Understanding agility as a parameter for fuel-flexible ships

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ABSTRACT

With the need for lower-emission maritime transport solutions, shipowners and designers face uncertainty when it comes to the selection of fuel today and in the future. The effects of this uncertainty can be mitigated to a certain extent by fuel-flexible machinery and containment systems When developing such fuel-flexible designs, capability, changeability and agility are important parameters to be considered. Thus, the required time and cost consumed for conversions or retrofits at a later stage during the vessel's lifetime need to be addressed in the early design phase. We apply and discuss the concept of agility for both existing flexible solutions and new ship design alternatives in this paper.

KEY WORDS

Agility; flexibility; fuel; uncertainty; ship design; greenhouse gas; emission

1 INTRODUCTION

Thriving to contribute to the goals of the Paris Agreement (United Nations 2015), shipping, though not being regulated under the same agreement, is setting tightening greenhouse gas (GHG) emission goals for itself (International Maritime Organization 2018). The translation of these goals into legislative requirements is still ongoing (International Maritime Organization 2021). Individual members of the IMO aim to increase the level of ambition, potentially through regionally stricter requirements (European Commission 2019; European Community Shipowners' Association 2020). Neither the level of ambition nor the concrete per-ship or per-fleet requirements can be seen as cast in stone and introduce significant uncertainty for decision-making today.
Additional uncertainty is brought to the game by various technical solutions at different development stages and with different effects on potential emission reductions (DNV GL 2019). As for alternative fuels, according to CE Delft (2020) with the largest emission reduction potential, the reduction effects hinge on the technological development of their availability and thereby often renewable electricity capacity and its prioritization.

Flexibility as a strategy to meet future unpredictability
The unclear requirements and immature technologies increase the contextual and behavioral complexity (Gaspar et al. 2012), while being additionally coupled with time. Flexibility can, however, be a valuable strategy for dealing with uncertainty, particularly time-dependent, in engineering systems (de Neufville and Scholtes 2019). The value of flexibility for ships has been shown by Buxton for a container ship: rather than investing into the "most generous ship capital can provide", it can be more preferable to design a smaller ship that contains certain options that can be exercised when the market development is known more clearly. Both Choi and Erikstad (2018) and Rehn (2018) have shown similar effects in different merchant vessel design cases.
Flexibility has also been chosen in Navy circles. Hornhaver (1995), Warship Technology (2006) and Volkert (2010), employ flexibility as a response strategy to future uncertainty with respect to mission requirements. Notably, these papers use standard modules to exchange or extend capabilities throughout their service life. In order to be able to exercise these options, the modules and particularly their interfaces need to be considered in the design process from the start (Schank et al. 2016). Andrews (2001) highlights the importance of margins for through-life changes.
In the light of stricter GHG emission requirements, flexibility has recently received a lot of attention in the shipping industry. The Spirit of British Columbia was converted from very low sulphur fuel oil (VLSFO) to liquid natural gas (LNG) (MarineLink 2018). In Europe, the Stena Germanica received capability of running on methanol (Naval Architect 2015). Maersk (2021) announced to build dual-fuel ships VLSFO and methanol and ColorLine investigates conversions to ammonia (Ammonia

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Energy Association 2020). On the engine side, Anglo Belgian Corporation is currently developing retrofittable four-stroke engines (Anglo Belgian Corporation 2021), while MAN Energy Solutions (2019) as well as WinGD (2021) are working on two-stroke combustion engines solutions capable of running on alternative fuels such as ammonia or methanol. Each of these alternative power options come with a certain level of flexibility with respect to fuel compatibility. For a given level of fuel-flexibility, however, the question "how quick and how costly should a fuel switch be?" arises. This question circles around the parameter of agility, which we will discuss in the remainder of this paper.

