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Maritime fuels of the future: what is the impact of alternative fuels on the optimal economic speed of large container vessels

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Abstract

This study aims to determine the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance. In this context, the most suitable alternative fuel technology minimizes the required freight rate while maximizing overall performance on technological, environmental, and other criteria. A decision support tool was developed combining the overall performance of alternative fuels based on technological, environmental, and other criteria via a simple multiattribute rating technique model with a financial model based on discounted cash flow analysis. In this model, also an optimization model is implemented to minimize the required freight rate by optimizing for economic vessel speed. This model provides quantified insights into the financial and operational effects of transitioning via either a 'market-based measure' regulatory scenario or an 'emission cap' scenario if current fuels do not reach the zero-emission targets in the future. Based on the analysis, it can be concluded that upgraded bio-oil, Fischer–Tropsch diesel and liquefied bio-methane can be considered the 'most promising' alternative maritime fuels of the future. Current fuels such as Heavy fuel oil and Liquified natural gas remain the 'most probable' to retain dominance without regulations. If there is a transition toward these alternative fuels, this will also lead to a shift toward lower sailing speeds.

Keywords: Maritime industry, GHG reduction policies, Alternative fuels, Decision support tool, Economic speed optimization, Scenario analysis

Introduction

The International Maritime Organization (IMO) aims for a total GHG emission reduction from international shipping by at least 50% by 2050 compared to 2008 while, at the same time, pursuing efforts toward phasing them out entirely (IMO 2018). In this light, international organizations and governments, in cooperation with shipowners, ports, and distributors, are continuously trying to reduce greenhouse and toxic gas emissions while ensuring business continuity for the shipping industry. This transition will require an ample supply of innovative technological solutions and support from a commercial perspective. Technology, finance, and the law must seamlessly align to form a sustainable

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basis for the transition toward the maritime fuel of the future. In this process, the industry is expected to face significant challenges.

Nevertheless, policymakers are shifting towards alternative maritime fuel technologies with various measures to accelerate innovation. Pollution prevention treaties and emission measures force parties to innovate in their fuel and exhaust technologies from a regulatory perspective. In contrast, from a financial perspective, subsidies are made available for R&D and innovative technologies (IMO 2019). As can be understood, the maritime sector supports innovation toward alternative maritime fuels as a whole. Due to the urgency for an industry-wide response to upcoming regulations and the need for a large scale solution, the scope of this study is limited to fuels applied in internal combustion engines that are fit for large scale application by 2030 or 2050, can meet proposed GHG reduction targets, and are suitable for deep-sea shipping.

In this paper, for a case study of a container vessel, it will be determined which of the best alternative fuel is to comply with the new emission regulation. Therefore, a model is developed to select the most appropriate alternative fuel technology to comply with the imposed emission regulations. Next to that, the impact of using an alternative fuel on the cost structure of the vessel and, therefore, also on the impact of the design speed of that vessel is researched. The main research questions of this paper are:

Which fuel types are most suitable for complying with GHG reduction targets?

What is the impact of using the selected alternative fuels on the optimal design speed of the vessel?

To answer these research questions, this research develops two models. The first model enables the selection of the most appropriate alternative fuel technology to comply with different imposed emission regulations. A selection of 3 most promising fuels is determined from a long list of possible alternative fuels. These selected alternative fuels are used in a subsequent model to assess the impact of applying these selected alternative fuels on the optimal design speed of the case study vessel.

This paper is structured as follows. In "Literature Overview" section, an overview of the literature on alternative maritime fuels is given. “SMART Decision Model” section deals with the developed SMART decision model to select the most suitable alternative fuels, while “Economic Evaluation Model” section provides the economic evaluation model. “Data” section provides the necessary data to perform the analysis. “Economic Speed Optimization” section deals with the economic speed optimization when applying the selected alternative fuels, while in “Sensitivity Analysis” section, a sensitivity analysis is performed for the most crucial key input parameters. The paper concluded with the main conclusions in “Conclusions and Recommendations for Further Research” section.

Literature overview

With the introduction and enforcement of the IMO rules, regulators have demonstrated their determination to regulate maritime emissions. This development has incurred an uptake in the already increasing research interest in alternative maritime fuels. To date, multiple studies have investigated and assessed a broad range of alternative maritime fuels (Ash and Scarbrough 2019; Balcombe et al. 2019; Bengtsson et al. 2014; Brynolf et al. 2014; Burel et al. 2013; CE Delft 2020; Chryssakis and Brinks 2017; De Marco et al. 2016; DNV GL 2019; E4Tech 2017; E4Tech 2018; Einemo 2017; Endres et al. 2018;

Erhard and Strauch 2013; Feenstra et al. 2019; Florentinus et al. 2012; Global CCS institute 2019; Hansson et al. 2020a, b; Hansson et al. 2019; Hsieh and Felby 2017; Lloyd's Register Group Limited et al. 2015; Lo 2013; Luo and Wang 2017; Mohd Noor et al. 2018; Mohseni et al. 2019; Nelissen et al. 2016; Parraga et al. 2018; Pavlenko et al. 2020; PICO and LORENZEN 2020; Raucci et al. 2015; Russo et al. 2012; Svanberg et al. 2018; The European Parlement and Council 2009; Thomson et al. 2015; Ytreberg et al. 2019; Zhou and Wang 2014).

Even though existing studies largely overlap alternative fuel types, no consensus has been reached on the optimal maritime fuel for the future. Additionally, a very limited amount of papers was found that study the problem from the perspective of the shipowner and specifically on the impact of installing alternative fuels on the optimal speed of the vessel. For shipowners, this is essential to successfully implement alternative fuels. Therefore, the goal of the research is to study how these alternative fuels could impact the design speed of the vessel.

Alternative fuels

A literature study was conducted on a broad range of alternative fuels to assess their feasibility to be considered for the future. Based on literature, several options were discarded based on a lack of scalability or suitability for deep-sea shipping. A selection of nine feasible alternatives remained. This includes Heavy Fuel Oil (HFO), Liquified Natural Gas (LNG) (as reference fuels), Fatty Acid Methyl Esters (FAME), Hydrotreated Vegetable Oil (HVO), Upgraded Pyrolysis Oil (UPO), upgraded bio-oil via hydrothermal liquefaction (UBO), Fischer–Tropsch diesel (FTD), liquefied bio-methane (LBM) and ammonia (NH3). An overview is presented in Table 1.

Future regulatory scenarios

A literature study was conducted on possible future regulatory scenarios in 2030 or 2050. The considered measures included market-based measures (MBM) in the form of an Emission Trading Scheme (ETS) or bunker levy. Next are emission cap (EC) regulations, which are a regional or global expansion of Emission Control Areas (ECAs) by limiting NOx and SOx emissions or installing greenhouse gas emission caps of 50% or 100% compared to a predefined benchmark. Based on literature by Balcombe (2019), Wan (2018), Kageson (2008), IMO (2012), Garcia et al. (2020), Kosmas and Accario (2017), ICS (2018), Perera and Mo (2016), and Woodyard (2009), the probability of different regulations being enforced in 2030 or 2050 was assessed, and a selection of four future regulatory scenarios was made. An overview is presented in Table 2.

To achieve this, current and possible future regulatory scenarios are analyzed, and a selection of regulatory scenarios is made to consider in the present study. Low-probability scenarios are discarded. Additionally, a broad range of alternative fuel technologies is analyzed, and their feasibility is assessed. Alternative fuels that do not meet requirements in scalability, GHG reduction targets, or suitability for deep-sea shipping are discarded. Furthermore, multi-criteria decision methods and modeling techniques are evaluated to address the specific problem and requirements of the present study. A decision support tool is devised to rank optimal fuel choices under different regulatory scenarios and assist in making substantiated future decisions regarding alternative fuel

Table 1 Selection of alternative maritime fuels in the research. *Source* own figure based on cited literature

Category	Fuel technology	Primary resource	Characteristics		Sources
			Postive	Negative	
Fuel oils	HFO with scrubbers	Crude oil	Low cost, reduced SOx and NOx emissions;	Carbon-heavy, high viscosity bunker fuel	McGill et al. (2013), Mohseni et al. (2019), Endres et al. (2018), Ytreberg et al. (2019),
Natural gases	LNG (Liquid-cooled methane/ethane gas)	Crude oil; natural gas	Low nitrogen oxide emissions, sulfur-free; low cost	High well-to-propeller GHG output	Burel et al. (2013), CE Delft et al. (2016), Pavlenko et al. (2020), Thomson et al. (2015), Brynolf et al. (2014), PICO and LORENZEN (2020)
Bio-fuels	FAME (bio-diesel)	Edible or used oils	Suitable clean alternative to MDO/MGO	Risk of acidic degradation	Einemo (2017), Mohd Noor et al. (2018), Hsieh and Felby (2017),
	HVO	Edible or used oils	High-quality drop-in diesel fuel	Higher cost; cross-sector interest	Florentinus et al. (2012), DNV GL (2019), E4Tech (2018), Hsieh (2017)
	UPO	Lignocellulosic; waste	Suitable clean alternative to HFO/IFO; high GHG reduction potential	Not commercially available	Florentinus (2012), E4tech (2018), Hsieh (2017)
	UBO	Lignocellulosic; wet bio-mass; waste	High potential; more straightforward production process compared to UPO	Low commercialization	E4tech (2018), Hsieh (2017)
	FTD	Lignocellulosic; waste	Drop-in diesel fuel; very high GHG reduction potential	More impurities	Parraga (2018), E4Tech (2017), E4tech (2018), Tzanetis et al. (2017)
	LBM (bio-LNG)	Lignocellulosic; landfill gas; waste	High GHG reduction potential	Potentially cost-competitive	Delft (2020), E4tech (2018), Tzanetis et al. (2017)
Ammonia	NH3	Hydrogen	No tank-to-propeller emissions	High cost; toxic; low maturity in marine applications	Ash and Scarbrough (2019), DNVGL (2019), Hansson (2020a; b), E4tech (2018)

technologies. At last, by conducting a case study, the most appropriate fuel alternatives are determined under different regulatory scenarios while ensuring optimal business performance.

