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A Proposed Methodology for the Technoeconomic Evaluation of Energy Efficiency Retrofits: A Bulk Carrier Case Study

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In light of the International Maritime Organization (IMO) directives on climate change and the continuous effort of shipping companies to reduce operating costs, this article proposes a methodology for the technoeconomic evaluation of energy efficiency retrofits. The aim of this article is to provide a management tool able to support the decision-making process of investing in energy efficiency methods. The introductory part briefly discusses the environmental problem caused by the gaseous pollutants as well as the regulatory framework that is going to seriously affect the bunker pricing in the near future. In the main part, a series of energy efficiency retrofits, suggested by IMO in the Ship Energy Efficiency Management Plan Annex, are presented with a view to applying them on a bulk carrier. The analysis focuses on the evaluation of these retrofits as potential investments from an owner's strategic point of view. The assessment takes into account major uncertainties of the data used through Monte Carlo simulations and conducts multicriteria analysis to include also nonfinancial criteria in the decision-making process.

Keywords: IMO; energy efficiency; technoeconomic evaluation; quantitative risk assessment; Monte Carlo

1. Introduction

The importance of the adverse effects of global warming has been understood by the scientific community since the late sixties. It took more than 20 years till the first adaptation of measures against global warming with the foundation of the Intergovernmental Panel on Climate Change in 1988 and the Kyoto Protocol agreement in 1997. According to the latest updates by the Earth System Research Laboratory in Hawaii, in 2013, carbon dioxide (CO_2) concentrations for the first time in recorded history exceeded 400 parts per million. International shipping, which accounts for over 90% of global transport, is estimated to have emitted 870 Mt or about 2.7% of the global emissions of CO_2 in 2007 (Buhaug et al. 2009). Today, the International Maritime Organization (IMO) has proposed a plethora of policies that target to the reduction of the gaseous pollutant emissions.

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The importance of such policies stems from the fact that the strict emission limits that have already been imposed are expected to gradually decrease more over the next 20 years. In addition to these measures, uncertainty and high volatility exists regarding the bunker prices, reaching an all-time peak in 2012 (Rotterdam 380 cSt: 712$/t) while dropping to under 500$/t prices during November 2014. Finally, the extremely low hire rates as a consequence of the general economic crisis and the existing overcapacity make it clear for the shipping companies that new technologies have to be implemented in order to achieve a sustainable future.

Several publications have appeared in recent years documenting the potential benefits of implementing innovative energy efficiency improvement methods. The most interesting and comprehensive approach to this issue has been reported in a study by IMO (Faber et al. 2011), where the economics and cost-effectiveness of technical and operational measures to reduce CO_2 emissions from ships are investigated. However, this study is intended primarily to evaluate the cost-benefit relationship of each method, where benefit is defined as the overall anticipated reduction in CO_2. Other studies compare the financial viability of a series of energy efficiency methods by evaluating based on static input data, thus not taking into consideration the high uncertainty and risk included in the evaluation parameters (Schnack 2009; Andersen et al. 2012; Nielsen & Schack 2012).

On the subject of Monte Carlo (MC) simulation as a risk analysis tool for investment approval in shipping-related subjects, Chien (1993) conducted experiments to measure the effects of changes in parameter values when evaluating different production and transportation policies, where demands were stochastic and followed a known probability distribution. Fagerholt et al. (2010) proposed a MC simulation framework built around an optimization-based decision support system for short-term routing and scheduling. Corbett et al. (2010a) evaluated the cost-effectiveness of six black carbon emissions reduction technologies and demonstrated the robustness of their results through MC simulations. Finally, Chen et al. (2011) developed an MC model to optimize the process of ship design, operations, and shore logistic system.

In regard to the importance of multicriteria analysis, Rousos and Lee (2012) discussed the need of widening the traditional perspective through which shipping investment decisions are taken by embedding them in a multicriteria environment. Other studies have also employed various multi-criteria decision making (MCDM) methods (analytic hierarchy process (AHP), PROMETHEE) to evaluate different alternatives in shipping-related subjects, such as optimal port selection, loan application, or shipping company performance (Chou & Liang 2001; Dimitras et al. 2002; Guy & Urli 2006; Lagoudis et al. 2006; Lirn et al. 2004; Song & Yeo 2004).

