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Techno-economic analysis for decarbonising of container vessels

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There are growing concerns on the effect of climate change and the environment. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018. In addition, the pace of carbon intensity reduction has slowed since 2015 with the average annual percentage changes ranging from 1 to 2%. The Levelised Cost of Mobility (LCOM) index is used to consider different options on a level field. This index comprises the CAPEX of the engines and tanks, the OPEX of the engines, the cost of the lost cargo space, fuel cost and CO2 cost. A Monte Carlo simulation is used to obtain the final unit of comparison of the LCOM which is expressed in Euros/1000DWT-km. The values utilised are sourced from literature review, or from a trained Artificial Neural Network (ANN) based on telemetry data of a 9000 TEU container vessel. Expected results are that LCOM values provide an indication of the cost that ship owners must bear to consider alternative fuels, or how policies may be invoked to encourage alternative fuels to be economically feasible to mineral fuels. Finally, given that vessels greater than 5000 gross tonnes must install fuel consumption sensors from 1 January 2019, this paper presents a framework on how telemetry data can be incorporated into a Machine Learning pipeline that can help answer specific business questions

Keywords: tech-economic analysis, decision analysis, zero carbon emissions, alternative marine fuels, green shipping.

1. Introduction

There are growing concerns on the effect of climate change and the environment. Based on the Fourth IMO Greenhouse Gas Study (Faber and Et al, 2021), the share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018. In addition, the pace of carbon intensity reduction has slowed since 2015 with the average annual percentage changes ranging from 1 to 2%. In the same report, it is highlighted that operating speeds of vessel remain a key driver of trends in emissions. It is predicted that in 2050 that 64% of the reduction in CO_2 is contributed by the use of fuel alternatives. Thus the objective of this paper is to determine the most cost effective option of alternative fuels in order to meet decarbonising goals specified in the Initial IMO Strategy on Reduction of GHG Emissions from Ships. This paper is organised in the following manner: in Section 2, a brief literature review discusses the current methods and the position of this paper to supplement current methods Section 3 discuss the theory and set-up of the index use to compare costs on a baseline, and how data from a relevant artificial neural network is used as input to the method. The results are presented in Section 4 including a discussion of validation of results. The conclusions of this study are presented in Section 5 submission.

2. Literature Review

The Marine fuels are currently considered in the context of two different objectives: reducing CO_2 emissions to mitigate climate impacts; and reducing emissions of SOX, NOX, and particles. With respect to the latter, the focus has been on fuel choice, since shipping companies will have to change from heavy fuel oil (HFO) mainly in use today to low-sulfur fuels and/or install abatement technologies as more strict exhaust emission regulations are being implemented at the regional level in Emission Control Areas by 2015 and at global level by 2020 as specified in the Initial IMO strategy on reduction of GHG Emissions from Ships. There are a large number of fuel options and fuel systems (Horvath et al., 2018) such as internal combustion engines to fuel cells (DNV GL, 2019). Most analysis conducted (Balcombe et al., 2019; Horvath et al., 2018; Taljegard et al., 2014) structured the analysis into two periods, as defined by the goals of the Paris Agreement, the years 2030 and 2040. To illustrate the use of situation-specific information, the study in this conference paper is limited to one fuel option for the year 2030 (Methanol) and one for the year 2050 (Ammonia). A study by Taljegard et al (2014) highlighted that a combination of LNG and Methanol is the most cost-effective alternative until 2050, while a study by DNV (DNV GL, 2019) indicated that internal combustion engines running on ammonia are likely to be available for order within 5-10 years, but uptake will be slow until regulations make ammonia competitive. DNV GL (2019) expect that fuel cells, in particular for ammonia, will mainly be used in pilot and early applications and for subsidized projects in the next 5-10 years.

The analysis conducted by Horvath et al (2018), which involves an index function that reduces the parameters of interest to a common denomination of interest, demonstrated that fuel costs remains a key cost parameter (by far) across fuel options that varies from mature (diesel) to not-so-mature options (hydrogen). Thus, it is proposed to utilise a previous study that looked at predicting fuel consumption of container vessels in different environmental conditions, in order to look at a key factor (fuel costs) and relative emissions based on actual data, actual ocean voyage patterns in order to provide an comparison index with more situation specific information.

3. Methodology

The study attempts to provide a basis for decision analysis on the type of alternative fuels to aid container vessels meet the IMO 2050 guidelines of zero carbon emissions. In this study, representative data such as ship size, average dead weight (DWT), fuel consumption on a range of operations profiles, and power utilized for the respective operation profile is used.