The results will demonstrate the performance of alternative fuels based on a set of predefined and weighted criteria under various combinations of regulatory, sentiment, and time scenarios. The selection of alternative fuels is evaluated under optimistic, average, and pessimistic sentiment scenarios under 'no regulation,' 'market-based measure' (MBM), or 'emission cap' (EC) regulatory scenarios in 2020, 2030, and 2050. Stakeholders will gain insights into how alternative fuels compare based on technological,

Table 2 Selected regulatory scenarios to be considered in this research

Measure		Vessel type	Description	Time frame
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2030
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2050
EC	50% CO_2 emission cap	New-built	New-built and Bench-marked 50% CO2 emission cap for all new-built vessels	2030
EC	50% CO_2 emission cap	New-built	New-built and Bench-marked 50% CO2 emission cap for all new-built vessels	2050

economic, environmental, and other criteria. This will assist in making substantiated future decisions toward employing alternative maritime fuels.

SMART decision model

This section contains the mathematical formulation of the multi-criteria decision model based on the simple multiattribute rating technique (SMART). SMART is applied in situations where different criteria carry weights, and minimal input is demanded from decision-makers. SMART relies on utility and preferential independence and allows for any type of weight assessment technique. In the present research, absolute weight assessments have been used after presenting a survey to shipowners. The SMART decision model output is a ranking based on individual preference for alternative fuels based on technological, environmental, and other criteria.

The selected evaluation criteria have been formulated to encompass as many essential aspects as possible towards making an optimal choice of fuel technology. To ensure this, a literature study is conducted to determine the most critical evaluation criteria when considering alternative fuels (Brynolf 2014; Hanson et al. 2019; Ren and Lutzen 2017; McGill et al. 2013, Bergsma et al. 2019, Deniz and Zincir 2016 and DNV GL 2019).

In a survey presented to seven deep-sea shipowning entities, shipowners have reviewed a selection of evaluation criteria and assigned scores to judge the importance of each criterion for decision-making on alternative fuel technologies in their firm. In the decision tool, these opinions are translated into criteria weights. The received responses were evaluated on a 5-point Likert scale. The Likert scale is a psychometric scale that analyses participants' views on five or seven points, ranging from not important at all' to' extremely important. For privacy reasons, survey participants are anonymized and identified by their job function. In contrast, the associated shipping firms are identified by their primary business line and the number of vessels under management. An overview of the participants is presented in Table 3.

Survey results are demonstrated in Fig. 1. The right-hand side of Fig. 1 shows the evaluated criteria, and the left-hand side shows the distribution of the responses. From Fig. 1, one can derive how shipowners have evaluated the importance of the presented criteria on the Likert scale. Although the degree of importance varies between different standards, the relatively low deviation in responses shows high consensus amongst survey respondents.

Table 3 Overview of survey participants

Job title	Origin	Primary business line	Vessels under management
Senior Manager	Denmark	Tankers, container vessels	700
General Manager	China	Tankers, container vessels, bulk carriers	600
Vice President	Norway	Tankers, gas carriers	370
Head of corporate and business dev	Greece	Container vessels, bulk carriers	50
Director	Norway	Chemical tankers	25
Senior Manager	Norway	Container vessels	25
Managing Director	Norway	Tankers, container vessels	10

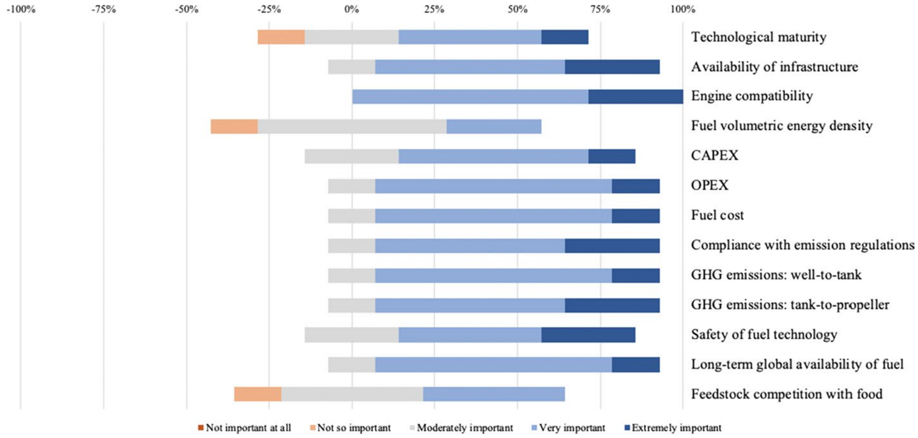

Fig. 1 Visualized survey results of evaluation criteria

Based on these responses, the absolute weights and the relative weight scores are calculated. The details for this can be found in appendix 1.

After having selected and weighed the importance of each of the criteria, alternative fuels are evaluated based on their performance. This evaluation is performed based on the literature. Where information was incomplete, an approximation has been made based on available literature. These scores are relative scores in which 10 is the best and 1 is the worst. The results are presented in Table 4, where performance parameters p are assessed for each alternative I under criteria j.

The technology readiness level (TRL) of the various fuel technologies has been determined based on their technological relevance in 2020. In designing a decision tool subject to future scenarios, these TRLs are expected to increase over time as technological development progresses.

The second and third criteria judge the availability of infrastructure and engine compatibility of fuel technologies respectively, FAME and ammonia perform below average. This can be attributed to the fact that both fuel technologies require major adjustments and/or investments in existing systems to ensure safety and durability in the long term. In the case of FAME, the low scores can be attributed to its clogging and acid degradation properties, while with ammonia, the low scores are attributed to its highly corrosive properties affecting infrastructure and engines.

Table 4 Performance parameters p for each alternative i for the average, unregulated, 2020 scenario. *Source* own figure based on cited literature

Evaluation criteria	Unit	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3	Source
Technological maturity	TRL	10	10	10	10	5,5	4,5	7	10	5,5	Bergsma et al. (2019), Hsieh and Felby (2017)
Availability of infrastructure	–	5	5	3	5	5	5	5	5	2	DNV GL (2019), E4Tech (2018)
Engine compatibility	–	5	5	3	5	5	5	5	5	2	DNV GL (2019), E4Tech (2018), Hsieh and Felby (2017), Hansson et al. (2020a, b)
Fuel volumetric energy density	MJ/l	41	22,2	33,2	34,3	34	34	34,5	22,2	12,7	Aatola et al. (2009), Agrilink (2019), Hacker and Kordesch (2010), DNV GL (2019), E4Tech (2018)
Compliance with emission regulations	–	4	5	3	3	3	5	5	5	2	Noor et al. (2018), NH3 Fuel Association (2018), Bergsma et al. (2019)
GHG emissions: well-to-tank	gCO2eq/MJ	14,3	21,2	32	30	34,5	22	5	19,5	7	E4Tech (2018), European Parlement and Council (2009), Pavlenko et al. (2020)
GHG emissions: tank-to-propeller	gCO2eq/MJ	81,2	57,5	0	0	0	0	0	0	0	Pavlenko et al. (2020), Cherubini et al. (2009), IPCC (nb), Edwards et al. (2017)
Safety of fuel technology	–	5	4	5	5	5	5	5	4	3	Burel (2013), Ash and Scarbrough (2019)
Long-term global availability of fuel	–	3	3	3	3	4	4	4	4	5	van der Kroft (2020), Noor et al. (2018), Hafiee and Topal (2009)
Feedstock competition with food	–	5	5	2	2	4	4	4	4	5	Bergsma et al. (2019), Hsieh and Felby (2017)

The data for the fourth till the seventh criteria are taken from literature. It might seem surprising when reviewing bio-fuels, is that tank-to-propeller emissions are 0 gCO_2/MJ. This is because under the Kyoto Protocol the emission factor for biomass is always zero (Netherlands Enterprise Agency 2020). However, this does not mean that the combustion of these bio-fuels does not emit any exhaust gases (well-to-tank). The net tank-to-propeller emissions of bio-fuels are zero because they are measured over the bio-fuels' life-cycle, where the growth of the feedstock has absorbed an equal amount of CO_2 from the air. Nevertheless, as Cherubini et al. (2009) explain, bio-fuel production does emit greenhouse gases from well-to-tank: "Biomass use for energy generation is considered "carbon neutral" over its life cycle because combustion of biomass releases the same amount of CO_2 as was captured by the plant during its growth. By contrast, fossil fuels release CO_2 that has been locked up for millions of years. Bio-energy has an almost closed CO_2 cycle, but there are GHG emissions in its life cycle largely from the production stages: external fossil fuel inputs are required to produce and harvest the feedstocks, in processing and handling the biomass, in bio-energy plant operation and in transport of feedstocks and bio-fuels.

