Table 1. The ship dimensions, tank volume, tank weight, endurance and speed are used to set operational targets for evaluation.

Table 1: Ship parameters

Parameter	Value	Unit
Length	150	m
Breadth	15.9	m
Draught	8.6	m
$Weight_{cargo}$	10200	mt
$Volume_{cargo}$	13644	m3
Fuel	MDO	
$Volume_{fuel}$	900	m3
$Weight_{fuel}$	873	mt
Design speed	11.5	kts
Target distance	8000	nm

Table 2 presents relevant data of several alternative fuel-converter combinations, the values have been compiled from literature and contain lower, mean and upper bounds to represent best and worst-case scenarios. Fuel density includes the storage system effect and is assumed to be constant. Ten different energy carrier options are considered, which are either converted using an internal combustion engine (CI or SI) or a fuel cell (SOFC or PEMFC). The onboard conversion performance is represented using a conversion efficiency range. Capital expenses are defined separately for storage and converter systems. Besides this, a broad range around the reference value is used for operational expenses.

Table 2: Details of alternative fuel options based on Hoecke 2021[1], Biert 2020[2], Baldi 2020[3], Balcombe 2019[4], Al-Aboosi 2021[5], Baldi 2019[6], DNV 2019[7], Hansson 2019[8], Deniz 2016[9]

Energy carrier/converter	Emission factor[4]	Gravimetric density[1,2]	Volumetric density[1,2]	Conversion efficiency[2,3]	CAPEX storage[3,6]	CAPEX converter[3,6]	OPEX[4,6,7,8]
	gCO2eq/kwh	MJ/kg	GJ/m^3	%	€/kWh	€/kW	€/MWh
MDO-CI	620,700,780	30	29	35,40,45	0.08,0.09,0.1	451,575,821	40,120,200
MDO-SOFC	620,700,780	30	29	45,50,55	0.08,0.09,0.1	573,868,1296	40,120,200
LNG-SI	580,690,770	27	13	35,41,47	0.28,0.31,0.33	451,575,821	60,90,180
LNG-SOFC	580,690,770	27	13	45,52.5,60	0.28,0.31,0.33	573,868,1296	60,90,180
Methanol-SI	700,800,980	16	12.6	45,48.5,52	0.13,0.14,0.15	451,575,821	90,105,130
Bio-methanol SI	10,100,160	16	12.6	45,48.5,52	0.13,0.14,0.15	451,575,821	70,140,200
Ethanol-SI	100,200,300	18	16	45,48.5,52	0.13,0.14,0.15	451,575,821	90,110,180[9]
Ren NH3-SI	5,30,50	14	10	45,48.5,52	0.13,0.15,0.17	451,575,821	80,140,230
NH3-SI	80,100,280[5]	14	10	45,48.5,52	0.13,0.15,0.17	451,575,821	160,260,370
Bio-LNG-SOFC	210,350,470	27	13	45,52.5,60	0.28,0.31,0.33	573,868,1296	60,90,180
Bio-LNG-SI	210,350,470	27	13	35,41,47	0.28,0.31,0.33	451,575,821	60,90,180
Bio-liquid-CI	140,200,270	27	25	35,40,45	0.08,0.09,0.1	451,575,821	130,230,270
LH2-PEMFC	0,590,1000	11	5	40.50,60	0.8,0.83,0.85	500,730,900	75,300,590
Batteries	0,500,1000	1	2	85,90,95	150,260,500	-	30,200,370

The interrelations within the vessel are described using a simplified model which is shown in Figure 1. The ship design is subdivided into three main components; the energy carrier, the energy converter and energy users (operational power). Additional systems or vessel changes are shown in circles and include exhaust treatment (i.e. scrubbing, CCS), energy-saving (i.e. waste heat re-usage), power assistance (i.e. sails) and operational changes (i.e. speed reduction). Only the operational changes are researched.

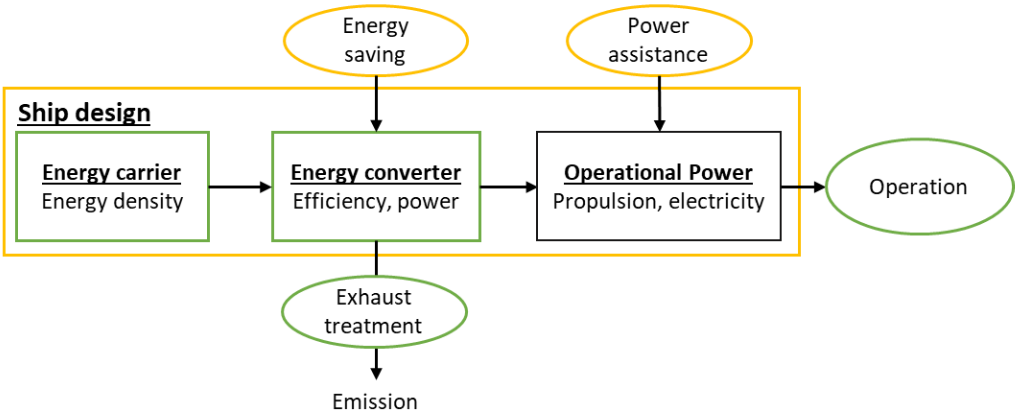


Figure 1: General vessel model

The vessel relations are modelled using functions that follow in Equation 1-4. The outputs include costs, emissions, necessary tank size, and mass, and are normalized against the current situation (MDO). Starting from the left part of the general vessel model, the necessary fuel stored for operation P_{store} in MJ is

$$P_{store} = 3.6\frac{s_{max}}{V_s}\left(\frac{W_e}{\eta_e+\eta_{save}}\right), \quad [1]$$

where η_e is the effective engine efficiency, which is dependent on the energy carrier and converter choice, v_s is the design speed, s_{max} is the maximum target sailing distance, and η_{save} is the efficiency increase due to energy saving engine measures. The total stored fuel power is translated to volume and mass is done using the volumetric density ρ_{vol} and gravimetric density ρ_{grav} or specific fuel consumption sfc respectively. The total necessary engine power in kW W_e is