Agility as a characteristic of flexibility and meeting low-emission goals
In this paper, we investigate agility as an adverb to flexibility in the light of low-emission goals. That is, flexible ship designs at different levels of agility, which shall help meeting future low-emission requirements. We do so by:

1. Establishing an operational definition of agility (grounded in both literature & daily use), Section 2
2. Illustrating design options with different levels of agility, Section 3
3. Discussing these options and their value in Section 4

Section 5 will conclude the paper.

2 LITERATURE REVIEW AND DEFINITIONS

Agility, and -ilities in the broader sense, are system capabilities/attributes in response to changing requirements and contexts. Section 2.1 will provide a short introduction to the -ilities. Section 2.2 aims to review and condense literature on agility in order to establish an operational definition for this paper. Section 2.3 provides some examples, both from general engineering and the maritime domain, for agility.

2.1 -ilities

Ross et al. (2008) provide a comprehensive set of definitions for various -ilities. They suggest that -ilities are system properties that contribute to a system's overall changeability. The purpose of changeability in turn is sustained value-robustness throughout the system's life cycle. Their proposed taxonomy characterizes changeability according to:

- *Change agent:* external (flexible) vs internal (adaptable)
- *Change mechanism:* "the particular path the system must take in order to transition […]" (Ross et al. 2008)
- *Change effect:* no system change (robust), parameter level changed (scalable), parameter set changed (modifiable)

We see this taxonomy as being generally useful, as it enables a systematic discussion of -ilities. However, their suggested definition for flexibility does not necessarily coincide exactly with the everyday use of this term. For this paper, we hence employ the definition "the ability to change to suit new conditions or situations" (Oxford Learner's Dictionaries 2022). We think that this definition better represents the everyday use of the word "flexibility".

2.2 agility

Instead of defining agility explicitly in their -ility framework, Ross et al. (2008) refer to Fricke and Schulz' (2005) definition of agility: "ability to be changed rapidly" indicates that agility is both linked to the duration of change and to an external change agent.
The following table provides a brief overview of alternative definitions of agility in literature and dictionaries:

Table 1: Alternative definitions of agility

Reference	Definition	Limitations
Haberfellner and de Weck (2005)	"flexibility at speed"	Time only
Fricke and Schulz (2005)	"ability to be changed rapidly"	External change agent, time only
Dove and LaBarge (2014)	"Agility is the ability of a system to thrive in an uncertain and unpredictably evolving environment; deploying effective response to both opportunity and threat, within mission. Effective response has four metrics: timely (fast enough to deliver value), affordable (at a cost that can be repeated as often as necessary), predictable (can be counted on to meet the need), and comprehensive (anything and everything within the system mission boundary)."	Uncertain and unpredictable environments
Oxford Dictionary (2022)	*(Business)* "The ability to change rapidly in response to customer needs and market forces; adaptability, flexibility, responsiveness."	Time only
Latin-English Dictionary (2022)	agilis *(latin, adjective)*: "agile, nimble, quick, swift; alert (mind), active; energetic, busy; rousing"	

Being strongly intertwined with concepts such as flexibility or adaptability, agility needs to be seen in relation to its neighboring -ilities (Dove and LaBarge 2014). Apart from flexibility, we employ Ross et al.'s (2008) definitions of -ilities. The limitations in the third column of Table 1 are therefore seen in relation to those definitions. From this viewpoint, Fricke and Schulz' (2005) definitions imply an external change agent. Moreover, Haberfellner and de Weck's (2005) as well as Fricke and Schulz' (2005) concept of agility considers the time of change as the only measure for agility. Dove and LaBarge (2014a) suggest a mixed construct for agility which comprises costs, predictability and comprehensiveness in addition to time. However, their definition is limited to uncertain and unpredictable environments with some associated strong limitations on probabilities.