This study focuses on the technoeconomic evaluation of energy efficiency retrofits. The aim of the study is to provide a comprehensive and simplistic methodology that will assist managers in the decision-making process of investing in energy efficiency improvement methods. The technoeconomic model developed, takes into account the future regulatory framework, delivers fuel oil price forecasts and assesses the input data uncertainty through MC simulations. In the multicriteria analysis developed, the method of weighted sums (WSM) is used, being the most commonly used among the sustainable energy systems bibliography (Wang et al. 2009).

1.1. Measures on CO_2, NO_x, and SO_x emissions

As stated in the aforementioned paragraphs, IMO has proposed a series of measures that aim to reduce the pollutant emissions. More specifically, Energy Efficiency Design Index provides a specific figure for an individual ship design, expressed in grams of CO_2 per ship's capacity-mile and is calculated by a formula based on the technical design parameters for a given ship. The CO_2 reduction level (grams of CO_2 per ton mile) for the first phase is set to 10% and will be tightened every 5 years to keep pace with technological developments of new efficiency and reduction measures. Moreover, under the revised Marine Pollution Annex VI, progressive reductions in NO_x emissions from marine diesel engines installed on ships are also included. Finally, since 2006, extended discussions have been made to the possibility of an adoption of a market-based measure (MBM), which will place a price on greenhouse gas emissions providing an economic incentive to the maritime industry to lower its consumption.

However, the most important regulation that is going to seriously affect the fuel oil price in the foreseeable future and create a new reality in commercial shipping is the measure on SO_x emissions. IMO has introduced the emission control areas (ECA) to reduce SO_x emissions further in designated sea areas. According to the requirements, after January 1, 2015, all vessels sailing in the ECA must reduce the sulfur level in fuel oil to 0.1% from 1%. Similarly in 2020 or 2025, the global requirements will be a reduction of the sulfur content in the fuel to 0.5% from a current 3.5%.

2. Methodology

2.1. Retrofits and ship presentation

The retrofits under evaluation were selected from IMO's guidelines for the development of a Ship Energy Efficiency Management Plan and cover a wide range of existing technologies (IMO 2012). The retrofits were further divided into four main categories for illustration purposes and are briefly described below:

1) Main engine modifications.

- Engine derating: increases fuel efficiency by optimizing the propeller's and engine's match to the vessel's operation speed and lowering the mean ratio between mean effective pressure and maximum pressure in the combustion chambers (Wettstein & Brown 2008).
- Waste Heat Recovery System (WHRS): utilizes the exhaust gas energy, which can be used to generate electricity through a steam turbine and thus decrease total energy consumption costs (Faber et al. 2011).
- Autotuning: achieves fuel efficiency through automatically optimizing and monitoring the maximum combustion pressures inside the chamber (Schnack 2009).
- Liquefied natural gas (LNG) conversion: The installation of a LNG engine can reduce fuel costs by approximately 17% when compared to heavy fuel oil (HFO) due to the price difference between the two fuels (see Section 2.3). It enables also a 20–25% reduction in CO_2 emissions, 80% in NO_x emissions, and 90–95% in SO_x emissions (Andersen et al. 2012).

2) Propeller flow optimization (DNV & SDARI 2011).

- Nozzle: airfoil shaped rings around the propeller that increase the total net thrust by accelerating the flow of the water into the propeller and reducing the pressure and the propeller required thrust.
- Mewis Duct: a combination of a vertically offset mounted duct positioned right in front of the propeller and an integrated asymmetric fin arrangement. Mewis Duct achieves increased efficiency by stabilizing the flow and reducing rotational losses in the propeller slipstream.
- Costa bulb: a bulb attached to the rudder directly behind the propeller boss that reduces vortici phenomena created by the turbulent flow of the water that trails from the boss.
- Propeller boss cap fins (PBCFs): small fins attached to the propeller hub that reduce the hub vortex generation by blocking the downward forces created after the blade.
- Integrated rudder and propulsion maneuvering system: e.g., Promas Lite.

3) Improvement of vessels operational profile.

- Weather routing: increases fuel efficiency by determining an optimum route based on the forecasted environments and seakeeping performance of a particular transit (Hagiwara 1989; Faber et al. 2011).