For the long-term global availability of fuels, fossil fuels, FAME and HVO score lower. According to Shafiee and Topal (2009), fossil fuel reserve depletion times for oil, coal and gas amount to approximately 35, 107 and 37 years, respectively. Even though these time spans are evaluated with high uncertainty, they do confirm that the current fossil fuel supply is finite, and is reaching its bottom at present consumption rates. As for FAME and HVO, the lower score has been assigned due to the present choice of feedstock used. Currently, FAME and HVO production is heavily dependent on edible oily feedstocks that compete with the food industry; meaning these fuels will likely be subject to future regulatory measures (Mohd Noor et al. 2018). Additionally, apart from FAME and HVO scoring low due to their dependence on edible oily products, other bio-fuels are not assigned a score of 5 due to the uncertainty surrounding the effects of Indirect Land Use Change (ILUC) (Bergsma et al. 2019).

As can be observed, Table 4 does not include CAPEX, OPEX, or fuel cost parameters. This is because the SMART decision model only considers technological, environmental, and other criteria. The economic performance of each alternative fuel is evaluated by an extensive financial model, further elaborated in "SMART Decision Model" section. The individual performance parameters are not yet translated into a normalized score. The normalization and weighing process of the unique performance scores is carried out by applying the simple multi-attribute rating technique (SMART).

The simple multi-attribute rating technique aims to calculate the relative evaluation factors Vij for each alternative i under each criterion j. Relative evaluation factors are determined by applying formulas 1 and 2 to each of the performance parameters Pij.

$$V_{ij} = \frac{P_{ij} - Min\left(P_j\right)}{Max\left(P_j\right) - Min\left(P_j\right)} \tag{1}$$

$$V_{ij} = \frac{Max\left(P_j\right) - P_{ij}}{Max\left(P_j\right) - Min\left(P_j\right)} \tag{2}$$

Table 5 Total SMART score of each alternative i for the average, unregulated, 2020 scenario

Evaluation criteria	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	0,11	0,11	0,11	0,11	0,02	0,00	0,05	0,11	0,02
Availability of infrastructure	0,11	0,11	0,04	0,11	0,11	0,11	0,11	0,11	0,00
Engine compatibility	0,11	0,11	0,00	0,11	0,11	0,11	0,11	0,11	0,00
Fuel volumetric energy density	0,08	0,03	0,06	0,06	0,06	0,06	0,06	0,03	0,00
Compliance with emission regulations	0,07	0,11	0,04	0,04	0,11	0,11	0,11	0,11	0,00
GHG emissions: well-to-tank	0,07	0,05	0,01	0,02	0,00	0,04	0,11	0,05	0,10
GHG emissions: tank-to-propeller	0,00	0,03	0,11	0,11	0,11	0,11	0,11	0,11	0,11
Safety of fuel technology	0,11	0,05	0,11	0,11	0,11	0,11	0,11	0,05	0,00
Long-term global availability of fuel	0,00	0,00	0,00	0,00	0,05	0,05	0,05	0,05	0,11
Feedstock competition with food	0,08	0,08	0,00	0,00	0,05	0,05	0,05	0,05	0,08
Total score	0,74	0,68	0,48	0,67	0,73	**0,75**	**0,87**	**0,78**	0,42

Formula 1 is used when preference is given to high scores (i.e. fuel volumetric energy density), whereas formula 2 is applied when priority is given to low scores (i.e. GHG emissions). *Max.pj* represents the maximum parameter value found under criterion *j*, whereas *Min.pj* represents the minimum parameter value found under criterion *j*. Furthermore, P*ij* describes performance parameter P for alternative *i* under criterion *j*.

To calculate Vij for all parameters Pij, the model automatically determines the Min and Max range for each criterion j under each regulation, scenario, and timeline. Finally, the total score received by each alternative *i* under criterion *j* with relative weight *W* is calculated. The total score ranges from 0.00 to 1.00 and is determined by summing all relative evaluation factors *vj* received by alternative *i*. As the goal of the SMART decision method is to maximize the total score, the alternatives that receive the highest score are the most preferred. An overview of the scores is provided in Table 5.

As shown in Table 5, the SMART decision model evaluates fuel alternatives in terms of technical, environmental, and other criteria *j*. From this analysis, it can be concluded that three alternative fuels perform the best: upgraded bio-oil (UBO), Fischer–Tropsch diesel (FTD), and liquefied bio-methane (LBM). These three alternatives are selected as alternatives for the economic evaluation. This model is elaborated in "Economic Evaluation Model" section.

Economic evaluation model

An economic model is developed to evaluate the fuel alternatives' impact on the vessel's design speed. The economic model that is incorporated in the decision tool accounts for operating revenues, voyage expenses, running expenses, and capital expenses according to the annual cash flow accounting method explained in Maritime Economics by Stopford (2013). In the following sections, all cost line items are described and elaborated such as to be able to reproduce the model. Equation 1 demonstrates how annual cash flow is calculated in the present model.

$$\mathrm{ACF_{vc,i}} = \mathrm{R_{vc,i}} - \mathrm{C_{voyage,i}} - \mathrm{C_{running,i}} - \mathrm{C_{capital,I}} \tag{3}$$

In which $\mathrm{ACF}_{vc;i}$ is the annual cash flow of vessel employing fuel *i* on voyage charter, $R_{vc;i}$ is the annual voyage charter revenue earned by vessel employing fuel i after cargo handling and operating cost revenue share, in USD, $C_{\text{voyage};i}$ is the annual voyage expenses of vessel employing fuel *i*, $C_{\text{capital};i}$ is the annual capital expenses of vessel employing fuel *I* and $C_{\text{running};i}$ is the annual running expenses of vessel employing fuel *i*.

Appendix 2 shows the detailed calculation of the voyage, running, and capital cost. All mentioned revenue categories, expense categories, and specific cost line items are further elaborated in the following sections.

Voyage expenses buildup

Voyage expenses are expenses related to a specific voyage that is sailed. These expenses include port charges, canal dues, fuel, and GHG emission costs. Port charges are calculated by ports based on a vessel's gross tonnage. The model calculates annual port charges based on the port charge per GT, gross tonnage, and yearly average port visits. As for canal passages, the Panama and Suez canal use different calculation methods for their canal dues. The Panama canal calculates canal dues based on vessel type, maximum cargo capacity (TEU), length overall (LOA), and beam (Wilhelmsen 2020a). The Suez canal establishes its canal dues on vessel type, draft, 'Suez canal net tonnage' (measured every time a vessel passes the Suez canal), sailing direction (north- or southbound), and gross tonnage (Wilhelmsen 2020b). Therefore, total annual canal dues are calculated by multiplying the sum of the Panama and Suez canal dues with the number of yearly canal exits. The number of annual port arrivals and canal exits varies per vessel employing a different fuel type due to each vessel's different average transit speeds. A vessel sailing with a lower average transit speed results in fewer annual port arrivals and canal exits than a vessel with a higher average transit speed.

Although port charges and canal dues contribute significantly to a vessel's annual voyage expenses, fuel cost is the most significant yearly voyage expense. Annual fuel cost is calculated by multiplying annual fuel consumption (in mt) with the specific fuel cost per unit of mass per fuel type (in $/mt). The method with which the present model establishes annual fuel consumption is further elaborated in "Fuel Consumption" section.

At last, annual GHG cost is dependent on the total energy consumption, CO_{2eq} emissions per fuel type, and the cost of CO_{2eq} emissions. However, under current regulations, greenhouse gas emission offsetting by certificate purchase is not mandatory. Therefore, GHG emission costs are only relevant under one of the investigated regulatory scenarios, which considers market-based measures. Thus, CGHG,i is zero for all fuels under the base case scenario. The different regulatory scenarios and their implementation are further elaborated under "Scenarios" section.