In order to not limit agility to environments with certain probabilistic attributes, we will employ a definition of agility as "ease to change". This definition is not limited to an external change agent, which means it can be used as an independent modifier for changeability. Within Ross at al.'s (2008) framework, agility thus becomes an attribute of the change mechanism that denotes the ease to change. Most importantly, the "ease to change" is a construct which includes not only time as an important factor, but also further resource expenditures such as cost or personnel. Such ease can be achieved through quick, but also cheap changes. Agility is hence inversely related to effort or resource expenditures: The less effort or cost required for change, the more agile system.

2.3 Engineering examples for different levels of agility

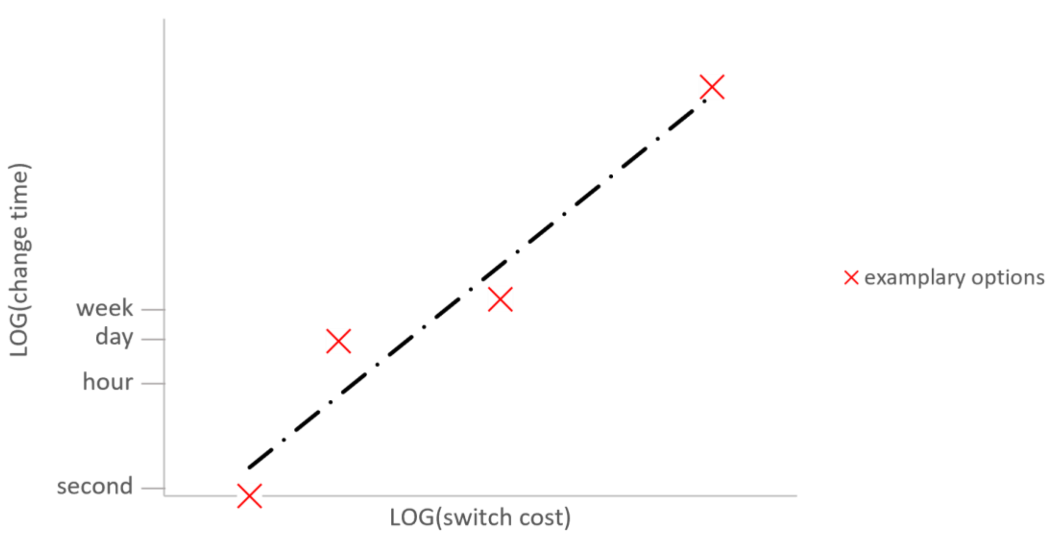
In Section 1, we have already given a few examples of flexibility in ship design. The previous paragraphs have put forward our proposition of agility as an adverb to flexibility. More specifically, an adverb that denotes the "ease to change". The following examples shall help illustrating this point:

Passenger cars are often used by one person at a time. However, there are occasions when many people shall be transported, hence more seats are required. In addition to fixed seats, larger cars sometimes feature foldable rear seats which provide such flexibility. But how easily should these seats be foldable, or perhaps even mountable? Is it better to store spare seats in a garage and mount them when needed? Or should they be folded to the floor and be put up, whenever and wherever necessary? If so, how easily should this be done: is a push-button mechanism required or are manual actions sufficient? These questions all relate to the appropriate or desired level of agility.

In maritime applications, the Danish Standard 300 Flex serves as an example for agility (Hornhaver 1995; Parker and Singer 2012). The ship is reconfigurable by swapping containerized modules in port. In that way, the ship is more agile than if only weight and spaces margins had been set beforehand. As indicated by Figure 1, higher switching costs are generally associated with longer times for switching. The relation does not necessarily be linear though: If the shipowner's contract always spending a certain amount of time in dock per year, there may not be any financial penalties unless the specified period is exceeded. The costs (and in turn cost-savings of agility) will thus be case-specific.

Combination carriers are another example of agility in marine designs (Sødal et al. 2008, Dahm 2022): these enable easy market switches between for example the dry and wet bulk market, a feature which shipowners can capitalize on when the two distinct markets are independently volatile. Additionally, market switches can be used to increase utilization of a ship: If the same cargo category is not available for return voyages, switching to a second market and cargo (which can necessitate cleaning cargo holds) avoids having to sail in ballast. Not only can this increase the shipowner's profit, but also lower GHG emission per ton transport work and thus help complying with tightening GHG emission requirements. The suitable level of agility consequently needs to be discussed.