$$W_e = \left(P_{aux} + \frac{c_1 V_s^3}{\eta_D \eta_{TRM}} - P_{ass}\right), \quad [2]$$

where c_1 is the factor of proportionality, P_{aux} is a constant auxiliarry power from hotel and operational load, η_D is the total propulsive efficiency, η_{TRM} is the total transmission efficiency, and P_{ass} is any power assistance that decreases the amount of total power. It is assumed that the total transmission and propulsive efficiency are constant and the vessel propulsion chain is simplified to have one propeller and one engine. The global warming potential in $tonne\ CO_2eq$ is

$$GWP = EF \cdot P_{store}, \quad [3]$$

where EF is the emission factor CO_2eq per kWh, which depends on the type of carrier, and P_{store} is the fuel stored for operation from Equation 1. The system costs C_{tot} is

$$C_{tot} = CAPEX_{conv} \cdot W_e + (CAPEX_{store} + OPEX) \cdot P_{store} + GWP \cdot C_{CO_2}, \quad [4]$$

where $CAPEX_{conv}$ is the capital cost of the converter system per installed kW, $CAPEX_{store}$ is the capital cost for storage per kwh, $OPEX$ is the operational expense for fuel, GWP is emission in tonne and C_{CO_2} is the potential cost per CO_2eq.

APPLICATION AND RESULTS OF EACH METHOD

The usability of each method is investigated by applying the methods stepwise. For every step, relevant criteria and insights for the application are discussed. Furthermore, it should be noted that the main goal is to use the case study to compare methods, rather then presenting insights for the maritime energy transition. Because of this, the case (ship model) is simplified and its findings should not serve as a basis for decision making, but rather as an indication of applicability.

Dynamic adaptive policy pathways (DAPP)

DAPP has been used to investigate alternative decisions in water management (Haasnoot, 2013). The method is an expansion of dynamic adaptive planning (DAP) (Kwakkel, 2010), which focuses on designing adaptive plans together with stakeholders. DAPP aims to further analyse multiple alternative decision sequences (pathways) to overcome deep uncertainty. The general setup of the method as adapted from Marchau et al. (2019) is shown in Table 3, which also includes the maritime energy transition case study approach.

Table 3: DAPP and case study setup

Step	Contains	Substeps	Maritime energy transition
1	Define decision context	Problem framing, system, objectives, outcomes and uncertainties	Case study setup, equal for all methods
2	Vulnerabilities & opportunities	Assess tipping points and develop (transient) scenarios and options	Identify emission reduction scenarios and options
3	Identify & evaluate options	Option efficacy	Model emission reduction option performance under uncertainty
4	Design & evaluate pathways	Create and explore pathways	Generate pathway map
5	Design adaptive plan	Select pathways, assess short term actions and long term options	Evaluate and analyse strategies
6-7	Implement and monitor	Apply and assess/change plan using signals	Not applicable for this analysis

DAPP step 1: Define decision context

During the context definition step, the decision environment, inputs, outputs and system relationships are established. This context definition is equal for all methods. The objectives of the case study are to comply with emission reduction, minimize cost and keep operational capability at a satisfactory level. Even though regulation compliance is dynamic (uncertain), the reduction of emissions is calculated relative to the current situation. Which is the initial general cargo vessel design, sailing on MDO, which is assumed to have no emission reduction measures. The design capabilities, including mass, volume, sailing distance, speed and endurance are used as a benchmark.

DAPP step 2: Vulnerabilities and opportunities

Step two is to further analyse the problem and determine tipping points, when the current situation can no longer meet target objectives. To establish tipping points, the original DAPP setup uses subjective scenario evaluation for a small number of extreme cases. However, because the performance of emission reduction measures can differ substantially due to input parameters, a quantitative method is deemed to be more suitable. Therefore, the vulnerability of the design to uncertainty is investigated using parameter ranges for cost (OPEX and CAPEX), energy conversion efficiency, and emission reduction performance instead. Furthermore, to research regulatory effects, an emission penalty of 0, 100 and 400 euros per tonne CO2eq is also simulated for the case study. The best, mean and worst-case performances are calculated using the general vessel model. The tipping point identified for the current situation is reached immediately, because the emission reduction is measured against the current situation. It is found that additional methods are necessary for ship design, because the original DAPP setup does not offer specific scenario and parameter sensitivity analyses.

DAPP step 3: Evaluate action efficacy

The efficacy of actions to outfit the initial design with other alternative fuels and converter technology from Table 2 are investigated. The best, mean and worst-case impact on costs, emission reduction percentage and vessel constraints (available mass and volume for energy options) of each action are shown in Figure 2. The values are normalized against the mean MDO case. The total capital expense has been normalized against the newbuilding cost. Batteries are found to be much too expensive for the sailing distance, showing that full electric solutions would only suit short sea shipping. The total CO2eq cost is normalized against the mean operational expense and shows the additional costs due to emission penalties. As can be seen in the Figure below, many of the energy carrier and converter combinations perform poorly in mass and volume categories. Besides this, the cost range for many options is still very broad, while emission penalties have the ability to greatly stimulate alternative fuel uptake.