– Optimal trim: decision support tool designed to provide guidance in selection of the right trim in relation to the loading condition and planned speed (Sherbaz & Duan 2012).
– Fouling release coating (FRC): reduces average hull roughness, thereby increasing hydrodynamic efficiency (Corbett et al. 2010b).

4) Utilization of renewable energy sources (Faber et al. 2011).

– Wind (Flettner) rotors: reduce fuel costs by aiding the ship's propulsion by means of the Magnus effect.
– Wind kites: utilize wind energy through an automatic towing kite propulsion systems and a wind-optimized routeing system.

The vessel selected for the evaluation is a Panamax bulk carrier (deadweight tonnage [dwt]: 78,932 t). The main engine used is a Mitsui MAN 7S50MC-C operating at a maximum continuous rating (MCR) of 9561 kW at 110 rpm. The engine is equipped with one MAN turbocharger model B&W TCA66. The overall length of the ship is 225 m, the length between perpendiculars 219 m, the beam 32.24 m, and the draught on summer freeboard 14.37 m. The service speed of the ship is 13.5 knots and the ship's operation profile includes 200 days per year at sea, of which 25 (or 12.5%) are within the ECA. Moreover, the main engine's fuel specific consumption at the above-mentioned MCR is 169 g/kWh, which results in a daily main engine consumption of 27–31 t of HFO.

This type of vessel was selected based on the wide usage of similar design vessels and the consequent generalization deduced from the results of the study. Specifically, in 2013, bulk carriers accounted for 42% of the total world's tonnage with an average vessel size of 68,366 dwt (Asariotis et al. 2013). Oil tankers that share similar technical characteristics with bulk carriers and operate at similar service speed, account for another 30.1% of the total tonnage.

The consumption reduction (CR) as well as the capital expenditure estimation of the energy efficiency retrofits for the specific vessel are summarized in Table 1 and are based on the aforementioned bibliography.

2.2. Technoeconomic model

The procedure used in order to develop the technoeconomic model followed a three steps approach as illustrated in Fig. 1:

a) Determination of a basic scenario, in which the estimated values of the technoeconomic input (estimated CR, fuel oil prices, days within ECA, operational costs, etc.) were used in order to calculate the expected cash flows for each individual retrofit throughout the investment horizon 2015–2030. The discount rate was then estimated through the utilization of the Weighted Average Cost of Capital (WACC) formula for seven (7) shipping companies listed on NASDAQ and NYSE stock markets. In the end, the evaluation indicators, namely the net present value (NPV), the internal rate of return (IRR), and the profitability index (PI), were calculated for the established basic scenario.
b) Sensitivity analysis and quantitative risk assessment based on the PI indicator due to its characteristic to evaluate more precisely investments with different initial capital expenditure (Aravossis et al. 2012). The quantitative risk analysis resulted in an initial classification of the retrofits based on their cumulative probability of rejection.
c) Multicriteria analysis based on three criteria; PI, CO_2 reduction, and technological maturity (TM).

2.3. Fuel price projections and discount rate calculation

As stated in the introductory part, in 2020 or 2025, all vessels sailing outside ECA must reduce the sulfur level in fuel oil to 0.5% from a current 3.5%. Such a measure will automatically mean that the wide usage of HFO has to be abandoned due to the technical limits that exist when blending different kinds of fuel oils. DNV suggests that by that year the demand for marine gas oil (MGO) will rise to 200–250 Mt from 30 Mt in 2012 and correspondingly HFO demand will dwindle to 80–90 Mt from 290 Mt in 2012 (DNV 2012). Although a medium to long-term estimation of the fuel oil prices hides an uncertainty that is difficult to gauge, this study approaches this task on a step-to-step basis. It is evident that the results of this study cannot be based on a single value. This weakness is equilibrated through MC