The final cost comparison is based on a value called the Levelised Cost of Mobility (LCOM) (Horvath, Fasihi, and Breyer 2018), which sums up the costs of multiple indices into a single number for comparison. The unit of LCOM in this study was Euros/ 1000 DWT -km.

$$\text{LCOM} = \frac{(CAPEX_{Tank} + CAPEX_{Power}) \cdot crf + OPEX_{Power} + Cost\ of\ lost\ cargo + Fuel\ cost + CO_2\ cost}{DWT \cdot Yearly\ Distance\ Travelled} \quad (1)$$

$$\text{crf} = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (2)$$

The study considers the analysis of 3 different types of fuel, Diesel, Methanol and Ammonia. Diesel is still one of the most commonly used fuel source in container vessels. In the 4th IMO GHG Study (Faber and Et al, 2021, p. 98), Methanol is the least common option with Heavy Fuel Oil, Marine Diesel Oil as the most commonly-used fuel. LNG is a far third. Thus there is potential for Methanol to be primed as a feasible option since it is already being utilised in some vessels and thus supporting infrastructure exists. It also has the lowest CO_2 emission factor among the above mentioned fuel factors. Methanol produces 1.375 g CO_2 /g of fuel (Faber and Et al, 2021, p. 74) as compared to Diesel, which produces 3.206 g CO_2 /g of fuel.

Ammonia does not produce carbon emission as it only consists of Nitrogen and Hydrogen, thus it serves as an ideal example for this analysis of zero emission fuel use.

The components of the LCOM are as follow:

Table 1 Components of the LCOM

Units	Description
$CAPEX_{Tank}$	CAPEX for the tank
$CAPEX_{Power}$	CAPEX for the installed power
Cost of Lost Cargo	Annual income lost to fuel space
Fuel price	Fuel price
CO_2 cost	GHG emission costs
$OPEX_{Power}$	OPEX for the installed power.
crf	Capital recovery factor, a discount factor from a weighted average cost of capital of 7%, and across an assumed lifetime, N, of the ship. The capital recovery factor is the ratio used to determine the present value of a series of equal annual cash payments.
N	Lifetime of ship

3.1. *Capital expenditures*

Capital expenditures (CAPEX) data is based on fuels and alternatives fuels and on internal combustion engines (ICE). The cost information were obtained from literature study. Diesel and Methanol CAPEX values were obtained from Horvath et al (2018) and Taljegard et al (2014). These values include construction cost, depending on the cost of engines, fuel tanks and other extra costs such as gas alarm system, pipelines or fuel processors. The data for the base case and the Monte Carlo analysis are derived from published sources such as European Maritime Agency. The data for Ammonia is obtained from Korberg et al (2021) based on similar assumptionsbefore.

Table 2 CAPEX values for Tank and Power for the three fuel options and the respective sources.

	CAPEX Power		CAPEX Tank	
	Value Euros/kW	Source	Value Euros/kWh	Source
Diesel	385	(Taljegard et al. 2014; Horvath, Fasihi, and Breyer 2018)	0.08	(Taljegard et al. 2014; Horvath, Fasihi, and Breyer 2018)
Methanol	400	(Taljegard et al. 2014; Horvath, Fasihi, and Breyer 2018)	0.14	(Taljegard et al. 2014; Horvath, Fasihi, and Breyer 2018)
Ammonia	503	(Korberg et al. 2021)	0.17	Assumption: 1.2 x of Methanol Based on calorific value of fuel type, and medium fuel exists as.

3.2. *Cost of lost cargo opportunity*

The cost of lost cargo due to extra space required if an alternative fuel to Diesel is used. The estimation is based on a Diesel ICE as a base case. Two values are used - the first is the volume of cargo space lost per trip. This is estimated based on conversion efficiencies and energy contents of the fuel. The second value is the price of shipping cargo per twenty-foot equivalent unit (TEU). In this study, the average price per TEU of 1280 Euros /TEU for based on the year 2015.

Horvath (2018) reported that for Methanol, the additional cargo space lost to fuel is 1,310 m^3 for a shipping vessel of 79,809 DWT. By linear scaling, it is assumed that the additional cargo space for a vessel of 108,000 DWT is 1,772 m^3. It is assumed that 1 TEU measuring (8.5 x 8 X 20) feet has an approximate volume of 38.5 m^3. Thus this amounts to approximately Euros 58,867 for Methanol.