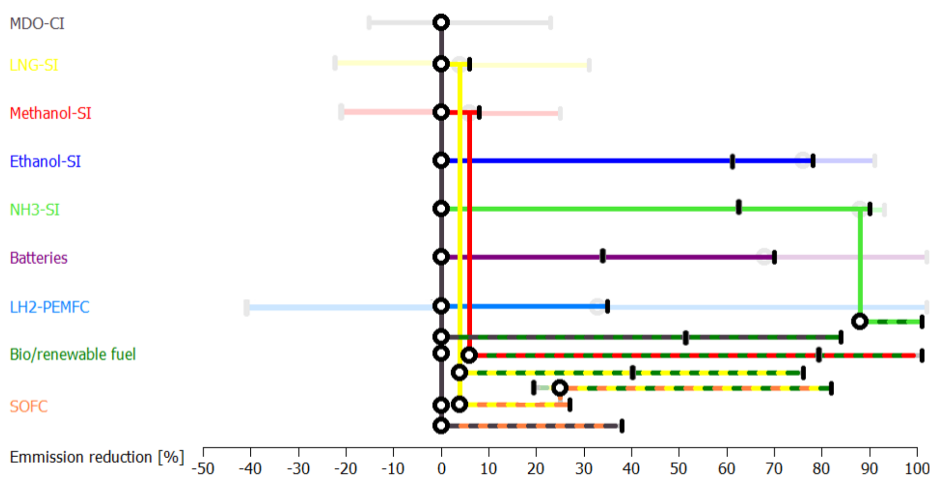
	Total CAPEX			Total OPEX			Total OPEX+CAPEX			CO2eq cost			Total cost		
Energy carrier-converter	**Best-case**	**Mean**	**Worst-case**	**Best-case**	**Mean**	**Worst-case**	**Best-case**	**Mean**	**Worst-case**	**Best-case**	**Mean**	**Worst-case**	**Best-case**	**Mean**	**Worst-case**
MDO-CI	96	100	107	30	100	190	36	100	183	0	58	297	23	100	296
MDO-SOFC	99	106	117	24	80	148	31	82	145	0	47	231	20	82	232
LNG-SI	103	108	117	43	73	171	48	76	166	0	56	293	31	83	283
LNG-SOFC	104	113	125	33	57	133	40	62	133	0	44	228	26	67	222
Methanol-SI	97	101	108	58	72	96	61	75	97	0	55	290	40	82	236
Bio-methanol SI	97	107	108	45	96	148	50	97	144	0	7	47	32	68	123
Ethanol-SI	97	101	108	58	76	133	61	78	131	0	14	89	40	59	138
NH3-SI	97	101	108	103	179	274	102	172	259	0	7	83	67	116	218
ren-NH3-SI	97	101	108	51	96	170	56	97	165	0	2	15	36	64	116
Bio-LNG-SOFC	104	101	125	33	57	133	40	61	133	0	22	139	26	53	169
Bio-LNG-SI	103	115	117	43	73	171	48	77	166	0	28	179	31	67	215
Bio-liquid-CI	96	100	107	96	192	257	96	183	243	0	17	103	63	130	220
LH2-PEMFC	116	127	138	42	200	492	48	193	459	0	39	333	32	150	498
Batteries	2606	4700	9484	11	74	145	248	497	999	0	19	157	162	336	746

	Emission reduction			Volume usage			Mass usage		
Energy carrier-converter	**Best**	**Mean**	**Worst**	**Best**	**Mean**	**Worst**	**Best**	**Mean**	**Worst**
MDO-CI	21	0	-27	39	44	51	86	97	111
MDO-SOFC	36	20	1	32	35	39	71	78	86
LNG-SI	29	4	-26	84	96	113	92	105	123
LNG-SOFC	45	25	2	66	75	88	72	82	96
Methanol-SI	23	6	-24	78	84	90	140	150	162
Bio-methanol SI	99	88	80	78	84	90	140	150	162
Ethanol-SI	89	76	62	62	66	71	124	133	144
NH3-SI	91	88	64	99	106	114	160	172	185
ren-NH3-SI	99	96	94	99	106	114	160	172	185
Bio-LNG-SOFC	80	62	40	66	75	88	72	82	96
Bio-LNG-SI	74	51	23	84	96	113	92	105	123
Bio-liquid-CI	82	71	56	46	51	59	96	108	123
LH2-PEMFC	100	33	-43	171	205	256	176	212	265
Batteries	100	68	33	270	285	302	1226	1294	1370

Figure 2: Option results for DAPP

DAPP step 4: Pathway map and evaluation

The next step for DAPP is the use of the pathways generator software tool developed by Deltares (Pathways generator). It is used to create a pathways map and scorecard that summarize the option results in Figure 10. The addition of fuel cells or renewable fuels is added as an additional step (dashed lines) from an initial energy carrier. An uncertainty range has been manually added to visualize the best and worst-case cut-offs. The current EU emission reduction target of 55% GHG reduction by 2030 can only be reached by 7 out of 13 pathways. The



Pathway	Volume	Mass	Rel. cost	Safety
	-	+/-	+/-	-
	+/-	-	+	-
	+/-	-	+	-
	-	-	-	---
	---	--	----	-
	---	---	---	--
	-	+/-	+	-
	+/-	+	++	-
	+/-	+	++	-
	+/-	+/-	-	-
	+	++	+	+/-
	-	-	+	---
	+/-	-	+	-

Figure 3: Pathways map and scorecard

scorecard further visualizes pathway performance regarding volume, mass, relative cost and safety. By providing such pathway information for a specific ship during its design phase, the decision-maker gains a global overview of the impact of different options on the capability and cost of the design. Furthermore, the future actions and uncertainty range offer a perspective of opportunities and vulnerabilities.

DAPP step 5: Designing an adaptive plan

Using the pathway evaluation, an adaptive plan is designed to outline how to reach target objectives. This plan includes preparation that enables promising pathways. Besides this, ways of monitoring are established to continually measure if the plan proceeds as expected or if one of the other pathways should be followed instead. For the case study, the requirements for several promising carrier-converter combinations are reviewed in Table 4. It is clear much more development is necessary before these options can be implemented. Typical design preparations include compliance with safety measures, storage requirements and enable additional system placement. Monitoring should primarily focus on logistics and system development, to understand when to adjust course.