Table 1 Retrofits capital expenditure/CR/estimation of applications

Serial No.	Description	Capital Expenditure ($)	Minimum CR (%)	Estimated CR (%)	Maximum CR (%)	Number of Applications
1	Weather routing	3000	0.1	2	4	>3000
2	Engine derating	1,100,000	2	4	6	nk
3	Optimal trim	150,000	1	2	5	>800
4	PBCF	80,000	2	4	5	>2000
5	Nozzle	150,000	2	6	10	nk
6	Costa bulb	270,000	2	3	4	>300
7	Promas lite	1,000,000	6	7	9	>30
8	Mewis Duct	350,000	4	6	9	>400
9	FRC	390,000	5	7	9	>500
10	Autotuning	40,000	1	2	3	nk
11	WHRS	1,600,000	8	9	10	nk
12	Wind kites	1,400,000	4	8	12	10
13	Wind rotors	1,200,000	8	9	12	1
14	LNG	7,600,000	*	*	*	>400

*This retrofit will be evaluated by the price difference of HFO and LNG.
nk, not known.

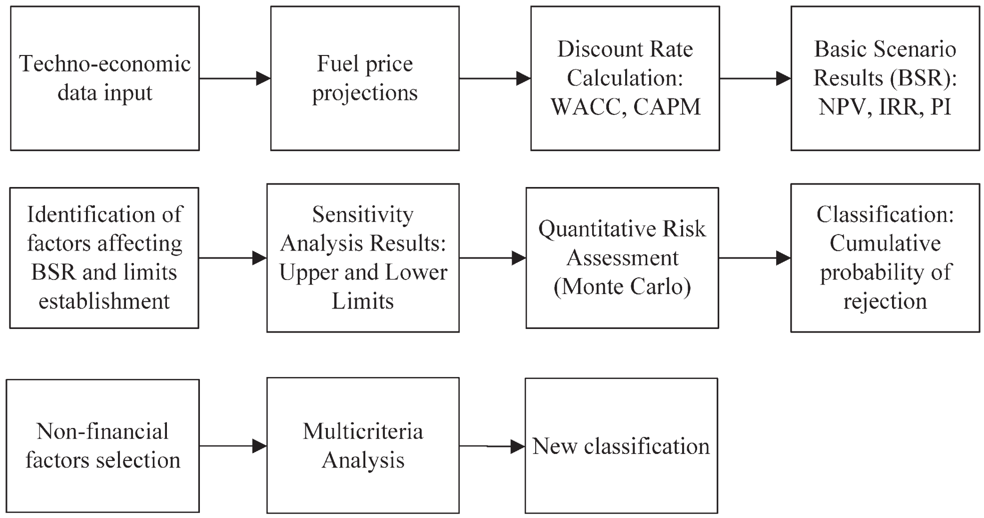

Fig. 1 Technoeconomic model flow chart

simulations that will be introduced in the following paragraph and can help to further solidify the conclusions on that matter.

The first step takes into account the crude oil price projections reported by the Energy Information Agency (Eia 2013) for the years 2020, 2025, and 2030 and converts them into HFO prices through the diachronic correlation of the West Texas Index ($/barrel) and the HFO180 ($/t) of Singapore (Faber et al. 2011). This results in a rate of 580, 640, and 700 $/t, respectively (based on 2011 U.S. dollars).

The second step includes the estimation of the low sulfur fuel oil price (LSFO: $<$ 0.5% sulfur content) that will replace HFO in 2020 or 2025. While several publications have appeared demonstrating a 30–50% difference in HFO (1.5%) and LSFO (0.5%) price (Kalli et al. 2009; Notteboom 2011; Faber et al. 2011), others equate the price of LSHO with that of MGO (0.1%) (Andersen et al. 2012). In general, doubt arises as to attaining the required availability of LSFO (0.5%) in 2020 or 2025, when in 2009 only 0.5% of the fuel used by global marine traffic was HFO with a sulfur content of less than 0.5% (Kalli et al. 2009). For our basic scenario, we estimated that LSFO will cost 35% more than HFO resulting in 790, 870, and 950 $/t and MGO that will cost 70% more than HFO resulting in a rate of 995, 1100, and 1200 $/t, respectively.