Fuel consumption

The vessel's annual fuel consumption needs to be determined to calculate the voyage costs. Once annual fuel consumption $FC_{\text{total,i}}$ is computed, it is multiplied by the specific fuel cost per mt for each fuel type to determine the yearly fuel cost for the considered alternative fuel types and the reference case (HFO). Table 6 demonstrates the cost range of the selected alternative fuels per MWh, including production and distribution costs.

The vessel's annual fuel consumption is the sum of the yearly propulsion fuel consumption and the annual auxiliary fuel consumption. The total propulsion fuel consumption is dependent on the propulsion energy consumption and the specific fuel oil consumption

Table 6 Fuel production and distribution cost for considered alternative fuel technologies in the average, unregulated 2020 scenario. *Source* own composition based on cited sources

Alternative	Production cost [$/MWh]		Distribution cost [$/MWh]		Total cost [$/MWh]		Sources
	Min	Max	Min	Max	Min	Max	
HFO (IFO-380)	30.5	34.8	–	–	30.5	34.8	Clarksons (2021); Chevron Marine (n.d.)
UBO via HTL	60.3	145.5	0.0	0.6	60.3	146.1	Demirbas (2005), Tzanetis et al. (2017)
FTD	61.0	165.6	0.0	0.6	61.0	166.2	Lappas and Heracleous (2011), EC (2017), Saddler et al. (2020), E4tech (2017)
LBM (bio-LNG)	46.0	144.9	11.3	18.9[a]	46.0	144.9	GIIGNL (2009), EC (2017), Saddler et al. (2020), E4tech (2018)
Ammonia	39.0	118.8	19.8	73.3[b]	58.7	192.1	Hacker and Kordesch (2010), DNVGL (2019), Hochman et al. (2020)

[a] Distribution and liquefaction costs of LBM are assumed equal to LNG

[b] Ammonia is assumed to be stored and distributed under 1 bar and –33 °C or 10 bar and 20 °C at equal cost

(SFOC) at each percentage of engine power output per fuel type. The propulsion energy consumption depends on the time the vessel spends in transit and cruising speed. The vessel's cruising speed is optimized for each fuel alternative to minimize the required freight rate: the devised optimization model to determine the optimal economic cruising speed is elaborated in "Economic Speed Optimization" section. The vessel's dimensions are assumed constant.

For diesel-like fuels such as HFO and biofuels, the use of conventional marine diesel engines is assumed. For gas-like fuels such as LNG and LBM, the use of dual-fuel engines is assumed. Dual fuel engines allow being operated on either conventional liquid marine fuels or LNG. For dual-fuel engines, a 9.5% higher engine efficiency is considered. The 9.5% higher efficiency figure is derived from research conducted by Wärtsilä[1] and Royal Dutch Shell Wartsila (2017). As for ammonia, of which there are no reliable engine efficiency figures available for ICEs, engine efficiency is assumed to be equal to when using diesel-like fuels due to its poor combustion characteristics such as high auto-ignition temperature, low flame speed, narrow flammability limits, and high heat of vaporization Ammonia Energy Association and Crolius (2020).

In the present model, the data input for specific fuel oil consumption per engine load $SFOC_{P,i}$ is taken from an 8-cylinder two-stroke diesel engine provided by MAN (2020). The engine is equipped with scrubbers to comply with global SO_x emission regulations and an exhaust gas recirculation (EGR) system to comply with Tier III NO_x emission regulations. The specifications of the specific engine type used in the present model are in appendix 3 (Table 11) and are assumed to be equal for all diesel-like fuel types. The power-SFOC relation data table used in the present model for calculating specific fuel oil consumption of diesel-like fuels and ammonia is appendix 3 (Table 12). For dual-fuel engines employing LNG and liquefied bio-methane, SFOC has adjusted accordingly.

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[1] It is a known fact that Wärtsilä invests heavily on the development of dual-fuel engines. Therefore, the proclaimed 9.5% higher engine efficiency might be subject to bias.

Running expenses buildup

Running expenses are all expenses related to the operation of a vessel regardless of its voyage. Running expenses include crew, stores, repairs and maintenance of the hull and auxiliary equipment, repairs and maintenance and lubrication of the engine (so-called 'Engine OPEX'), insurance, and administration. Of all running expenses, expenses for stores and repairs and maintenance of the hull and auxiliary equipment are not fuel-dependent. The detailed formulation of the running expenses can be found in appendix 2. A higher cost per crew member is considered for vessels employing alternative fuels due to premiums paid for trained and specialized personnel.

Capital expenses buildup

Capital expenses are expenses related to the financing and periodic maintenance of the vessel. Periodic maintenance costs are incurred when the ship is dry-docked for significant repairs and special survey, which carries considerable expenditure. For this reason, these expenses are not generally treated as part of operating expenses Stopford (2013). Financing costs include the shipowner's cash contribution to the vessel's purchase, interest expenses over the remaining debt, principal debt payments during the repayment time agreed in the loan agreement, and a single bullet payment of a fixed portion of the agreed debt at the end of the repayment time. Additionally, scrap value is accounted for under capital expenses as an income. Appendix 2 presents the details of the capital expenses buildup as found in the model.

Escalation factor

For the model to account for changes in future cost, the possibility of applying an escalation factor (ef) is built-in. Escalation factors are annual percentage adjustments to how the cost of a certain item develops over the years. Their application is best understood when considering inflation or technologies that become more affordable with increasing scale. In the current application, inflation is assumed constant at 2.5% per annum. The formula for determining the cost 'C' in year 'Y' is presented below.

$$\mathrm{C_Y = C_{Y-1} ef^{Y-1}} \tag{4}$$

The above formula is applied to all line items subject to inflation and (if desired) additional escalation. This includes revenues, port charges, canal dues, and expenses for fuel, crew, stores, repairs, maintenance, lubrication, insurance, administration, dry docking, special survey, and scrapping.

Financial indicators

In order to make a financial decision, shipowners commonly resort to a number of financial indicators. In the present thesis, the net present value (NPV), the internal rate of return (IRR), and the required freight rate (RFR) are discussed. The NPV and IRR are general indicators used for judging the attractiveness of a business opportunity or project in a wide variety of applications and industries. The required freight rate is a specific indicator used in the transportation industry. In this research the

’projects’ that are evaluated consist of a container vessel employing different alternative fuels.

The required freight rate is a common financial indicator in commercial shipping. Watson defines in Practical Ship Design (Watson 1998): "The required freight rate (RFR) is that which will produce a zero NPV, i.e. the break-even rate". The present research expresses the required freight rate in \$/TEU-mile. The general formula for calculating the required freight rate as found in Watson (1998). If Watson’s formula for the required freight rate is subsequently adapted for the specific use case of the present research, being a container vessel transporting TEUs we get the following formula:

$$RFR_i = \frac{\sum_{Y=1}^{lt} \frac{Cvoyage;i+Crunning;i+Ccapital;i}{(1+r)^Y}}{\sum_{Y=1}^{lt} \left[TEU_{Annual,i}.d_{Annual,i}\right]} \tag{5}$$

In this formula the numerator represents the total cost of the vessel expressed in US dollars, while the denominator represents the transport performance of the vessel expressed in TEU.nm.

Economic speed optimization

To minimize costs, shipowners are recommended to optimize the design speed of their vessels to the optimal economic speed. The optimal economic speed is the speed at which a vessel employing fuel ’i’ demands the lowest required freight rate to meet the shipowner’s target return on investment. In the present model, the optimal economic vessel speed for a vessel employing fuel ’i’ is determined by a non-linear optimization model that minimizes the required freight rate (RFR) by adjusting vessel cruising speed. Therefore, in this optimization, the objective is to minimize the required freight rate $\mathrm{RFR_i}$ by changing cruising speed, subject to constraints of the cruising speed being greater than $\mathrm{V_{min}}$ and smaller than the maximum cruising speed at loaded condition $\mathrm{V_{load}}$. The minimum vessel speed is constrained due to the minimum required engine running load MAN (2020). The engine’s operating limits and sea margin limit the maximum cruising speed at loaded conditions. The decision variable is constrained to be non-negative. Therefore the optimization model can be described by:

MINIMISE: $\mathrm{RFR_i}$

$$\begin{array}{ll}\text{Subjected to}: \mathrm{V_{load}} > \mathrm{VC_i} > \mathrm{V_{MIN}} & \forall \mathrm{i} \in \mathrm{F} \\ \qquad\qquad\qquad \mathrm{VC_i} > 0 & \forall \mathrm{i} \in \mathrm{F}\end{array} \tag{6}$$

In which F is Set of alternative fuels i, i = 1, …., n; n = F, $\mathrm{RFR_i}$ the required freight rate for vessel employing fuel I, $\mathrm{V_{load}}$ the maximum vessel speed in loaded condition, $\mathrm{V_{min}}$ the minimum vessel speed in loaded condition and $\mathrm{VC_{,I}}$ the optimal economic speed for vessel employing fuel i.