Table 4: Promising carrier converter requirements

	Storage	Ship systems	Safety	Logistics	Other
Bio-methanol	tank + cofferdam, cargo mass decrease	Double-walled piping, 0.8m from hull plating, special vent placement	low toxicity, low flashpoint, flammable	Increase 'green' production	
Ammonia	new tanks pressurized & refrigerated, special placement, large cargo mass decrease	Double0walled piping, 0.8m from hull plating, special vent placement, reactor.	High toxicity, flammable	Feedstock problems	NOx problem
Bio-liquids	small cargo mass decrease	no changes	Toxic to environment	Feedstock problems	NOx problem
Ethanol	tank + cofferdam, cargo mass decrease	Double-walled piping, 0.8m from hull plating, special vent placement	low flashpoint	Feedstock problems	

DAPP step 6 and 7

The last two steps, adaptive plan implementation (step 6) and monitoring and adapting (step 7), concern the application of the plan during the lifetime. For the case study, the implementation will have to be executed together with a yard and shipowner, during the building or retrofit phase of the vessel. By regularly monitoring the development of technology and logistics, the plan can be adapted to ensure compliance. Besides this, ship owners can pro-actively contribute to technology development that suits their pathways. Nevertheless, because of the nature of ships, design preparation can be difficult and will involve large investments. Therefore, it is important to include a more detailed exploration of different path enablers as part of the adaptive plan, to be able to evaluate the costs and impact of these measures.

DAPP findings

The focus of DAPP is to create and implement adaptive plans that allow decision-makers to map a pathway toward meeting set targets. This proactive way of dealing with uncertainty could be effective for ship design because the delivery and continual adaptation of a plan stimulate dealing with deep uncertainty. Furthermore, DAPP can be used to structurally implement the development of adaptive plans in the ship design process.

However, to gain detailed information about pathways and uncertainty effects additional methods are needed. It is important to carefully select a method, as it affects DAPP input quality from the action efficacy step onward (steps 3-5). For example, the best- and worst-case range method that was used in this case study lacked detailed scenario analysis. Therefore, it was difficult to track outcome sensitivity to specific inputs, which is necessary for vulnerability analysis. Besides this, even though the pathways map and scorecard allow clear insights, the number and detail of options and outcomes that can be visualized are limited. DAPP offers a beneficial framework to create adaptable plans for dealing with uncertainty during the lifetime, but it needs to be expanded with more detailed inputs and modelling.

Responsive systems comparison (RSC)

RSC is an extension of epoch era analysis (EEA) and multi-attribute tradespace exploration (MATE), it is used to explore the effect of uncertain scenarios by evaluating alternative decisions in multiple short-term events (epoch) and randomly combined epochs (era) (Ross 2008). The setup of the method is shown below, it primarily differs from EEA because of the additional changeability assessment in terms of the filtered outdegree (Ross 2009). The method was previously used to evaluate the flexibility of retrofits to deal with market changes (Rehn 2016). It offers multiple ways to analyse design performance and might also provide valuable insights into the maritime energy transition.

1. Value driving context definition
2. Value-driven design formulation
3. Epoch characterization
4. Epoch analysis
5. Multi-epoch analysis
6. Era analysis and multi-era analysis
7. Changeability assessment

RSC step 1 & 2: Value driving and design context definition

The first two steps of RSC are to establish performance measures and define what design options to investigate. In the case study, the objective is to design a value robust ship that is able to deal with uncertain technology development and emission reduction regulation. Utilities can be identified in discussion with stakeholders. For the case study, utilities for design capability and emission reduction are estimated independently and are shown in Table 4. The target is to maximize total utility, while also analysing each attribute separately. To adjust the focus of the total utility, weight factors for each attribute can be used. However, even though utility can be useful for suitable design option identification, utility is still subjective and thus subject to bias.

Table 5: Value driving attributes

Attribute	Values	Unit	Utility
Emission reduction	0 – 100	%	0 – 1
Endurance	20 – 50	Days	0 – 1
Distance	0 – 8000	Nm	0 – 1
Speed	10 – 14	kts	0.6 – 1
Cargo volume	1000 – max	m^3	0 – 1
Cargo weight	9000 – max	tonne	0 – 1

A few exemplary design variables are shown in Table 5 below. The basic vessel is calculated with different combinations of speed, energy converter and energy carrier. This results in 97 different design alternatives.

Table 6: RSC Design variable

Design variable	Values	Unit
Speed	10, 12 ,14	kts
Distance	4000, 8000	nm
Converter-Carrier option	MDO - … - Batteries	-

RSC step 3: Epoch characterization

The next step is to establish scenarios for research and to translate these to epochs. Epochs are combinations of several predefined values, as shown in Table 6. The values 0,1 or 2 correspond to the technology-dependent worst, average or best case from Table 2. The vessel model is used to calculate the performance of every alternative design in each scenario.

Table 7: Case study epoch variables

Epoch variable	Values	Unit	Number of steps
Emissions	0, 1, 2	g/kWh	3
Emission tax	100, 250, 400	$/tonne	3
Tech availability	0, 1	yes or no	2
η_{conv}	0, 1, 2	-	3
$CAPEX_{storage}$	0, 1, 2	$/kWh	3

$CAPEX_{system}$	0, 1, 2	\$/kW	3
OPEX	0, 1, 2	\$/MWh	3
Total epochs			1458

RSC step 4: Epoch analysis
RSC provides multiple tools to analyse the performance of an epoch, of which most are so-called trade-space visualizations. For example, Figure 3 shows the total utility versus cost for all epochs and all designs. One of the findings in the case study is the effect of sailing distance, where ammonia (grey) has a better total utility for lower distances, while bio-methanol (brown) is a better alternative for higher distances. For more detailed epoch specific information, epochs need to be inspected manually.