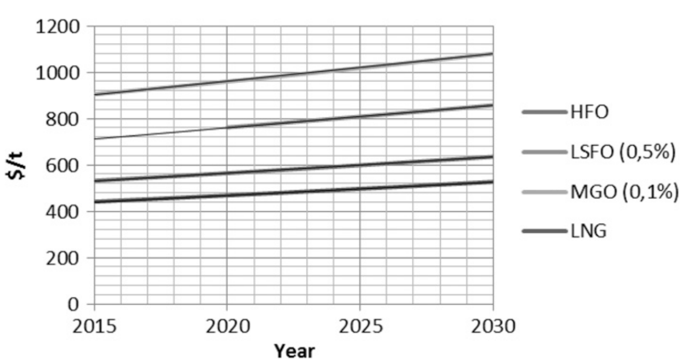

Fig. 2 Fuel oil projections 2015–2030

Finally, a 17% price difference between LNG and HFO is estimated based on the study of the Danish Maritime Authority, which equals to 585$/t (euro to dollar currency: 1.33) in 2030 (Danish Maritime Authority 2012). For visual representation of the fuel oil prices estimations, the reader is referred to Fig. 2.

For the calculation of the base scenario discount rate, the WACC was calculated through the capital asset pricing model:

$$\mathrm{WACC} = r_{\mathrm{E}}\frac{\mathrm{E}}{\mathrm{E}+\mathrm{D}} + r_{\mathrm{D}}(1-\mathrm{T_C})\frac{\mathrm{D}}{\mathrm{E}+\mathrm{D}} \tag{1a}$$

$$r_{\mathrm{D}} = \mathrm{CAPM} = \beta_{\mathrm{Dept}}[\mathrm{E}(r_{\mathrm{M}}) - r_{\mathrm{f}}] \tag{1b}$$

where r_E is the firm's cost of equity, r_D is the cost of debt, T_C is the marginal corp, E and D refer to the market values of equity and debt, β_{Dept} is the beta value, $E(r_M)$ is the historical market premium, and r_f is the risk-free rate (Benninga & Czaczkes 2000). The data of seven shipping companies are listed on NASDAQ and NYSE stock markets have been used for the calculation of the average WACC value: Paragon Shipping Inc., Diana Shipping Inc., Navios Maritime Holdings Inc., Safe Bulkers Inc., Free Seas Inc., Seanergy Maritime Holdings Inc., and Baltic Trade Limited and Dry Ships Inc. (Faber et al. 2011).

3. Results and discussion

3.1. Base scenario results

Calculation of the discount rate resulted to an average of 9.79% (November 16, 2014), which was rounded to 10% for the basic scenario. Table 2 depicts the basic scenario results obtained for the worst case in terms of investing, i.e., sulfur level requirement outside ECA implemented in 2025.

Profitability Index (PI) is the ratio of the present value of the cash flows to the initial investment. A ratio of 1.0 is the lowest acceptable measure on the index (Aravossis et al. 2012).The results show that the vast majority of the retrofits, with the exception of the engine derating method, prove to be quite attractive for investing

Table 2 Base scenario results with sulfur level requirement implemented in 2025

Serial No.	Description	Average Annual Capital Savings ($)	Payback Period (Years)	NPV ($)	IRR (%)	PI
1	Weather routing	77,304	<1	573,572	2272	192.2
2	Engine derating	120,070	10	−211,844	7	0.81
3	Optimal trim	53,520	3	248,230	32	2.65
4	PBCF	153,076	<1	1,061,392	169	14.27
5	Nozzle	228,643	<1	1,554,640	135	11.36
6	Costa bulb	108,011	2	533,907	36	2.98
7	Promas lite	240,054	4	783,923	21	1.78
8	Mewis Duct	222,171	1	1,304,986	56	4.73
9	FRC	259,793	1	1,545,369	59	4.96
10	Autotuning	57,080	<1	385,539	126	10.64
11	WHRS	279,013	6	470,431	14	1.29
12	Wind kites	266,027	5	574,929	16	1.41
13	Wind rotors	291,957	4	969,740	21	1.81
14	LNG	2,681,874	7	3,016,687	15	1.4

since they manage to lie above the indicators acceptance limits (NPV $>$ 0, IRR $>$ discount rate, PI $>$ 1). More specifically, six methods present a payback period of less than 1 year, while another four demonstrate payback periods of less than 4 years. In addition, the study showed that the implementation of the sulfur level requirement in 2020 results in higher values of PI of around 8–10%.