To estimate the volume of lost cargo due if Ammonia is used as an alternative fuel, the different energy density is used to scale the corresponding cargo space forgone. Ammonia has 1.36 times less volumetric energy density than Methanol (11 MJ/l vs 15 MJ/l) (DNV GL 2019). Thus the volume of lost cargo is adjusted with the same multiplicative factor of 1.36. This amounts to approximately Euros 80,059 for Methanol.

Table 3 Cost of lost cargo

Methanol	Ammonia
Euros 58,867	Euros 80,059

3.3. *Cost of CO_2*

Pricing CO_2 has resounding effects across the industry. There is a range of 18 – 2000 Euros/ tonne CO_2 reported in literature (Pinel, Korpås, and Lindberg 2021). Thus far, only the Danish and Norwegian Shipping Associations have made statements on CO_2 costs to be in the range of double the cost existing fuel costs (Kristiansen and Pico 2020). Maersk (Wittels 2021) proposed US $150/tonne of CO_2 so as to achieve the effect of doubling existing costs of fossil fuels to bridge the price gap between greener alternatives. In the study, an arbitrary base cost of Euros 1000/ tonne CO_2 is utilised. To estimate the amount of CO2 produced by the fuel type (Diesel, Methanol), mass-based emission factors per the 2018 EEDI Guidelines is utilised (Faber and Et al 2021) and as shown in table below:

Table 4 Fuel-based emission factors and carbon content per fuel type

Fuel Type	Carbon content	Emission Factor g CO_2/ g Fuel
Diesel	0.8744	3.206
Methanol	0.3750	1.375

3.4. *Fuel price*

Fuel prices are estimated from market reports from a commodities trading perspective such as Bloomberg reports (Horvath, Fasihi, and Breyer 2018). The cost of Diesel is forecasted to be Euros 44/MWh in 2030 by Horvath et al (2018).The cost of Methanol is then estimated as a multiplicative factor of 1.29 times of Diesel costs based on primary energy prices, investment costs, conversion efficiencies, operation and maintenance cost and distribution costs. From this perspective, the cost of Ammonia is significantly higher than both Diesel and Methanol at approximately Euros 117/MWh (Korberg et al. 2021).

Table 5 Estimated costs of fuel per MWh

Fuel type	Cost (Euros/MWh)	Source
Diesel	44	(Horvath, Fasihi, and Breyer 2018)
Methanol	56.7	(Horvath, Fasihi, and Breyer 2018)
Ammonia	117	(Korberg et al. 2021)

3.5. *Operational expenditure*

Low-speed diesel is assumed to have an operational expenditure (OPEX) of Euros 9.42/kW (Horvath, Fasihi, and Breyer 2018). Methanol in an ICE engine is assumed to have a similar OPEN to Diesel engines as it is a similar fuel (Horvath, Fasihi, and Breyer 2018). LNG engines were assumed to cost about 10% more than Diesel (Horvath, Fasihi, and Breyer 2018) and thus an assumption 20% was made on Ammonia.

4. Extrapolation from ANN model to estimate operation profiles

In the paper by Fam et al (2021) on using ANN to estimate operation profiles, the most frequently occurring profile is determined by plotting density functions. At each peak of a density function, the range of values is considered by taking into consideration the standard deviation of the values of the peak between the adjacent minima of the density function (see Fig.1 (top & middle)). The operational profiles derived provides three scenarios of favourable, unfavourable and neutral environmental conditions (see Fig.1 (bottom)). Within each profile, the standard deviation is used to represent the upper and lower bounds of the specific operation profile in order to give more credibility to the LCOM data estimated from the Monte Carlo simulation. It is also a reflection of the Base case, Minimum and Maximum values typically used in such simulation as observed in the work of Taljegard et al (2014).

5. Results and Discussion

A Monte Carlo analysis was carried out by varying 9 parameters of the LCOM (see Table 1). The base case is the neutral case, and the minimum and maximum cases are defined by the favourable and unfavourable operation profiles. Several other studies (Horvath, Fasihi, and Breyer 2018; Taljegard et al. 2014) generally indicate that economical advantages of the fossil fuels (Diesel) has a strong footing over alternative energy sources. It is estimated that LNG or Methanol would be the mostly likely substitute up to the year 2030, and Ammonia beyond 2050 based on the regulatory requirements of cutting CO2 emissions. The results in general is supported by other analysis(Horvath, Fasihi, and Breyer 2018; Taljegard et al. 2014; Perčić, Vladimir, and Fan 2020; Korberg et al. 2021) suggesting that the cost of alternative fuels needs to be reduced to be competitive against fossil fuels.