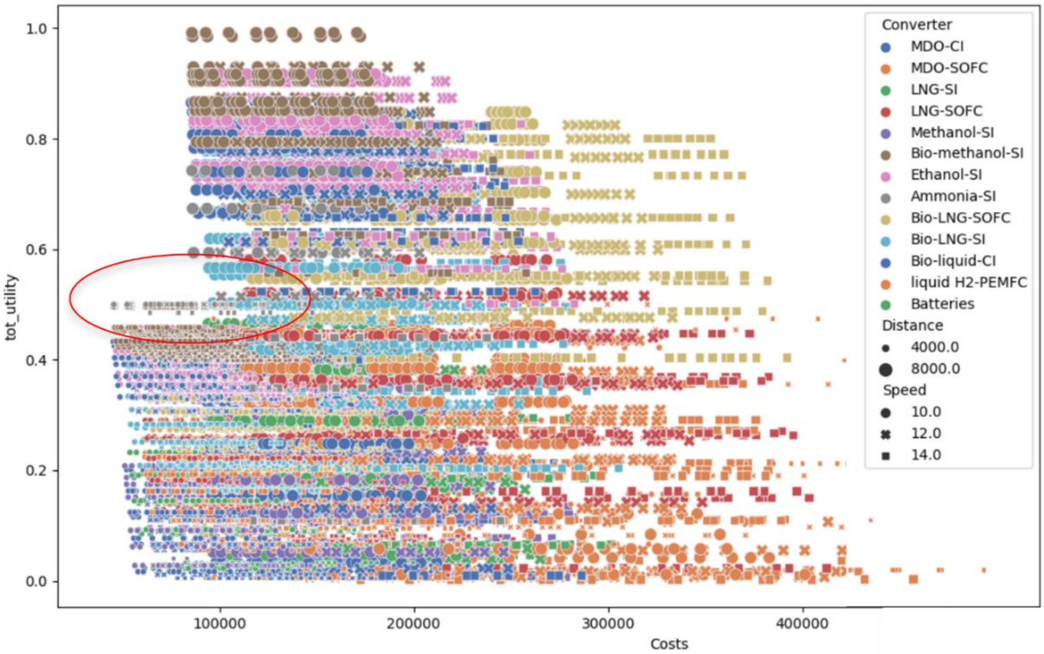


Figure 4: Total utility versus cost for different options, varying design speed and sailing distance

RSC step 5: Multi-epoch analysis
RSC can also be used to research the robustness or performance of a design in multiple scenarios (epochs). An example of a parameter occurrence plot has been visualized in Figure 4. It shows the fuel volume that is necessary to meet objectives (speed, sailing distance), including the maximum available volume (red line at 900 m3). Graphs like this might be used to determine if the ship design should be altered (fuel volume increased) in support of future emission reduction measures. The difference in design performance between multiple epochs can also be visualized using a Pareto trace. When performance differs widely, a design might be vulnerable to important scenarios and needs to be adjusted or avoided.

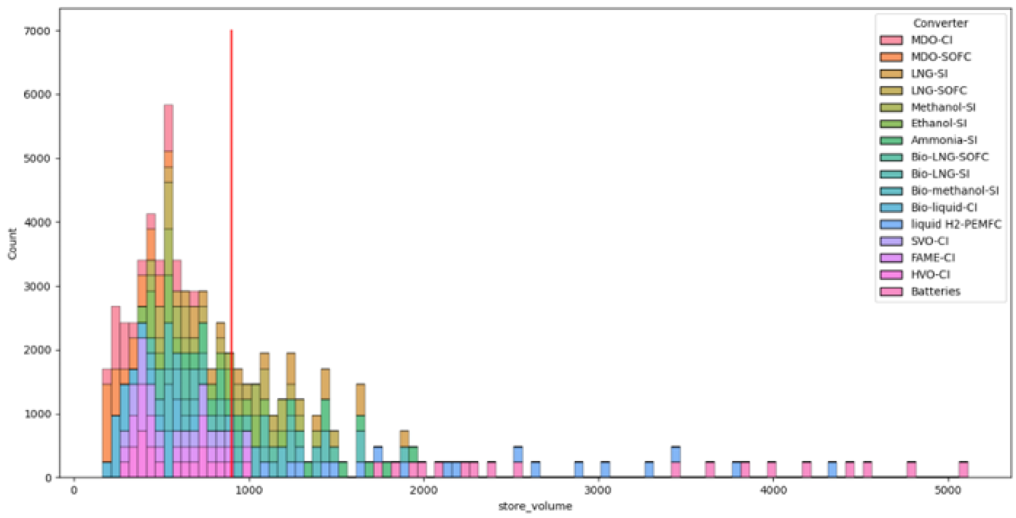


Figure 5: Fuel storage volume occurrence plot

RSC step 6: Era analysis
By analysing eras, the performance of designs during a lifecycle (random combination of epochs) can be investigated. For example, Figure 6 shows the performance of emission reduction options in an interesting lifecycle for the case study. The scenario starts with an epoch that represents the current situation, without regulation, while much of the emission reduction technology is still under development. Next, technology becomes available, but fuel availability is still low (fuel cost increases). In the third epoch, 40% reduction is regulated, which results in an omission of LNG. Next, additional emission taxes are charged and fuel demand increases (cost increase). Lastly, a 90% reduction regulation is mandated. Single eras like these can be used to investigate specific scenarios. Furthermore, a multi-era analysis can again be used for sensitivity analysis.