3.2. Sensitivity analysis

As stated in the previous paragraphs, the most important component of an investment evaluation is the recognition of all the related factors that can have a positive or negative influence on the objective function (PI in our case) and the monitoring of their impact in a certain range of values. In this way, a more spherical and comprehensive picture is provided to the decision maker that enables her to weigh the threats and opportunities that may occur during the implementation of a project. In Table 3, those factors are presented and their value range is defined based on the different estimations of the bibliographic data.

It has been found that the value of the discount rate is the factor with the greatest impact on PI, which results in an average 42% increase of PI when selected in its lower limit (5%) and in an average 71% decrease when selected in its upper limit (20%). Moreover, the annual opex returns an 18% average decrease of PI when calculated at a rate of 7%. All the other factors seem to influence PI in a scale of 1–8% on average. At last, it should be underlined that the price of LNG related to HFO price has also a strong impact on the evaluation indicators of LNG conversion retrofit resulting in a differentiation of PI between 0.54 and 2.26.

Table 3 Factors affecting the objective function (PI)

Serial No.	Factors Description	Lower Limit	Basic Scenario	Upper Limit
1	Price difference of LSFO and HFO	105%	135%	165%
2	Price difference of MGO and HFO	140%	170%	200%
3	Price difference of LNG and HFO	53%	83%	113%
4	Annual HFO price increase	1%	1.19%	2%
5	Annual opex (% of capex)	2%	3%	7%
6	Discount rate	5%	10%	20%
7	Days outside ECA	150	175	200
8	Annual retrofit efficiency decrease	0.1%	1%	2%
9	Annual opex increase	0.1%	1%	2%

3.3. Quantitative risk assessment

In order to observe the results within the whole value spectrum of the factors and reach a valid classification of the retrofits in terms of acceptance probabilities, an MC simulation was developed. To achieve this, 1000 triangles distributed random values were generated within the factors' ranges, and in turn resulted in each retrofit Gaussian probability density and cumulative distribution functions (in terms of PI) (Savvides 1994; Regio 2008). To generate the triangular distribution on (a, b), the inversion method has been used. The density (f) and cumulative distribution (F) are given by:

$$\mathrm{f(x)} = \begin{cases} 0, & x < a \\ \dfrac{2(x-a)}{(b-a)(c-a)}, & a \le x < c \\ \dfrac{2}{b-a}, & x = c \\ \dfrac{2(b-x)}{(b-a)(b-c)}, & c \le \mathrm{x} \le b \\ 0\,, & b < x \end{cases} \tag{2a}$$

$$\mathrm{F}(x) = \begin{cases} 0, & x < a \\ \dfrac{(x-a)^2}{(b-a)(c-a)}, & a \le x \le c \\ \dfrac{1-(b-x)^2}{(b-a)(b-c)}, & c \le x \le b \\ 1\,, & b < x \end{cases} \tag{2b}$$

Therefore,

$$\mathrm{F}^{-1}(u) = \begin{cases} a + \sqrt{(b-a)(c-a)u}, & 0 < u < \dfrac{c-a}{\mathrm{b-a}} \\ b - \sqrt{(b-a)(c-a)(1-u)}, & \dfrac{c-a}{b-a} \le u < 1 \end{cases} \tag{2c}$$

where a, b, and c are the lower, upper, and basic scenario values of Table 3, respectively. If u is a uniform (0,1) variate, then F^{-1}