Figure 1: switch time and costs



3 CASE STUDY: DESIGN OPTIONS WITH DIFFERENT LEVELS OF AGILITY

Flexibility, with different levels of agility, can be implemented in different physical ways. To illustrate the range of options with different levels of agility, we will use a Supramax bulk carrier as an illustrative example. We limit ourselves to VLSFO and LNG as fuels. These definitions shall only refer to the fuels' physical composition (i.e. long-chained hydrocarbons and methane as a primary energy carrier), not the feedstock of these fuels (fossil, bio or electro). Both energy carriers can, primarily in a cleaner form, be derived from biomass or renewable electric energy if available.

The system-level agility is dependent on both the agility of the engine (with the function energy conversion) and the tank (energy storage function), all with their respective sub-systems. We consider the following discrete options for the engine:

- E1: Mono-fuel diesel engine
- E2: Retrofittable diesel engine
- E3: Containerized mono-fuel engine (combined with generators and electric motors)
- E4: Dual-fuel gas engine (diesel cycle, diesel destillates plus LNG)

For the tank system, the following options are considered:

- T1: Diesel only (integrated tanks)
- T2: Diesel integrated plus LNG retrofittable
- T3: Diesel integrated plus LNG containerized
- T4: Diesel integrated plus LNG

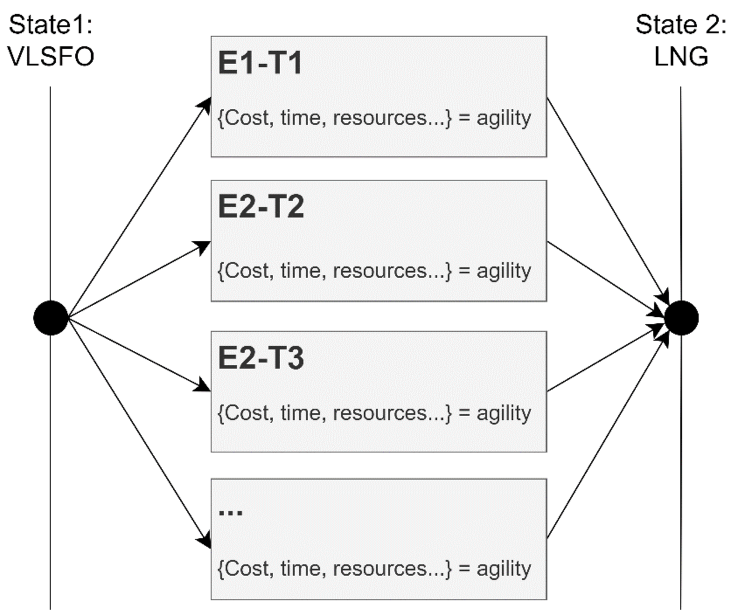
These categories result in the following combinations of engine and tank systems:

Table 3: Combinations of engine and fuel options

		Tank			
		T1 Diesel only	T2 Diesel plus LNG retrofittable	T3 Diesel plus LNG containerized	T4 Diesel plus LNG
Engine	E1 Diesel mono-fuel	X			
	E2 Diesel retrofittable		X	X	X
	E3 Containerized mono-fuel		X	X	X
	E4 Dual-fuel		X	X	X

As can be seen from Table 3, all options except for the pure "diesel only" engine and tank (E1-T1) come with recourse options, i.e. possible changes that be executed as a response to fuel (price) developments. Figure 2 schematically shows the various options for changes between VLSFO and LNG, each with their respective agility level.