The modified Watson’s formula describes the required freight rate calculation method (Eq. 6). By varying vessel speed, cost parameters such as fuel cost, emission cost, port charges, and canal dues are influenced on an annual basis, and other parameters such as annual distance sailed and TEU transported. The resulting non-linear relationship between vessel cruising speed and required freight rate is different for each vessel employing fuel i due to each alternative's different cost structure. This approach is based on a similar approach which was discussed by Jansson and Shneerson (1982).

Data

In this section, the data used in the analysis is shown. In "Scenarios" section the inputs for the different scenarios are presented, while in "Case Study Vessel Input" section the inputs for the case study are given. In Sect. Case study input the remaining data of the case study are provided.

Scenarios

The methods with which scenarios are implemented in the decision tool and the parameters that are influenced are summarized in the following paragraphs.

For the 2020, 2030 and 2050 time scenarios, two types of criteria are varied. These criteria include fuel cost and technical relevance level (TRL). In the 2020 time scenario, the base case for fuel cost and TRL is assumed. In the 2030 scenario, HFO and LNG fuel costs vary by − 10% in the lower and + 10% in the upper bound. For the other ('new') fuels, fuel cost varies by − 20% in the lower and 0% in the upper bound compared to 2020 levels. In the 2050 scenario, HFO and LNG fuel costs vary by − 20% in the lower and + 20% in the upper bound. 'New' fuels are varied by − 40% in the lower bound and − 20% in the upper bound compared to 2020 levels.

In the case of mature fuels such as HFO and LNG, price variances are applied to current fuel prices due to a degree of price uncertainty over time. Lower fuel prices are expected over time for newer fuels due to efficiencies achieved by economies of scale. The applied variances are chosen as test assumptions. In "Economic Speed Optimization" section, a sensitivity analysis is performed on fuel price to determine its influence over time on financial outputs such as required freight rate (RFR).

The technical readiness level (TRL) is expected to increase over time following developments in each respective fuel technology. In 2030, the current TRL (lower, average, and upper bound where applicable) is expected to increase by two points. In 2050, as two decades will have passed, TRL is expected to increase by 6 points. These figures are based on the assumption that developments in these fuel technologies will continue to progress at a moderate pace, as no clear preference has yet been shown by shipowners, fuel producers, and engine manufacturers. If the industry decides on a preferred fuel alternative, TRL is expected to increase at a much higher pace. In that case, model assumptions can be adjusted to represent the new information.

At last, the impact of regulatory scenarios on the general feasibility of fuels is studied as well as on the GHG emission cost. The base case for all fuels is assumed in the 'no (additional) regulation' (NR) scenario. Under market-based measures (MBM), a bunker levy per emitted annual ton CO_2 is charged to shipowners. However, this levy only impacts the selected fossil fuels (HFO and LNG). As agreed under the Kyoto Protocol, the emission factor for biomass is always zero (Netherlands Enterprise Agency 2020). This is because CO_2 emissions are measured over the biofuels life-cycle, where

Table 7 Case study vessel specifications

Specification	Value	Unit	Source
Vessel name	Azalea		COSCO (2021)
Vessel type	Container		COSCO (2021)
Class	New Panamax		COSCO (2021)
Operation area	Deep-sea		COSCO (2021)
Installed Power	49,920	kW	MAN Diesel and Turbo (2020)
Engine speed at 100% SMCR	84	rpm	MAN Diesel and Turbo (2020)
Propeller diameter	10	m	MAN Diesel and Turbo (2020)
Length overall	366	m	COSCO (2021)
Beam	48	m	COSCO (2021)
Molded draught	16	m	Estjmated with Hollenbach Method
Depth	10,7	m	COSCO (2021)
Deadweight	145,000	m	COSCO (2021)
Gross tonnage	143,197	–	COSCO (2021)
Lightweight	51,750	t	Lutzen (2013)
TEU capacity base	13,500	TEU	COSCO (2021)
Crew	20	pax	Estimated
Max. ballast speed	19,9	kts	Estimated with Hollenbach Method
Max. loaded speed	18,9	kts	Estimated with Hollenbach Method
Min. loaded speed	9,1	kts	Estimated with Hollenbach Method

the growth of the feedstock has absorbed an equal amount of CO_2 from the air. Therefore, the net tank-to-propeller emissions of biofuels are zero. In the case of ammonia, the bunker levy does not apply since ammonia combustion does not emit any detrimental greenhouse gases apart from fossil pilot fuel. Due to the very low consumption of pilot fuel or the option to opt for a bio-fuel alternative, this levy is assumed negligible. Nevertheless, fossil pilot fuel used for ammonia combustion is expected to be levied in practice. A feasibility check is performed for the 'emission cap' (EC) scenario on all alternatives. It is deemed infeasible if an alternative fails to comply with the emission cap of emitting less than 50% tank-to-propeller GHG emissions per MJ energy compared to 2008 levels. This measure impacts HFO and LNG, which both fail to deliver the desired 50% GHG emission reductions.

Case study vessel input

In this research, the case study vessel is defined as a 13,500 TEU New-Panamax container liner operating on the around the world sailing route. Therefore, it is categorized as a deep-sea vessel and limited to the sizing of the New Panama canal. Inspired by the engine configuration of the COSCO Shipping Azalea, the container liner in the present model is equipped with a 49.920 kW marine diesel engine and a 10 m fixed pitch propeller Clarksons (2020). The exact dimensions, configuration, and other relevant vessel specifications are summarized in Table 7.

Case study input

To make the calculations for the case study, a set of inputs are needed, such as the operational and financial inputs. In Table 8, an overview of the operational case study inputs is provided. For the dry dock and special survey interval, the case study vessel is assumed

Table 8 Case study inputs

Case study inputs	Value	Unit	Source
Operational input			
Dry docking & ss interval	5	Years	IMO (1974)
Dry docking & ss duraton	16	days	Bimco estimate
Broker commission	1,5	%	Industry std
Cargo handling and terminal op. cost	60	%	Stopford (2013)
Time loading at full utilization	36	hours	Stopford (2013)
Time discharging at full utilization	24	hours	Stopford (2013)
Additional auxiliary power requirement	5	%	Stopford (2013)
Financial input			
EUR/USD exchange rate	1,17	EUR/USD	As of July 2020
Base vessel purchase price	116,8	m$	Clarksons Research (2020)
Equity share	20	%	Stopford (2013)
Gearing	80	%	Stopford (2013)
Bullet % of debt share	10	%	Stopford (2013)
Interest rate	7,5	%	Stopford (2013)
Discount rate	8	%	Industry experts
European CO_2 EA cost	25	$/ton	Stopford (2013)

Table 9 Case study inputs. *Source* based on Searoutes (2020)

Origin port	Destination port	Distance (nm)	Utilization (TEU)	Freight rate ($/TEU)
Shanghai (CN)	Rotterdam (NL)	11,999	13,000	810
Rotterdam (NL)	New York (USA)	3918	12,500	390
New York (USA)	Los Angeles (USA)	5734	6000	600
Los Angeles (USA)	Nagoya (JP)	4988	4000	530
Nagoya (JP)	Shanghai (CN)	1007	6200	350

to comply with SOLAS (IMO 1974) regulations and follows the regular dry-docking interval schedule every five years (IMO 1974). A special survey is carried out concurrently. Broker commission for both time- and voyage charters is set at 1.5%, a general industry standard. Cargo handling and terminal operating cost are set at 60% of the total revenue, as suggested by Stopford (2013). Time spent loading and discharging at full capacity are established at 36 and 24 h on average, respectively (Stopford 2013). The fraction of additional power required for auxiliary equipment is set at an average of 5% of propulsion power and assumed to be produced by the vessel's main engine following guidelines in Stopford (2013).

Table 9 provides an overview of the charter specification inputs required to generate a revenue model. In the case study, the liner route around the world is considered, starting and ending in Shanghai, China. The case study vessel is assumed to repeat this cycle during the year continuously. For each route, sailing distance is calculated with assistance from SEAROUTES, and average TEU utilization and FCL freight rates are estimated and checked alongside spot rates (Searoutes 2020).[2]

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[2] It need to be mentioned that the data used in this case study predates the high freight rates of 2021/2022 period.