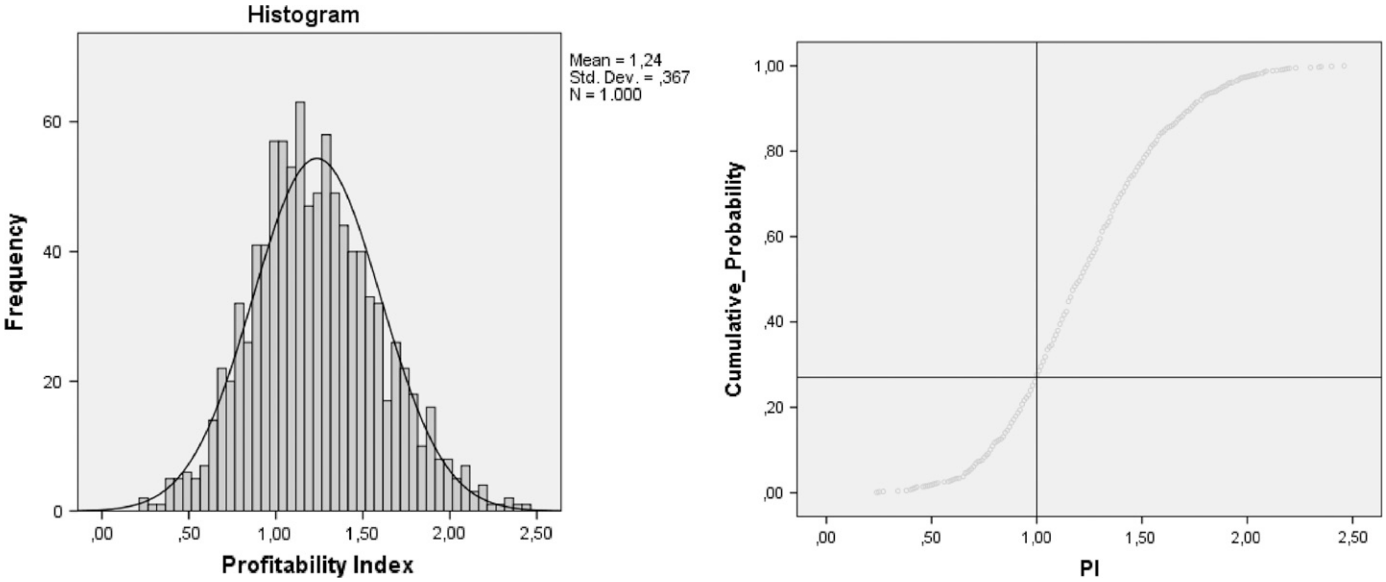

Fig. 3 PI histogram and cumulative distribution function for LNG conversion with sulfur level requirement implemented in 2025

(u) will be triangular on (*a*, *b*) (Hill 2012; Stein & Keblis 2009). Figure 3 depicts the histogram and cumulative distribution function for the method of LNG conversion.

From this figure, it can be seen that there is a 27.6% cumulative probability that the method will present PI < 1. Following the same procedure for all retrofits, they were classified based on their cumulative probability of rejection. Table 4 demonstrates this classification.

3.4. Multicriteria analysis

Up to this paragraph, the evaluation is based uniquely on financial indicators. Nonetheless there is a plethora of factors that should also be taken under consideration by the decision maker before investing in an option. In this article, the probability of rearrangements in our initial classification is explored when nonfinancial factors are involved in the evaluation procedure. These nonfinancial factors include the TM of the method and the CO_2 reduction that can be achieved. As previously mentioned, the method of WSM was selected mainly due to its wide usage in the energy systems bibliography and it's fit on the purposes of this article. Also, due to the heterogeneity of the three criteria, the method of linear percentage normalization between the minimum and maximum values of each scale was applied (Roy 1996):

$$\mathrm{Score}(a_{\mathrm{j}}) = \sum_{n=1}^{N} w_{\mathrm{i}} v_{\mathrm{i}}(s_{\mathrm{ij}}) \tag{3a}$$

$$v_{\mathrm{i}} = (s_{\mathrm{ij}}) = \frac{s_{\mathrm{ij}} - \min(s_{\mathrm{ij}})}{\max_{\mathrm{j}}(s_{\mathrm{ij}}) - \min_{\mathrm{j}}(s_{\mathrm{ij}})} \tag{3b}$$

where N is the number of criteria, v_i is the value function of criterion c_i, s_{ij} is the score from alternative a_j for criterion c_i, and w_i is the weight of criterion c_i.

The former nonfinancial factor has been assessed in a scale of 1–5 based on the number of applications and the current market

Table 4 Retrofits classification

Serial No.	Description	Cumulative Probability of rejection (PI $<$ 1) (%)	Minimum PI Value
2	Engine derating	91.0	0.12
12	Wind kites	24.0	0.31
14	LNG	27.6	0.37
11	WHRS	20.0	0.64
7	Promas lite	0.4	0.89
13	Wind rotors	0.2	0.98
3	Optimal trim	0.0	1.21
6	Costa bulb	0.0	1.24
8	Mewis Duct	0.0	2.09
9	FRC	0.0	2.27
5	Nozzle	0.0	3.19
4	PBCF	0.0	5.36
10	Autotuning	0.0	5.42
1	Weather routing	0.0	18.12