Figure 2: Change options with agility levels



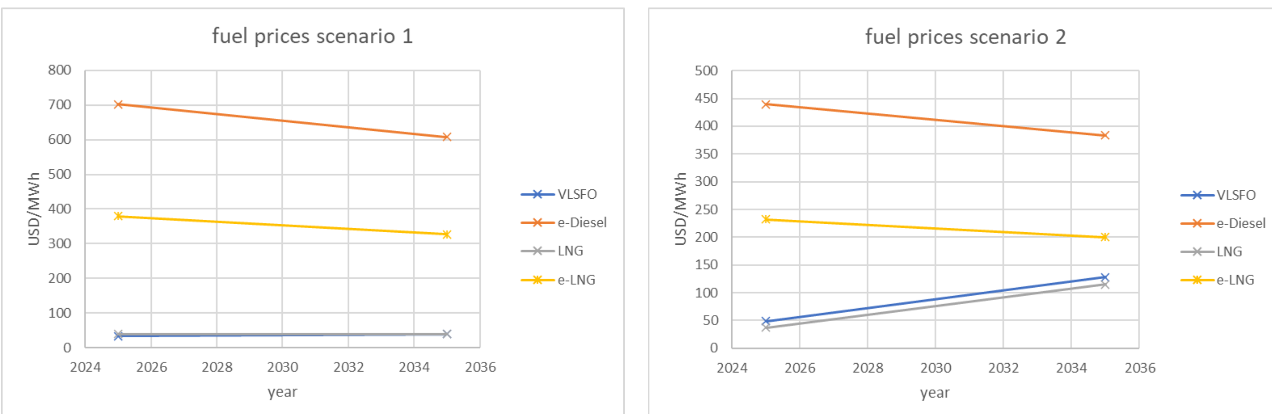
We express the level of agility with a cost function. The conversion time is modelled as a lost opportunity cost that comes in addition to the actual cost of changing the onboard systems. The assumed investment and change costs are displayed in the following table:

Table 4: Investment and change costs

Option	Investment cost [mUSD]	Change time [days]	Change cost [mUSD]
E1-T1	30.0	-	-
E2-T2	32.5	21	2.175
E2-T3	32.9	1	1.175
E2-T4	36.6	0	1.125
E3-T2	34.4	21	3.3
E3-T3	34.8	1	2.3
E3-T4	38.5	0	2.25
E4-T2	31.4	21	1.05
E4-T3	31.8	1	0.05
E4-T4	35.5	0	0

We assume two discrete exogenous scenarios for the fuel prices. The prices are depicted in Figure 3 and are based on cost estimates by Lloyd's Register and UMAS (2020).

Figure 3: Fuel price developments for scenarios



Scenario 1 is meant to represent a business-as-usual scenario: intermediate fossil fuel prices are combined with high electro-fuel prices. In Scenario 2, fossil fuel prices rise from the lower to upper bound projection, while electro-fuels are comparatively cheap. In addition, a carbon tax increase from 50 USD/$tCO2_{eq}$ is assumed to increase to 300 USD/$tCO2_{eq}$.

3.1 Evaluating the value of agility for different options

Agility as an attribute to flexibility can be valued by means of real-options analysis (Knight and Singer 2012). Combined with stochastic programming (King and Wallace 2012), the problem can be defined as a maximization of an expected performance yield indicator. Such indicators can be of economic nature (useful discussion by Benford 1966) or measure the environmental performance (e.g. Energy Efficiency Design Index, EEDI or Carbon Intensity Indicator, CII). For our case study, we assume the targeted transport work to be constant and minimize the expected total cost of ownership (eTCO) in order to maximize profit. The formulation is based on an optimization model presented by Lagemann et al. (2022). The model applied here incorporates the following simplifications and adaptations:

- The model is single-objective, meaning that GHG emissions are penalized through possible carbon taxes only
- The lost opportunity costs are dropped (since these are comparatively small for this specific narrow range of fuels)
- A scenario formulation is adopted to account for uncertainty and illustrate the value of agility