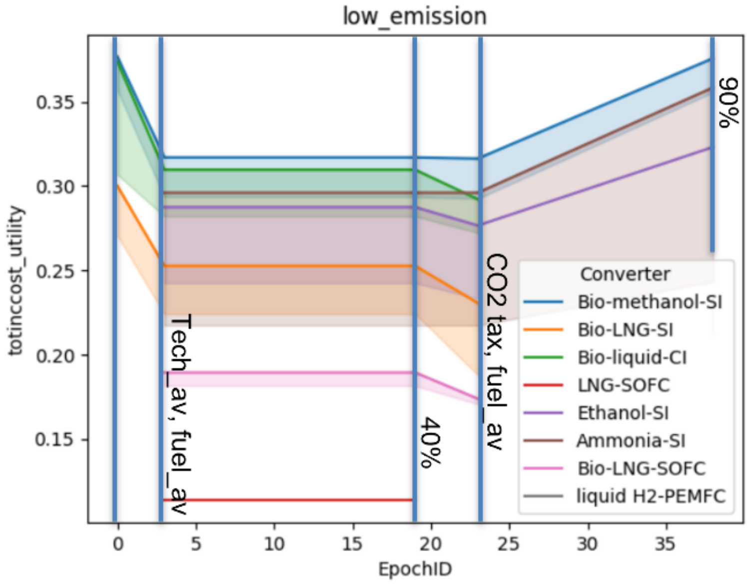


Figure 6: Era analysis consisting of 5 different relevant epochs

RSC step 7: Changeability assessment
RSC evaluates the possibility to transition between multiple design options (e.g. retrofit) by using the filtered outdegree measure (Ross 2008). This measure represents the number of designs that an initial option can be changed to, below an acceptable cost threshold C. First, a set of transition rules on what can be changed have to be defined. For example, the rules that are considered in the case study are to either increase fuel storage size, change emission reduction technology, or add on-deck storage. For each transition rule and epoch, a transition matrix has to be created that represents design relations, such as the cost of transition and its impact on capability (cargo volume and weight).

An example of the filtered outdegree plot versus investment cost per kWh is shown in Figure 7. Depending on the initial energy carrier-converter combination (in colour), the graph visualizes the increasing amount of other options that can be reached for an increasing cost threshold. Such a changeability assessment can be used to determine what initial design is more changeable. For the case study, bio-LNG (brown and purple lines) is found to be cheaper to change from. However, it should be noted that the filtered outdegree isn't time-bound and doesn't show specific transition options. These options might even result in worse emission reduction than the initial design, the starting options could be more expensive, or the transition might not be possible in reality. Furthermore, the transition matrices are difficult to expand or adjust.

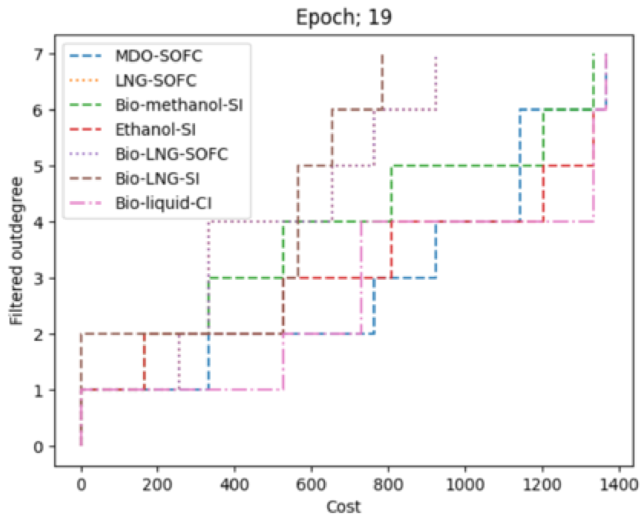


Figure 7: Filtered outdegree for multiple start options versus investment cost/kwh

RSC findings

When value, design and scenario variables are assigned carefully, many different design options in specific scenarios can be investigated. However, besides variable selection, relationships need to be properly modelled to ensure meaningful results. Consequently, because of the large number of inputs, unclear variable sensitivity and case-specific setup, RSC is more suitable for scientific use, instead of supportive use in the design process.

Robust decision making (RDM)

RDM is typically used to evaluate the robustness of a decision in multiple scenarios, while iteratively developing decision improvements (Lempert 2019). The steps of robust decision making are described below. To apply RDM to the case study, the exploratory modelling and analysis (EMA) workbench was used (Kwakkel, 2017).

1. Pre-specify alternatives
2. Explore scenarios using sampling
3. Measure robustness
4. Vulnerability analysis
5. Iterate new alternatives

RDM step 1: Pre-specify alternatives

The first step is to identify decision options (levers), uncertainties, outcomes and a model that approximates relationships. For the case study, the simplified vessel model from Figure 1 has been coupled to the EMA toolbox. The decision options (levers) are different emission reduction technologies. The decision-maker selects relevant uncertain values for research. Table 7 shows the value range that should be researched. The speed and distance are also selected to be able to explore the effect of these parameters on outcomes. The outcome parameters that are specified for the case study are fuel volume, fuel mass, cost, possible emission reduction, and vessel attainment (how much distance travelled with a fuel volume).

RDM step 2: Explore scenarios

To explore the effect of the uncertain factors, EMA uses range sampling. Specifically, Latin hypercube sampling (LHS) has been used for the case study, as it aims to describe the full range. The emission range is dependent on each emission reduction. The cost per kW for conversion and fuel cost, and the cost per kWh for storage are varied to represent technological uncertainty.

Table 8: Scenario variables

Input	Lower	Upper	Unit	Note
Emission tax	100	400	$/tonne	
η_{conv}	0.3	0.8		
$CAPEX_{storage}$	450	1300	$/kWh	
$CAPEX_{system}$	0.1	0.9	$/kW	
$OPEX$	150	1000	$/kWh	
Emission	0	1	g/kWh	Fuel dependent
Speed	12	14	kts	
Distance	4000	10000	nm	

RDM step 3: Measure robustness
Several measures for robustness are available to explore the robustness of a design against uncertainty and to establish the vulnerability of alternative designs. The EMA toolbox provides measures like max-regret, satisficing and signal to noise. Figure 4 shows an example of the max-regret measure, where the difference in performance between the best and worst scenarios is calculated for multiple outcomes (lower value is less difference). Such measures can be used to understand how sensitive an option's performance is to different scenarios. In the case below, biofuels look pretty good, while ammonia are more sensitive to attainment.