Table 10 Economic speed (kts) for all alternative fuels under optimistic (O), average (A), pessimistic scenarios (P), as well as no regulation (NR), market-based measures (MBM), and emission cap (EC) regulatory scenarios in 2020, 2030 and 2050

Alt	Reg	2020			2030			2050		
		O	A	P	O	A	P	O	A	P
HFO	NR	16,20	16,00	15,60	16,70	16,00	15,10	17,30	16,10	14,90
	MBM	15,50	15,20	15,00	16,10	15,20	14,60	16,60	15,30	14,20
	EC	–	–	–	–	–	–	–	–	–
UBO	NR	13,00	11,10	9,90	13,90	11,40	9,90	15,70	12,30	10,60
	MBM	13,00	11,10	9,90	13,90	11,40	9,90	15,70	12,30	10,60
	EC	13,00	11,10	9,90	13,90	11,40	9,90	15,70	12,30	10,60
FTD	NR	13,00	10,60	9,30	13,80	10,90	9,40	15,60	11,70	10,40
	MBM	13,00	10,60	9,30	13,80	10,90	9,40	15,60	11,70	10,40
	EC	13,00	10,60	9,30	13,80	10,90	9,40	15,60	11,70	10,40
LBM	NR	13,60	11,20	9,80	15,00	11,60	9,80	16,30	12,40	10,60
	MBM	13,60	11,20	9,80	15,00	11,60	9,80	16,30	12,40	10,60
	EC	13,60	11,20	9,80	15,00	11,60	9,80	16,30	12,40	10,60

Economic speed optimization

As elaborated in "Data" section, the optimization model that runs the decision tool to determine the optimal economic speed is constrained by minimum and maximum speeds. The maximum speed is determined at 18.9 knots, limited by the maximum continuous rating for the engine and sea margin. The minimum speed is determined at 9.1 knots, limited by the engine's inability to run below 10% SMCR.

As can be deducted from Table 10, each alternative has its own specific economic speed, which varies per scenario. The difference between each alternative's economic speed can be attributed to different fuel costs, energy density, and engine choices. The RFR-speed curve presents the required freight rate of a vessel against its cruising speed and varies per alternative.

In Fig. 2, the RFR speed curves for the optimistic and pessimistic scenarios are demonstrated for Fischer–Tropsch diesel (FTD). Comparing the RFR-speed curve of the optimistic and pessimistic scenarios, two key observations can be made: at lower (fuel) cost, the required freight rate drops to lower base levels, and the RFR-speed curve gradient decreases, demonstrating its preference for higher economic speed. At higher fuel costs, the opposite effect is observed. These observations underpin the results of Table 10, which show that vessels sailing on more expensive fuels have lower optimal economic speeds, and vessels sailing on cheaper fuels have higher optimal economic speeds. Similar relationships between required freight rate and vessel speed are observed for all alternatives and are further elaborated in "Sensitivity Analysis" section.

As is evident from both Table 10 and Fig. 2, the transition toward alternative fuels in the maritime industry will most likely lead to a shift toward lower sailing speeds. Assuming equal transport demand, slow steaming will increasingly be applied to vessels employing expensive alternatives. When sailing at high speed, the marginal cost exceeds the marginal returns from the increase in annual TEU-mile transported.

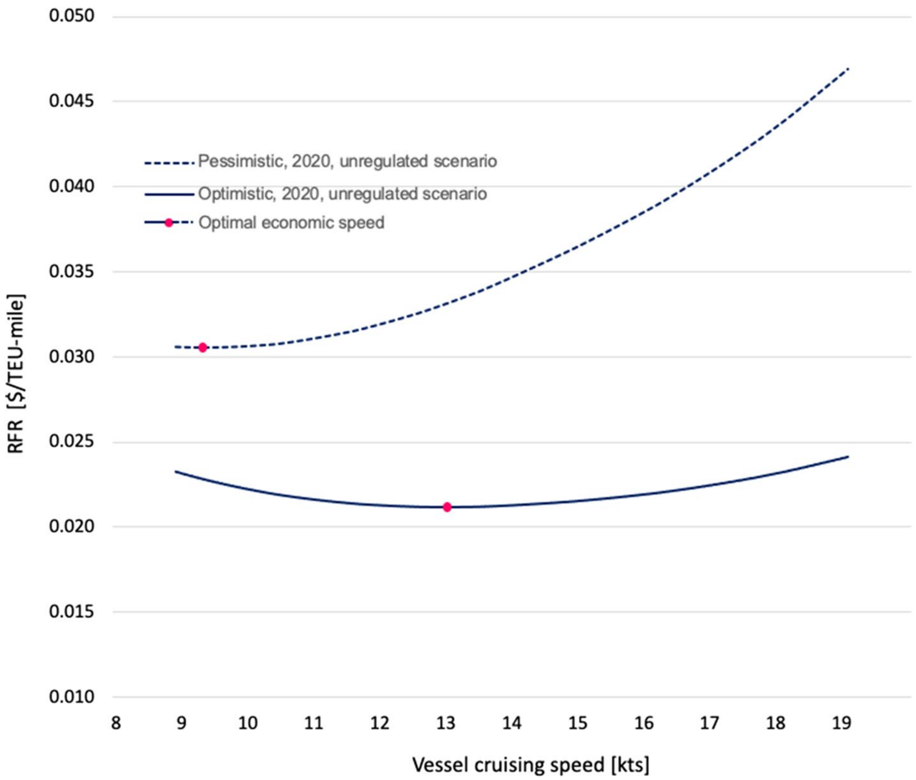

Fig. 2 RFR-speed curves for Fischer–Tropsch diesel (FTD) in the optimistic and pessimistic 2020, unregulated scenario

From Table 10, several conclusions can be drawn. First, as can be deducted from the differences between optimistic, average, and pessimistic scenarios, the optimal economic speed declines with higher fuel cost. This observation is confirmed by Fig. 2. Additionally, following scenarios of future price reductions for alternative fuels, the optimal economic speed can be observed to increase gradually.

Significant differences in economic speed between high and low-cost alternatives in specific fuels are noticed. For instance, comparing FTD to HFO, average economic speed lies approximately 28% and 24% lower under the 'no regulation' or 'market-based measures' scenarios. An evident correlation between the required freight rate and economic speed can be observed.

At last, although LNG, LBM, and ammonia do not necessarily carry lower required freight rates, their economic speed can be observed to average at slightly higher levels than bio-fuels with similar RFR. This can be attributed to higher capital costs which cause a proportionally smaller share of voyage costs in RFR.

In conclusion, the optimal economic speed for an alternative and fossil fuels lies significantly lower than the intended design speed. Therefore, slow steaming can be expected to become increasingly common if regulators incite a transition towards alternative fuels.

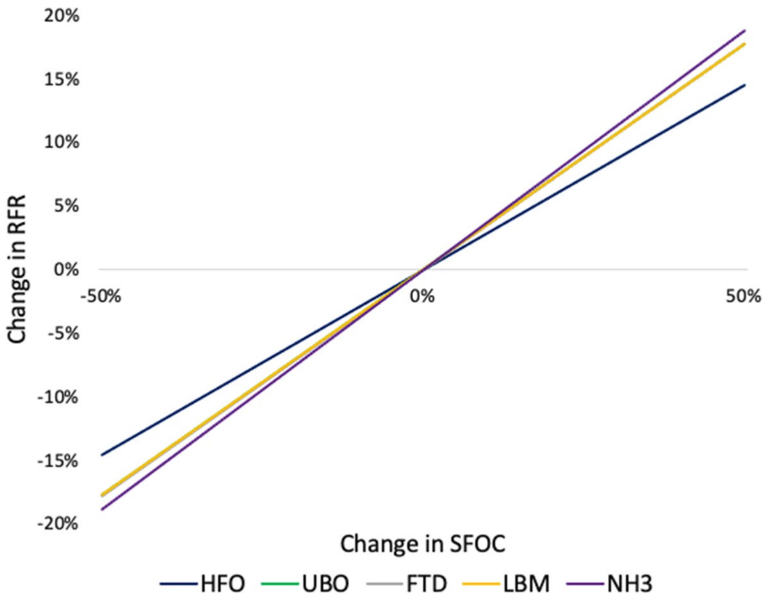

Fig. 3 Sensitivity analysis on SFOC for HFO, UBO, FTD, LBM and NH3 under the average, 2020, no regulation scenario

Sensitivity analysis

This section performs sensitivity analysis on multiple input parameters, including SFOC and fuel cost in "SFOC and Fuel Cost" section and the vessel speed in "Vessel Speed" section.

In this sensitivity analysis, four fuels are analyzed: heavy fuel oil (HFO), Fischer–Tropsch diesel (FTD), upgraded bio-oil (UBO), and liquefied biomethane (LBM). HFO is selected due to its current presence in the maritime industry, designating it as an ideal benchmark. The target variable is the required freight rate (RFR) in all analyses, and each of the four most interesting fuels is evaluated.

SFOC & fuel cost

In this section, a sensitivity analysis is performed to demonstrate the relationship between required freight rate and specific fuel (oil) consumption (SFOC) during transit for the three most interesting fuels (UBO, FTD, and LBM), NH_3 and HFO (which is used as a reference case). NH_3 is added to demonstrate how changes in a high-cost fuel impact change in RFR (see Fig. 3).