Availability of fuels is not included explicitly with hard constraints (as it could be the case for a specific route), but rather in a general way by means of the fuel price. The simplified and adapted model reads as follows:

Sets

Set	Description	Modeling comment
$\mathbb{T}$	set of discrete ***time periods***, indexed by t	
$\mathbb{F}$	set of ***fuel options***, indexed by f	refers to main chemical composition and physical state
$\mathbb{S}$	set of pre-generated ***ship system options*** for energy storage and power conversion, indexed by s	refers to a ship with an energy storage of a certain type and size, and a power converter of certain type and size
Ω	set of scenarios, indexed by ω	complete realization of random parameters

Parameters

Parameter	Description	Modeling comment
C_s^N	***newbuild cost*** of ship with system option s	
$C_{s's}^R$	***retrofit cost*** from option s' to option s	
$C_{ft\omega}^F$	***fuel cost*** of fuel f at time period t in scenario ω	
P_ω	***probability of scenario v***	
B	***energy consumption*** per time period	assuming the fuel conversion efficiencies do not change over time, equidistant time periods
E_f^{WTT}	***well-to-tank emissions*** of fuel f	
E_f^{TTW}	***tank-to-wake emissions*** of fuel f	assuming tank-to-wake emissions do not change over time.
K_{fs}	1 if fuel f and system s are ***compatible***, 0 otherwise	
ε	constraint on global warming potential	ε-constraint method, ε iteratively increased

Decision variables

$x_{ft\omega}$ 1 if ***fuel*** f is chosen at time t, 0 otherwise

$y_{s0}, y_{st\omega}$ 1 if ***ship system option*** s is chosen at time t, 0 otherwise

Auxiliary variables (implicit, required for linearization)

$r_{s'st\omega}$ 1 if retrofit is to be made from system option s' to system option s after period t. 0 otherwise

Objectives

We define our first objective of minimizing the expected total cost of ownership (eTCO) as:

$$min\, eTCO = \tag{1}$$

$$= \sum_{s\in\mathbb{S}} \left[\underbrace{C_s^N \cdot y_{st_0}}_{building\ cost} + \sum_{\omega\in\Omega} P_\omega \left[\sum_{t\in\mathbb{T}} \left(\sum_{s'\in\mathbb{S}} \underbrace{C_{s's}^R \cdot r_{s'st\omega}}_{retrofit\ cost} \right) \right] \right] + \sum_{\omega\in\Omega} \sum_{t\in\mathbb{T}} \sum_{f\in\mathbb{F}} \underbrace{P_\omega \cdot B \cdot x_{ft\omega} \cdot C_{ft\omega}^F}_{fuel\ cost}$$

subject to:

First stage:

$$\sum_{s\in\mathbb{S}} y_{st} = 1, \qquad \forall t = 0 \tag{2}$$

$$y_{st} \in \{0, 1\} \qquad \forall s \in \mathbb{S},\ t = 0 \tag{3}$$

Constraints (3) ensure that only one ship system option is selected at the first time step. Constraints (3) declare that decision variable y_{st} is of binary type.

Second stage:

$$y_{st\omega} = y_{st} \quad \forall s \in \mathbb{S}, \forall t = 0, \omega \in \Omega \tag{4}$$

$$\sum_{f\in\mathbb{F}} x_{ft\omega} = 1, \qquad \forall t \in \mathbb{T}, \omega \in \Omega \tag{5}$$

$$\sum_{s\in\mathbb{S}} y_{st\omega} = 1, \qquad \forall t \in \mathbb{T}, \omega \in \Omega \tag{6}$$

$$x_{ft\omega} + y_{st\omega} \leq 1 + K_{fs} \qquad \forall t \in \mathbb{T},\ \forall f \in \mathbb{F},\ \forall s \in \mathbb{S},\ \forall \omega \in \Omega \tag{7}$$