Table 5 Multicriteria retrofits classification

Serial No.	Description	c_1:PI	c_2:Technological Maturity	c_3:CO_2 Reduction (t)	Score (a_j) (%)
12	Wind kites	1.41	1	2304	0.9
13	Wind rotors	1.81	1	2304	1.0
2	Engine derating	0.81	2	1152	9.0
11	WHRS	1.29	2	1920	9.4
7	Promas lite	1.78	2	1728	9.5
6	Costa bulb	2.98	3	768	18.3
9	FRC	4.96	3	1728	19.2
10	Autotuning	10.64	3	576	20.6
14	LNG	1.40	3	13,475	22.6
3	Optimal trim	2.65	4	960	27.0
8	Mewis Duct	4.73	4	1728	27.9
5	Nozzle	11.36	4	1920	30.1
4	PBCF	14.27	5	960	39.4
1	Weather routing	192.20	4	768	86.3

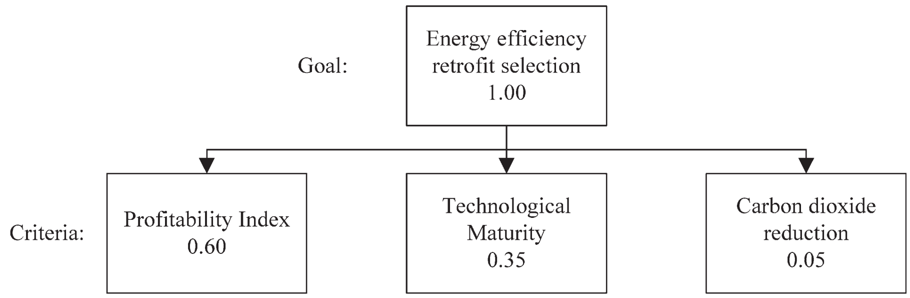

Fig. 4 Criteria and weights

knowledge, whereas the latter has been calculated utilizing the data of the basic scenario. It is possible that low CO_2 emissions will be of a great strategic importance in the foreseeable future due to the possibility of a MBM implementation in the years to come. Different scenarios of the factors' weigh distribution were investigated. Table 5 presents the results when PI, TM, and CO_2 reduction account for 60%, 35%, and 5%, respectively (see Fig. 4). From the results of the analysis, it can be observed that methods with lower TM, such as wind kites and wind rotors, are degraded in the classification, while others that combine a good rating in all three criteria, such as LNG conversion, take better places when compared to the initial classification.

4. Conclusion and discussion

The contribution of this article is divided into two parts; the case study findings and the added value of the proposed evaluation methodology. From the outcome of our case study, it can be concluded that the majority of the retrofit systems prove to be attractively and suitably eligible for the investor. More specifically, it has been observed that 8out of 14 retrofits presented minimum values of PI of more than 1, meaning that based on the techno-economic data used they are highly attractive for investment. Weather routing proved to be the most profitable method, mainly because of its very low initial capital requirements compared to the other retrofits, while propeller flow optimization methods (PBCF, nozzle, Mewis Duct, etc.) ranked among the most preferable methods as a whole. Finally, it should be underlined that the implementation of the sulfur level requirement in 2020 resulted in higher values of PI of around 8–10%, meaning that such a scenario would favor the early adaptors of the respected retrofit systems. Further study would be of interest to validate the obtained results in other types of vessels and vessels' size categories. In addition, future research on the results when several energy efficiency methods are combined is desirable.

The proposed methodology, which can be readily be used in practice, originally used a holistic technoeconomic evaluation approach and employed several techniques in order to reach a fair and valid classification of the retrofits. Specifically, the investments' risks have been identified and measured in order to present a quantitative probabilistic result. Moreover, this article has addressed the importance of multicriteria decision-making processes. In line with the findings of Aravossis and Pavlopoulou (2013), we strongly believe that such a holistic approach is able to lead to a more sustainable decision-making process from the ship-owners' side and safeguard a smooth transition to a social responsible perspective. This will ensure the creation of shared value among all industry's stakeholders and proactively accelerate social progress.

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