As can be deducted from Fig. 3, the relationship between the required freight rate and SFOC is nearly linear in all discussed fuels. However, the gradient of the line is different between the presented fuel alternatives. Noticeably, the gradient is significantly larger in the alternatives where fuel expenses take up a larger proportion of the total cost. This is made clear when looking at the gradient of NH3, a more expensive alternative. Furthermore, UBO, FTD, and LBM overlap due to their similar cost levels. However, upon closer inspection, small differences in their sensitivity are observed.

The sensitivity analysis produces very similar results for fuel cost due to the correlation of SFOC and fuel cost. Nevertheless, although a > 50% improvement in SFOC is

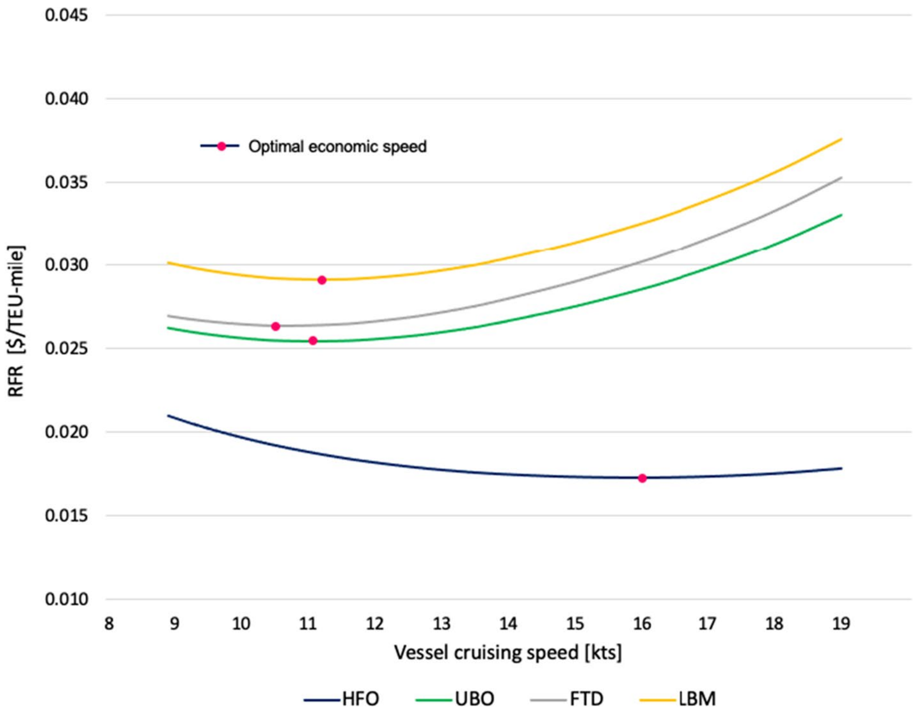

Fig. 4 Sensitivity analysis on vessel speed for HFO, UBO, FTD and LBM under the average, 2020, no regulation scenario

doubtful, a > 50% reduction in fuel cost may not be as ambitious. In many industries, cost advantages due to the increasing scale of operations have significantly impacted production costs and prices. It is therefore not impossible that in the future, alternative fuels could potentially become cost-competitive with current fossil fuel prices due to the increasing scale of production.

Additionally, one must consider that the sensitivity analysis of Fig. 3 is performed based on a static optimized vessel speed. During the sensitivity analysis, vessel speed remains constant and equal to the optimal economic vessel speed determined at 0% SFOC. When performing a sensitivity analysis based on a dynamically determined optimal economic vessel speed, the optimized economic RFR-SFOC relationship proves to be non-linear.

Vessel speed

As discussed in "Economic Speed Optimization" section, vessel speed significantly impacts fuel consumption and total cost. In Fig. 4, a sensitivity analysis is performed to demonstrate the relationship between the required freight rate and vessel speed for the four most interesting fuels under the average, 2020, 'no regulation' scenario.

Additionally, the optimal economic speed (at minimum RFR) is demonstrated. As was earlier determined from Table 10, the choice of fuel alternative leads to significant differences in RFR and optimal economic speed. For more expensive fuels, the minimum RFR is significantly higher than that of HFO. Additionally, as is observed in all alternatives, deviating from economic speed significantly impacts the required freight rate. The

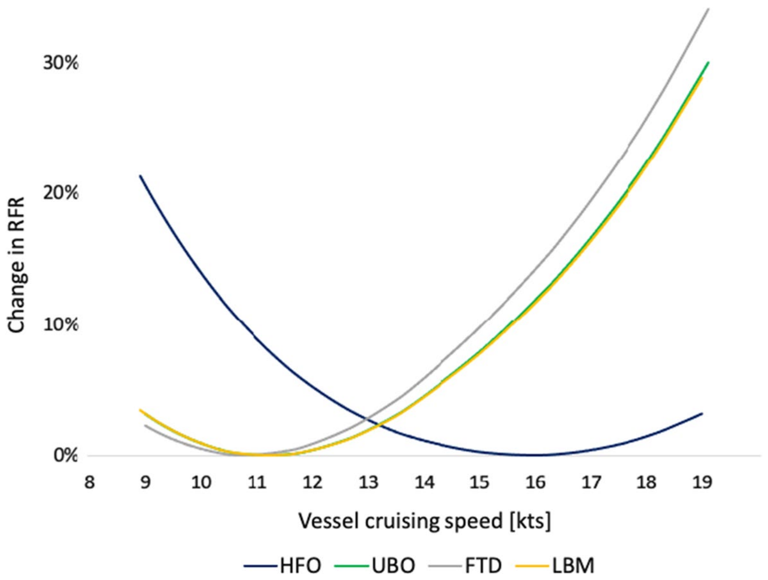

Fig. 5 Sensitivity analysis on vessel speed for HFO, UBO, FTD and LBM under the average, 2020, no regulation scenario

parabolic curves indicate a non-linear RFR-speed relationship, which can be attributed to the 'cubic law' of the Hollenbach power-speed curve (Birk 2019).

To better demonstrate the parabolic shape of the curves and the differences in cost dominance between expensive and more economical fuels, Fig. 5 is devised. This figure has chosen the optimal vessel speed as the baseline for RFR (at 0% change). Doing so demonstrates the difference in dominance between voyage expenses or fixed expenses at each vessel speed for each displayed alternative. The dominance of voyage expenses or fixed expenses at each speed can be determined by observing the RFR at each cruising speed compared to the optimal economic speed. At the optimal economic speed, fixed and voyage expenses have found a balance in which the vessel produces the lowest possible total cost per TEU-mile (RFR). Fixed expenses become dominant when the cruising speed is below the optimal economic speed. When cruising speed exceeds the optimal economic speed, voyage expenses become dominant. This relationship can be attributed to the reduction of voyage expenses per TEU-mile at lower cruising speeds, such as less fuel consumption, fewer port visits, and fewer canal passes, as well as the increase of fixed expenses per TEU-mile due to the reduction in TEU-mile transported.

Therefore, the optimal economic speed position on the RFR-speed curve demonstrates the relationship between voyage expenses and fixed expenses in each alternative fuel. As shown in Fig. 5, voyage expenses weigh heavier in fuels such as UBO, FTD, and LBM due to their high fuel cost, whereas, in the case of HFO, fixed expenses weigh heavier due to the fuel's relatively low cost.

Conclusions and recommendations for further research

The maritime industry must change to achieve the goals set in the Paris agreement of 2015. Therefore, the International Maritime Organization has drafted the initial IMO strategy to reduce GHG emissions from ships (IMO 2018). In this strategy, alternative fuels are considered essential in achieving the emission reduction targets set by the United Nations. However, due to the many criteria and external factors impacting the decisions of shipowners, no consensus has been reached on the most appropriate alternative fuel choice to comply with possible different imposed emission regulations.

Therefore, in this research both a selection method is developed to see which fuel types are most suitable for complying with GHG reduction targets. Next to that also a model is made to research the impact of using the most appropriate alternative fuels on the optimal design speed of the vessel. For both models that are used in this research different data sources are used to create comprehensive overview of the state of the art of the alternative fuels as well as a the cost and prices in the container shipping sector. It is recognized that these data are subjected to changes (such a development of shipping fuel technology and market conditions). Therefore, different scenarios were created to in cooperate this uncertainty.

With respect to which alternative future fuels should be used FTD and UBO can be entitled the ’most promising’ alternative maritime fuels of the future, whereas HFO and LNG remain the ’most probable’ to retain dominance without regulatory intervention. This suggests that for the maritime industry to transition towards sustainable alternative fuels, policymakers, governments, international organizations, and lenders must collectively align their policies to enable a more sustainable shipping industry. Not only by enforcing stricter regulations but also by providing the correct financial incentives.

Based on the modeling outcomes, HFO performs best, followed by LNG in the medium term and UPO and UBO in the longer term. Nevertheless, the average difference in required freight rate of UPO and UBO compared to HFO remains substantial, at 36% and 39% under a no regulation scenario and 32% and 34% under market-based measures, respectively. For FTD, the average difference in required freight rates compared to HFO is higher at 43% and 38% under a no-regulation and market-based measures scenario.