$$y_{s'(t-1)\omega} + y_{st\omega} - 1 \leq r_{s'st\omega} \qquad \forall s', s \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\},\ \forall \omega \in \Omega \tag{8}$$

$$y_{s'(t-1)\omega} + y_{st\omega} \geq 2r_{s'st\omega} \qquad \forall s', s \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\},\ \forall \omega \in \Omega \tag{9}$$

$$r_{s'st\omega} = 0 \qquad \forall s', s \in \mathbb{S}, \forall t = 0,\ \forall \omega \in \Omega \tag{10}$$

$$x_{ft\omega} \in \{0, 1\} \qquad \forall f \in \mathbb{F},\ \forall t \in \mathbb{T},\ \forall \omega \in \Omega \tag{11}$$

$$y_{st\omega} \in \{0, 1\} \qquad \forall s \in \mathbb{S},\ \forall t \in \mathbb{T},\ \forall \omega \in \Omega \tag{12}$$

Constraints (4) link the first stage decision variable to the second stage. Constraints (5) and (6) ensure that exactly one fuel and one ship system option are selected at the same time. Constraints (7) imply that a fuel and power conversion system need to be compatible. Constraints (8)-(9) control the auxiliary retrofit variable, which is set to zero for the first time period by constraint (10). Constraints (11) and (12) make sure that also the second stage decision variables are of binary type.

4 RESULTS AND DISCUSSION

The model is implemented and solved with a commercial optimizer (Gurobi 9.1). Table 5 shows the optimal initial system choice for different probability distributions between scenario 1 and 2. Note that $p_1 = 1 - p_2$ in our case.

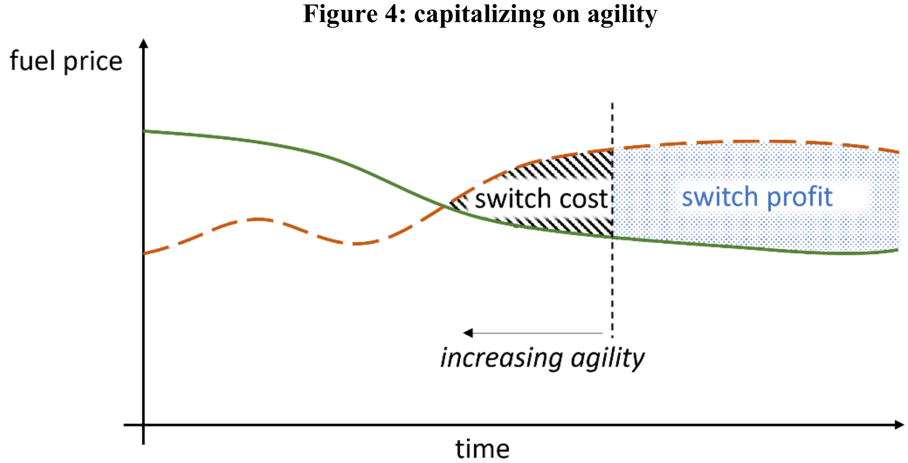
Table 5: Cost-optimal solutions with different levels of agility

p_2	cost-optimal solution	Agility
$0 \leq p_2 \leq 0.34$	E1-T1	inflexible
$0.34 < p_2 \leq 0.4$	E4-T2	↓ increasing agility
$0.4 < p_2 \leq 0.76$	E4-T3	
$0.76 < p_2 \leq 1$	E4-T4	

The results indicate that flexibility pays off for probabilities larger than $p_2 = 0.35$ for scenario 2. The level of desired agility of the system depends as well on the probability distribution. Thus, the probabilities determine the trade-off between upfront investment costs and potential retrofit costs, similar to the one depicted in Figure 1.