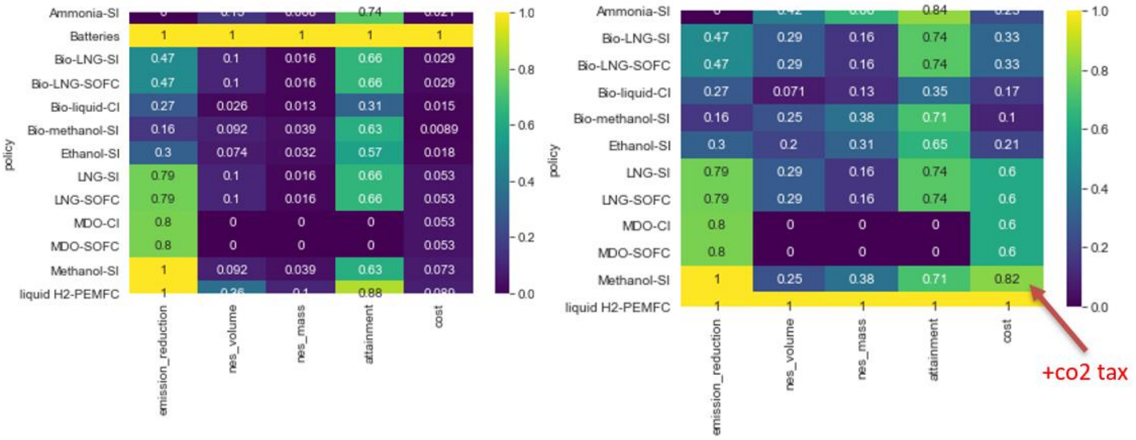


Figure 8: EMA max regret robustness measure

RDM step 4: Vulnerability analysis
Scenario discovery is used to identify under what circumstances (scenarios) a target outcome can still be met. Such information can be used to investigate the vulnerability of an option to specific uncertain parameters. Figure 5 shows a vulnerability scoring analysis that visualizes the circumstances (combination of uncertain parameters) for the case study under which a design option meets an emission reduction target. The squares from dark blue to yellow show zero to full compliance with the target below the figure (carrier-converter, emission reduction). The uncertain parameters are shown on the sides with a range from 0 (low) to 2 (high).

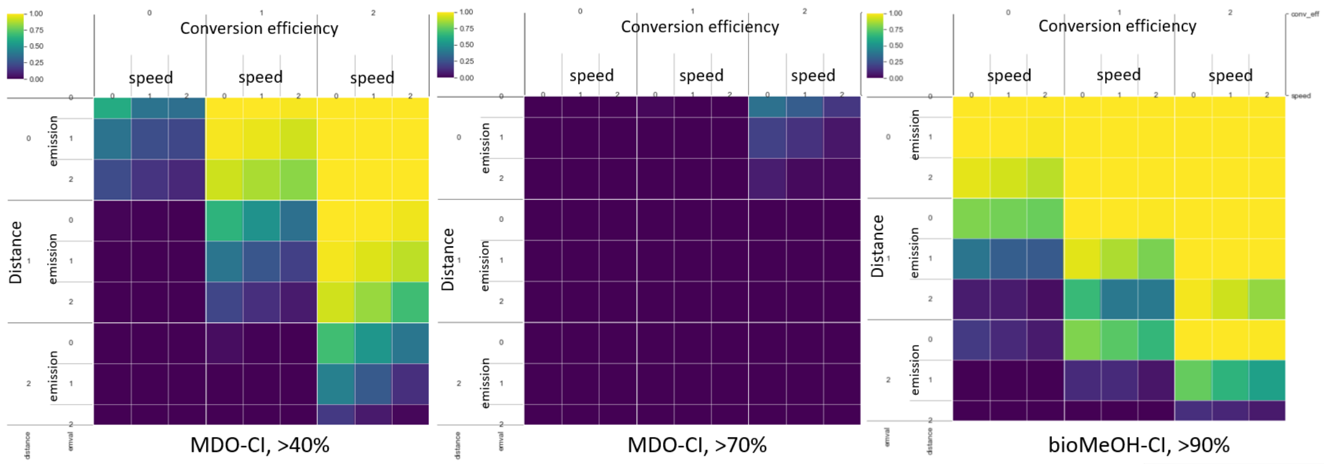


Figure 9: RDM vulnerability feature scoring analysis

Besides vulnerability, the figure can be used to establish trade-offs between parameters. By including more changeable parameters in the analysis, such as speed and distance, the decision-maker can establish what measures they have to delay more drastic actions. The EMA toolbox also offers a more detailed compliance range estimation with PRIM algorithm. As shown in Figure 6, such an algorithm can be used to enable decision-makers a straightforward way to explore more detailed scenarios. For example, the minimum technological performance (conversion efficiency, emission reduction performance) for compliance can be established. This information can be used by designers to understand and reject unrealistic expectations and focus on other options. Nevertheless, it is important to use a large enough sampling size and to ensure convergence in EMA.

RDM step 5: Iterate new alternatives

After establishing the vulnerability of different options, other alternatives could iteratively be researched. For example, promising carrier-converter options can be reassessed in combination with power assistance or energy saving options. However, this has not been done for the case study.

RDM findings

RDM is a versatile method that allows for detailed exploration of the effect of uncertain parameters. As found in step 4, by cleverly determining what research parameters (uncertainties) to analyse, the method can be used for a type of backwards analysis, to find compliance ranges for a wide range of scenarios. This allows for detailed parameter sensitivity and specific scenario analysis, without pre-definition of scenarios and their ensuing bias. Furthermore, because scenario assessment is undertaken as a part of the final analysis, value and outcome parameter estimation is less complicated when compared to other methods. Nevertheless, the properly modelling of system relationships is still a crucial part, but it might be modelled in such a way that reusing (of parts) becomes possible. Further research should look into developing a system model that can be used for multiple ship types for application during the design process.

Besides modelling, the number of design options are limited to the levers and uncertain parameters. This might be solved by going through multiple iterations (step 5), but when many options are needed this could become exhaustive. To deal with this, methods that expand upon RDM, like multiple objective RDM (MORDM) might be used. This method adds an initial design optimization step, which is also easily applied using the EMA toolbox. However, even with extensions, RDM lacks a framework like DAPP that guides decision-makers on how to deal with the identified vulnerabilities.