Therefore, without regulations or financial incentives from policymakers, HFO is expected to remain the dominant fuel of the maritime industry. However,if policymakers do take action to support the uptake of sustainable alternative fuels. In that case, Fischer–Tropsch diesel (FTD) and upgraded bio-oil (UBO), and liquefied bio-methane (LBM) could prove to be a suitable future drop-in alternative fuels.

Significant differences are noticed in economic speed between high and low-cost alternatives in specific fuels. For instance, comparing FTD to HFO, average economic speed lies approximately 28% and 24% lower under the ’no regulation’ or ’market-based measures’ scenarios. At last, although LNG, LBM, and ammonia, their economic speed can be observed to average at slightly higher levels than bio-fuels with similar RFR. This can be attributed to higher capital costs which cause a proportionally smaller share of voyage costs in RFR.

From the analysis, the transition towards alternative fuels in the maritime industry will shift towards lower sailing speeds. Ships sailing at lower speeds, will lead to the use of more vessels if the vessel size remains constant. It can also be argued that due to the lower designed speed, the block coefficient of the vessel can increase. This leads to vessels with more "full" hulls, which could increase their deadweight if the main dimensions of the vessel (length, width, and draft) are kept constant. This could lead to bigger vessels with an increase in load capacity, implying that the energy transition can also impact the load capacity of the container vessels. These vessels with a larger load capacity will impact port operations and the functioning of the maritime supply chain. All of these changes impacts the reconfiguration of the container liner service networks. All of this lead to changes in the impact of the inventory costs during the maritime transport phase of the transport chain. And this will impact the shippers as was indicated by Maloni et al. (2013) and Yin et al. (2014). All of these elements needs to be researched further to gain more insights into this aspect. But it can be argued that introducing alternative maritime fuels will have a very broad impact on all of the above mentioned elements.

Appendix 1: Weighing determination

Criteria weight assessment w of each criterion j. Scores are assessed on Likert scale: 1: Not important at all; 2: Not so important; 3: Moderately important; 4: Very important; 5: Extremely important.

Relative weights W are assessed by dividing each individual weight wj over the sum of all criteria weights. The results are shown in the table.

Criteria	Median weights (wj)	Relative weights (W)
Technological maturity	4	0,08
Availability of infrastructure	4	0,08
Engine compatibility	4	0,08
Fuel volumetric energy density	3	0,06
Compliance with emission regulations	4	0,08
GHG emissions: well-to-tank	4	0,08
GHG emissions: tank-to-propeller	4	0,08
Safety of fuel technology	4	0,08
Long-term global availability of fuel	4	0,08
Feedstock competition with food	3	0,06

Appendix 2: Detailed cost calculation

Voyage cost calculation

In the following equations, the voyage expenses buildup as implemented in the model is presented.

$$\mathrm{C_{voyage,i}} = \mathrm{C_{port}} + \mathrm{C_{canal}} + \mathrm{C_{fuel,i}} + \mathrm{C_{GHG,i}}$$

In which $\mathrm{C_{voyage;}}$i Annual voyage expenses of vessel employing fuel i,

The above mentioned variable can be calculated with the following formulas:

$$\mathrm{C_{port,i}} = \mathrm{GT.C_{GT}.\ port_{a,i}}$$

$$\mathrm{C_{canal,I}} = \mathrm{C_{ce,NP}} + \mathrm{C_{ce,S}.\ Canal_{e,i}}$$

$$\mathrm{C_{fuel,i}} = \mathrm{FC_{total,i}\ .\ C_{mt,i}}$$

$$C_{GHG,i} = EC_{total,I} .E_{CO2eq,i}. C_{CO2eq,i}$$

In which

$C_{mt;i}$ is the cost per unit of mass per fuel type ($/mt),.

The equations below show the calculation method for arriving at the annual fuel consumption for each fuel type i. The vessel's speed-power curve is determined using the Hollenbach Method (Birk 2019).

$$FC_{fuel,i} = FC_{prop,i} + FC_{aux,i}$$

with:

$$FC_{prop,i} = EC_{prop,i}. SFOC_{P,I} . (1 - ECF_i)$$

$$FC_{aux,i} = pFC_{aux}.FC_{prop,i}$$

and:

$$EC_{prop,i} = t_{t,i}. P_{vc,i}$$

$$T_{t,i} = \sum_{l=1}^{l} \frac{td_l}{vc_i}$$

$P_{vc,i} = 5.4031.vc_i^3 - 10.619.vc_i^2 + 241.32\ vc_i - 353$ (Regression formula, R^2 = 0.999).

Running cost calculation

In the following equations, the running cost buildup as implemented in the model is presented.

$$C_{running,I} = C_{crew,i} + C_{stores} + C_{r\&m,h\&a} + C_{eOPEX,i} + C_{insurance,i} + C_{admin,i}$$

with:

$$C_{crew,i} = c_{cm,i}. cm$$

$$C_{stores} = (C_{food}. CM + C_{other}).cd_a$$

$$C_{stores} = (C_{food}. CM + C_{other}). cd_a$$

$$C_{r\&m:h\&a} = C_b. PC_{b,r\&m:h\&a}$$

$$C_{r\&m:h\&a} = C_b. PC_{b,r\&m:h\&a}$$

$$C_{eOPEX,I} = P_{inst}. C_{ekW,i}$$

$$C_{insurance,I} = C_{tv,i}. PC_{tv,insurance}$$

$$\mathrm{C_{admin} = C_{tv,i}.\ PC_{tv,admin}}$$

Capital cost calculation

In the following equations, the capital cost buildup as implemented in the model is presented.

$$\mathrm{C_{capital,i} = C_{purchase,i} + C_{interest,i} + C_{principal,i} + C_{bullet,i} + C_{dd,i} + C_{ss,i} - C_{scrap}}$$

In which:

$$\mathrm{C_{purchase,i} = \left(1 - g\right) .C_{tv,i}}$$

$$\mathrm{C_{interest,i} = i_{rate}.\ d_{lt,i}}$$

$$\mathrm{C_{principal,i}} = \frac{d_{lt,i} - C_{bullet,i}}{rt}$$

$$\mathrm{C_{bullet,I} = b.\ d_{lt,i}}$$

$$\mathrm{C_{dd,i} = pc_{dd}.\ C_{tv,i}}$$

$$\mathrm{C_{ss,I} = pc_{ss}.\ C_{tv,i}}$$

$$\mathrm{C_{scrap} = LDT\,.\,v_{LDT}}$$

$$\mathrm{C_{scrap} = LDT\,.\,v_{LDT}}$$

and:

$$\mathrm{d_{lt,i} = g\,.\,C_{tv,i}}$$

$$\mathrm{C_{tv,i} = C_b + C_{eCAPEX,i}}$$

$$\mathrm{C_{eCAPEX,i} = C_{ckW,i}.\ P_{inst}}$$

Appendix 3: Engine characteristics data

See Tables 11 and 12.

Table 11 Engine specifications for the engine assumed to calculate fuel efficiency for all diesel-like fuels. *Source* MAN (2020)

Engine parameters	Value	Unit
Engine type	8G90ME-C10.5	
Scrubber	Yes	
Exhaust Gas Recirculation (EGR)	Yes	
NOX emission compliance	Tier III	
100% SMCR power	49,920	kW
100% SMCR speed	84	r/min
Sea margin	15%	
Propeller diameter	10.0	m
Propeller type	FPP	
Cooling system	Central	
Hydraulic power supply	Mechanical	
Turbocharger type	High eff	

Table 12 Power-SFOC relation data table used in the present model for calculations of specific fuel oil consumption of diesel-like fuels and ammonia. *Source* MAN (2020)

Power	Speed	SFOC(SMCR)
[kW]	[r/min]	[g/kWh]
49,920	84.0	165.5
47,424	82.6	163.8
44,928	81.1	162.4
42,432	79.6	161.2
39,936	78.0	160.9
37,440	76.3	160.7
34,944	74.6	160.3
32,448	72.8	160.2
29,952	70.8	160.5
27,456	68.8	160.9
24,960	66.7	161.5
22,464	64.4	162.6
19,968	61.9	163.7
17,472	59.2	165.1
14,976	56.2	166.1
12,480	52.9	168.1
9984	49.1	171.1
7488	44.6	176.1
4992	39.0	184.1

Abbreviations

DCF	Discounted cash flow
EC	Emission cap
FAME	Fatty acid methyl esters
FTD	Fischer–Tropsch diesel
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
LNG	Liquified natural gas
MBM	Market-based measure
NH3	Ammonia
RFR	Required freight rate
SFOC	Specific fuel (oil) consumption

SMART	Simple multi-attribute rating technique
TRL	Technical readiness level
UBO	Upgraded bio-oil
UPO	Upgraded pyrolysis oil
WACC	Weighted average cost of capital

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