The appropriate level of agility, and thereby the cost of change, is hence directly dependent on our expectations with respect to exogenous conditions. This example illustrates that agility, that is easy-to-conduct changes, is valued high under uncertain conditions. In addition, agility can pay off if change is to happen frequently (Sødal et al. 2008; Christensen et al. 2018). This can be seen from equation (1), where the second term is the sum of change costs. Figure 4 illustrates the dependency of worthwhile fuel switches on the system's agility, here shown as a switch cost. Lower switch costs facilitate earlier profit from the change. In case the fuel prices cross again, the system's agility determines whether the switch is worthwhile at all or not.

Figure 4: capitalizing on agility



Agility could thus be advantageous if a shipowner wanted to capitalize on frequent fuel switches, i.e. running on LNG whenever that is cheaper than VLSFO. Similarly, agility could be a worthwhile strategy if availability of a certain fuel is restricted on certain trades or in certain scenarios. Both these latter cases have not been investigated in this case study, but could be readily modeled with this approach. Last but not least, the concept of agility is not limited to uncertain conditions: If external conditions are known to change (deterministic future), agility can ease or reduce costs for adaptations to the changing external circumstances (Lagemann et al. 2022).

5 CONCLUSION

Section 2 has reviewed various definitions of agility. For fuel-flexible ships, we have found that a definition for agility as "ease to change" is most appropriate. Sections 3 and 4 have illustrated how this definition can be made operational, i.e. how agile ships can be evaluated. The results indicate that the value we attribute to agile systems is dependent on our expectations for the future: If change is seen to be likely, agile systems can ease this change by bringing down the associated costs and resource expenditures. The presented optimization model can be used to identify the optimal level of agility for a given set of exogenous scenarios.

In addition to the simplifications outlined in Section 3.1, our study has several limitations: Notably, the number of scenarios and the number of fuel options are significantly reduced to analyze agility more closely. For a more comprehensive and systematic study of agility, we see the following challenges:

1. The number of options to be evaluated: The number of options to be evaluated quickly becomes large if multiple fuels and multiple change mechanisms shall be evaluated. That means that matrix sizes increase significantly. Some options may be more flexible (i.e. enable to change between more fuel options), while others may be more agile, but restricted in flexibility.
2. Reliable cost estimates for different options: Reliable cost estimates, both for investment and change costs, are hard to obtain if the set of design options is large. Preferably, such estimates are based on a common methodology to avoid bias. Databases such as MARIN (2021) can help cross-checking multiple sources for cost estimations.
3. Capturing the uncertainty/randomness appropriately: Capturing the uncertain external properties (fuel prices or carbon tax) in an appropriate way is perhaps the most challenging task. Real options analysis is perhaps the most suited technique for this problem (Knight and Singer 2012), but requires probability distributions. For short-term predictions, such as fuel price variation over a year, the properties of the distributions may be more or less well-known (e.g. Christensen et al. 2018), which simplifies quantification of changeability. For long-term fuel price predictions, the data are scarcer. The International Energy Agency's forecasts have been existent around for about 23 years (International Energy Agency 1999), that is less than the typical service life time of a ship. Capturing different sources and evaluating the effect of different probability distributions seems to be a necessity.

Agility, as put forward in this paper, can be seen as an important adverb to flexibility and changeability and can thereby help mitigating the effects of uncertainty. We see the following links between agility and the 4T's of risk and loss control management literature (Bird and Germain 1985):

- *Terminate:* Our proposition in this paper has been that the aspect of agility should be considered during the design process. Eventually, the desired level of agility needs to be discussed in the light of technical feasibility (Andrews 2003). Given that the best options for different levels of agility are on the table, terminating (not pursuing a design) as a possible outcome of a design process with thorough requirements elucidation.
- *Treat:* When designing agile systems, risk and uncertainty is treated in a technical way. That is, agility enables responding to risk by adapting the technical system to changing circumstances.
- *Transfer:* Agility does not necessarily transfer risk to others per se. However, leasing or pay-per-use business models can contribute to a ship's agility.
- *Tolerate:* Uncertainties and risks which can neither be terminated, treated or transferred, need to be tolerated.

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CREDIT AUTHOR STATEMENT

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