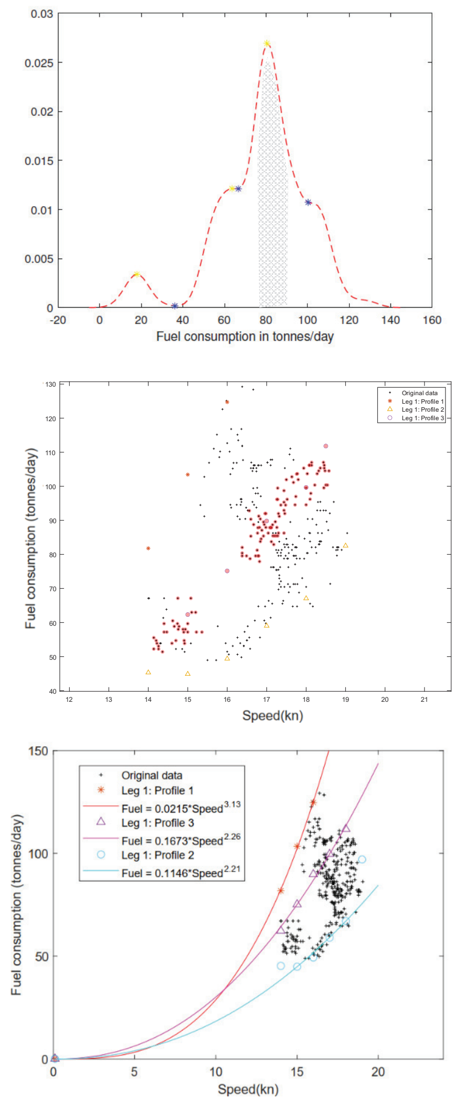

Fig. 1 (top) Demonstration of range of operation power values (shaded in grey) on fuel consumption density plot. (middle) One sample operational profile (red shaded cloud) derived from the density function and represented on a Fuel-Speed plot. The width of the red-cloud also represents the standard deviation. (bottom) Three operational profiles derived from the ANN.

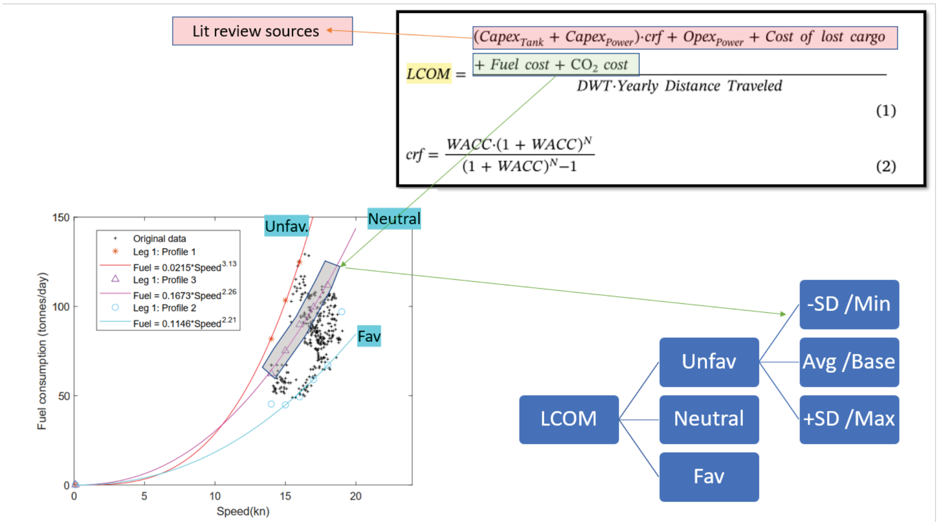

Fig. 2 A mindmap indicating how results of the ANN model fits in the LCOM index, and the same ANN model is used to define base case, minimum and maximum cases.