COMPARISON OF RESULTS

DAPP deals with level 3 uncertainty and up. The method is applied during three ship-cycle stages, the design stage (strategy creation), production stage (implementing strategy) and operation stage (measuring and adapting strategy). Because of its continual development during the lifetime of the ship, it can include many alternative system models, options, outcomes and scenarios, even those that were initially unknown. DAPP provides a global, but clear overview of the possible future adaptive strategies toward compliance of the design. Nevertheless, because of its global nature, the output is limited to a low level of detail. Fortunately, the input from other methods, that allow more detailed design exploration, can be used to extend its capability. However, a coupling method should be comprehensive by itself, because nuances are neglected in the global output of DAPP. Therefore, to apply DAPP in the design process, uncertainty identification and pathway map input should be standardized. Nevertheless, the benefit and innovation in using DAPP for the maritime energy transition is the implementation of an adaptive plan, monitoring tipping points and further adapting strategy during the lifetime of a ship.

RSC deals with level 3 and 4 uncertainty and can be used to research many future scenarios. Furthermore, by using eras, it can even research previously unknown (and sometimes implausible), combined scenarios. However, because epochs are pre-determined and detailed analysis is limited to a few scenarios, bias may occur and important scenarios can easily be overlooked in a large amount of output data. The method does however offer a wide range of analysis tools and is able to research many alternative options. Nevertheless, since RSC uses discrete value ranges and outcome selection to decrease computational strain, it is possible to miss unusual option effects. The method does provide a more detailed insight into technology options in specific scenarios and includes the evaluation of strategy transition in a scenario. RSC is useful for in-depth research, but is susceptible to bias, because a limited amount of pre-determined scenarios and alternatives are selected for further analysis. Furthermore, the design process focus shifts toward RSC, due to the significant workload of identifying transition matrices, method variables and extensive modelling of functional relationships. Therefore, RSC is deemed to be a scientific tool for specific scenario exploration, rather than a useful addition to the design process.

RDM deals with level 3 and 4 uncertainty and uses range sampling to describe the full trade space of each uncertain parameter. The initial method only deals with a limited amount of design options, but could lead to unknown solutions due to its iterative nature. Furthermore, extensions are able to deal with more alternative options and objectives. Because the method is focused on establishing the vulnerability of an option to uncertainty, it is especially useful to identify pro-active designs. It allows the detailed exploration of uncertain parameters and the circumstances under which these result in a desired outcome. The use of the EMA toolbox also presents an advantage, because it can be added upon to create a toolbox for the ship design process. However, because the number of options is limited and the method is mainly focused on identifying the vulnerability of one input design, the analysis of a large number of designs might become extensive. Furthermore, it is left to the designer to propose improvements to the design. Besides this, implementing an adaptive strategy is more difficult. However, since the identification and improvement of vulnerabilities are iterative, the method can fit well within the current design process. Furthermore, increasing the number of alternative designs and adding multiple objectives is possible by using an extension of RDM (Marchau, 2019).

The criteria for the ship design process are scored and compared in Table 8. It is clear that the strengths and weaknesses of each method lie in specific parts, while none fulfil all of the criteria to the desired degree. DAPP provides a strategy overview that can further be developed during the lifecycle, but it lacks a detailed option and scenario exploration. Alternatively, RSC and RDM allow a more detailed analysis of specific scenarios and parameter sensitivity respectively. However, the methods are focused on a few pre-defined design options without developing an adaptive strategy. By using RSC or RDM as input for DAPP, a lifetime strategy can be developed from the extensive analysis. By using such a method in parallel with the ship design it can be better equipped to deal with deep uncertainty. Nevertheless, further research is required to be able to develop a combined method that is able to satisfactorily meet the criteria.

Table 9: Method comparison criteria scoring

Criterion	DAPP	RSC	RDM
Max uncertainty level	5	4	4
Uncertainty vulnerability	2	4	5
Scenario analysis	2	5	4
Parameter sensitivity	1	3	5
Design exploration	4	3	4
Design robustness	4	3	5
Adaptive design	4	3	3
Adaptive strategy	5	3	2
Supportive setup	3	2	4

Both RSC and RDM might be used as input for the DAPP framework. However, for the ship design process, RDM performs better than RSC in most criteria. More importantly, RDM is identified to be more suitable as a supportive method. Nevertheless, much should be done to properly combine DAPP and RDM. Besides coupling, to ensure valuable results and proper usability, a general setup and modelling framework needs to be created, while carefully integrating it into the design process.

CONCLUSION

Three promising methods from different research fields were applied to a preliminary case study of a general cargo ship. The methods were compared to research what insights could be gained on uncertainty and alternative fuels and establish how such methods might be of use to the ship design process. Dynamic Adaptive Policy Pathways (DAPP) evaluates alternative options (compliance limit) and develops possible pathways to compliance. The Responsive Systems Comparison (RSC) method combines Epoch Era Analysis (EEA) and multi-attribute tradespace exploration (MATE), which evaluates the performance of a design in established scenarios (epoch), also allowing evaluation including retrofit (changeability). Robust Decision making (RDM) explores the effect of uncertainties on a pre-specified design and analyses under which circumstances objectives are met.

Based on this evaluation, each of the researched methods delivers different but valuable insights into option performance in uncertain conditions during the early design stage. DAPP provides a global, but clear overview of the possible future pathways toward emission reduction compliance of the design. RSC gives a more detailed insight into technology options in specific scenarios (including evaluation of changeability in a scenario). RDM enables more in-depth research of uncertain parameters and the circumstances under which an option might comply. By applying a method that combines aspects from DAPP with RDM during the ship design process, the ship designer can explore the vulnerability of design options and develop a continual adaptive strategy to deal with uncertainty.

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