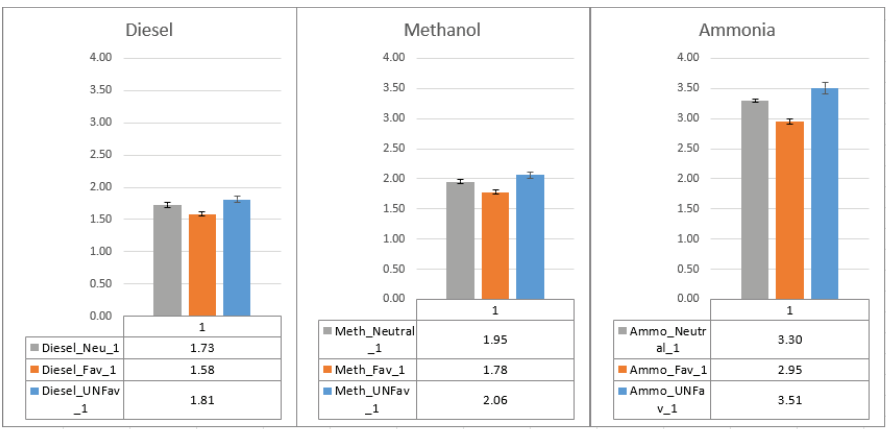

Fig. 3 General results of LCOM from simulation of costs across 3 operation profiles characterised by 'neutral', 'favourable', and 'unfavourable' environmental conditions. The figures are expressed in Euros/1000 DWT km.

It can be observed that the LCOM index (Euros/1000 DWT km) for the 'neutral' operation profile for Diesel (1.73 Euros/1000 DWT km) and Methanol (1.95 Euros/1000 DWT km) shows that cost difference is minimal, and can likely be addressed by adjusting policies to push for Methanol adoption. The differences in the components of the cost (see Table 3) reflects marginal differences in Engine CAPEX, Tank CAPEX, Engine OPEX. Interestingly, Tank CAPEX is higher for Methanol because of its lower calorific value as compared to Diesel, thus a larger volume is required for the same energy value – however this does not translate to significantly less cargo space. In the report - The Fourth IMO Greenhouse Gas Study (Faber and Et al 2021), the carbon content of Diesel is at 0.84 (normalised to 1) while that of Methanol is at 0.38, and produces less than half of the CO_2 (1.3375 g CO_2/g fuel as compared to 3.114 g CO_2/g fuel). In this modelling exercise, a carbon tax of 1000 Euros/tonne of CO_2 is used as a cost factor, and clearly reflects that it has little impact on improving the economic position of Methanol with respect to Diesel. This is also further underscored by the prices of Diesel (44 Euros/MWh) and

Methanol (56.7 MWh) respectively (see Table 5) . Methanol is 1.29 times more expensive than Diesel is, yet Diesel produces 2.33 times more CO2. The imbalance in the contribution to the overall LCOM index from carbon taxation and fuel costs shows where policies could make the greatest impact – subsidizing alternative fuel costs or increase carbon taxation to level the cost field.

In terms of the third fuel, Ammonia, it is recognized that the current maturity level is low, and also explains the significantly higher LCOM index at 2.95 Euros/1000 DWT-km. Many of the technologies being analyzed in these studies are not widely utilized on ships which has led to some speculation about projected technology costs and consequently their use in the future. Further development of each of these technologies is necessary to determine their cost effectiveness in solving emission problems. Some attributes of Ammonia does provide insights on the higher cost, for example, Ammonia has the lowest energy density as compared to Methanol and Diesel. Ammonia provides 1.36 times less calories than Methanol. Methanol provides 2.3 times less calories than Diesel. This suggests that ammonia requires more fuel tank space on a vessel and that takes up cargo space. Retrofitting the vessel with a system suitable for Ammonia is also costly (DNV GL 2019).

It can be observed that every parameter is of a significantly higher cost than the Diesel and Methanol alternatives – specifically in the CAPEX in Engine and Tank installation, and fuel cost (at 117 Euros/MWh). It can be observed that at the arbitrary carbon tax of 1000 Euros/ tonne of CO_2 is insufficient to level the playing field of alternative fuels. This value is initially selected as a mid-point of the study by Pinel et al (2021). It takes a carbon tax of 50 times of the arbitrary carbon tax value for Ammonia to be attractive over Methanol and Diesel. However for Methanol to be attractive over Diesel, a carbon tax 5.5 times the arbitrary carbon tax value would level the economic differences in the cost of fuel. Pinel et al (2021) investigated in a study of CO_2 taxation for zero emissions neighbourhoods and building that the price of externalities compensation could go up to 2000 Euros/tonne CO_2. Based on the modelling conducted in this paper, and considering actual ship operation data, a carbon tax of 5.5 times the arbitrary carbon tax value is in the ballpark of policies that drive the attractiveness of alternative fuels.

In general, comparison with other papers demonstrated similarity in results in two areas: (i) Methanol (or LNG) would be the mostly substitutes in the marine industry up to 2050 (Horvath, Fasihi, and Breyer 2018; Korberg et al. 2021) and (ii) current CO2 taxation policies do not reduce

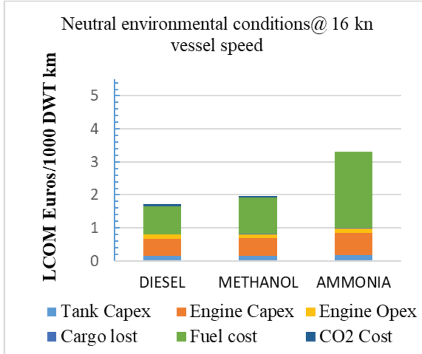

Fig. 4 Proportion of contributing components of the LCOM. It can be observed that fuel costs (green) remain a big part of the LCOM. Carbon costs are not priced at a level to make alternative fuels competitive.

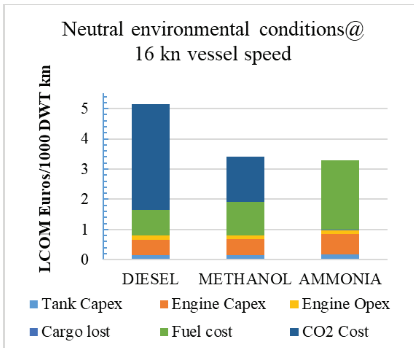

Fig. 5 Proportion of contributing components of the LCOM, with addition of a carbon tax of 50,000 euros/tonne CO_2 (dark blue) as compared to 1000 Euros/tonne CO_2 in Fig 4.

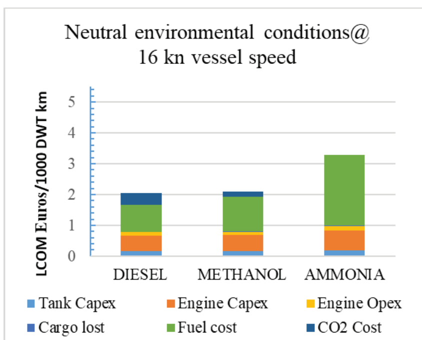

Fig. 6 Proportion of contributing components of the LCOM, with addition of a carbon tax of 5500 euros/tonne CO_2 as compared to 1000 Euros/tonne CO_2 in Fig 4 in order for Methanol to be economically feasible as an alternative fuel.

the cost gap of alternative fuel sources (Horvath, Fasihi, and Breyer 2018; Pinel, Korpås, and Lindberg 2021). In terms of the LCOM values – the results for LCOM index Diesel generally agrees with the analysis conducted by

Horvath et al (2018) – it was reported that Fossil Diesel without CO_2 tax (since this value assumed in this paper is different from Horvath et al's analysis) was at a value of slightly less than 1.0 Euros/1000 DWT-km for an internal combustion engine for a container ship with engine size of 23,000 kW. The engine size of the container vessel studied in this paper is 51,000 kW, which is about 2.22 times bigger. Since there are economies of scale enjoyed in bigger engines, the LCOM of the larger container vessel would likely not be as large as the difference in the physical size of the engines. The LCOM of Diesel in this paper is 1.58 Euros/1000 DWT-km. The difference between the LCOM Methanol and LCOM Diesel in both Horvath et al's (2018) paper however is comparable with the results obtained in this paper – the LCOM of Methanol is 1.2 times that of LCOM Diesel in Horvath et al's analysis with respect to 1.1 times (as modelled in this paper).

6. Conclusion

This study provides demonstrated that LCOM values provide an indication of the cost that ship owners must bear to consider alternative fuels, or how policies may be invoked to encourage alternative fuels to be economically feasible to mineral fuels. In general, comparison with other papers demonstrated similarity in results in two areas: (i) Methanol (or LNG) would be the mostly substitutes in the marine industry up to 2050 and (ii) current CO_2 taxation policies do not reduce the cost gap of alternative fuel sources. Finally, given that vessels greater than 5000 gross tonnes must install fuel consumption sensors from 1 January 2019, this paper presents a framework on how telemetry data can be incorporated into a Machine Learning pipeline that can help answer specific business questions for current operations needs or for future needs.

In terms of future work, it is visible that carbon emissions goals are aggressive and alternative fuels without the aid of supportive policy measures indicates difficulty in moving the industry towards zero or low carbon emissions. Some researchers have indicated carbon storage systems, and emissions trading across a global emissions reduction system (i.e. including stationary energy systems) to aid in the situation and this can be studied in depth alongside vessel operational data for a more accurate view of feasibility of these external carbon mitigation systems.

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