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Life Cycle Assessment as a complementary utility to regulatory measures of shipping energy efficiency

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Abstract

The purpose of this paper is to document that LCA, aside from showing indication of compliance to both current IMO regulatory metrics (i.e. EEDI and EEOI) –not only as a practical environmental indicator, but also as a tool able to highlight energy efficiency–, can also be used in parallel to these, serving as a complementary utility able to assist with their practical implementation.

An LCA model formulation is summarised and also applied on a case study vessel, utilising it for validation, and additionally for comparing the LCA approach to the IMO regulatory metrics.

Results show that aside from the environmental score of CO_2 emissions per unit of work –recognised by the current regulatory metrics–, LCA can also offer NO_x and SO_x scores, along with other hazardous releases. Moreover, LCA –aside from showing compliance to the formulation of both IMO regulatory metrics– is able to present material and energy utilisation throughout different stages within the vessel's lifetime.

Lastly, it is documented that LCA can be used in parallel to the regulatory metrics, in order to efficiently emphasise detailed environmental information. Furthermore, the implementation of LCA could be considered as a potential aid for the European Commission's recent MRV legislation.

Keywords: LCA, Shipping, Shipbuilding, Shiprepair, EEDI, EEOI, MRV.

Abbreviations

A/F	Antifouling paint
AIS	Automatic identification system
Cd	Cadmium
CFC	Chlorofluorocarbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EPI	Environmental Performance Indicator
EVDI	Existing Vessel Design Index
FRC	Fouling Release Coating
GHG	Greenhouse gas
GT	Gross tonnes
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MRV	EU system for monitoring, reporting and verification of carbon dioxide emissions from maritime transport
NO_x	Nitrogen Oxides
PM	Particulate Matter
Ro-Ro	Roll-on/Roll-off vessel
SFC	Specific fuel consumption
SO_x	Sulphur Oxides

1. Introduction

LCA is a methodology which has been constantly evolving for the past three decades (Guinée et al., 2011). What started out as a theoretical approach into the assessment of the potential environmental impacts of a chosen and predefined system, has developed into a highly pragmatic application, which could, additionally from the environmental standpoint, produce relevant impacts encompassing economic and social angles (Guinée et al., 2011; Weidema, 2006).

The methodology can also serve to identify environmental improvement opportunities within the different phases of the life cycle of a product or system, in turn providing prospects for product and process design or re-design. Most importantly, however, is the recognised potential of the tool to allow for the proper selection of a relevant indicator of environmental performance, including measurement techniques and indicator appraisal (ISO, 2006a, b; PE-International, 2011).

As far as the shipping and shipbuilding and repair industry goes, LCA application extends from process or product design (Ellingsen et al., 2002; Koch et al., 2013), construction and repair or retrofitting (Blanco-Davis, 2013b; Fet, 1998), transportation and fishing (Fet and Michelsen, 2000; Utne, 2009), alternative power sources and fuels (Alkaner and Zhou, 2006; Bengtsson et al., 2012), onboard system assessment (Blanco-Davis and Zhou, 2014; Cabezas-Basurko and Mesbahi, 2012), and systems engineering and management (Fet et al., 2013).

The application of the methodology within this paper, however, is focused specifically at underlining LCA as an environmental performance indicator (EPI) for ships, which could additionally highlight and report energy efficiency. This has been briefly mentioned by Blanco-Davis (2014), and while in a different context than presented herein, also endorsed by Fet et al. (2013), relative to implementing EPIs on ships' life cycle designs.

2. Current energy efficiency metrics

2.1. Introduction

The aim to measure and improve energy efficiency within a ship, relative to an environmental context, is not novel. The discussion, however, has been intensified during the past decade; probably due to the harmonised advertisement from intergovernmental and global environmental organisations, with regards to the potentially irreversible downsides brought about by climate change. In 2013, for example, the Intergovernmental Panel on Climate Change remarkably underlined, in their IPCC's Fifth Assessment Report, that the current climate warming trends are highly likely to be induced by human activities (BBC, 2014; IPCC, 2013).

Following this trend, the shipping industry has reacted accordingly in order to strive to regulate shipping energy efficiency, and consequently improve the reduction of greenhouse gas (GHG) emissions. The International Maritime Organization (IMO), shipping's main regulatory body, has dedicated relevant efforts to develop technical and operational measures aimed at enhancing onboard environmental efficiency. These measures include the following:

- The Energy Efficiency Design Index (EEDI),
- The Energy Efficiency Operational Indicator (EEOI), and
- The Ship Energy Efficiency Management Plan (SEEMP).

Aside from these regulatory measures, other metrics have also been developed, voluntary in nature, and allegedly offering to cover the gaps of the previous. Examples of such metrics are the Existing Vessel Design Index (EVDI), developed by Rightship (2014), and the AIS-based performance metric proposed by Smith et al. (2013); the former offers an attempt to develop a single efficiency metric capable of being applied to new ship designs as well as to existing vessels, while the latter proposes separate formulations, not specifically in favour of a single or simplified energy efficiency indicator.

To add to the above mix of energy efficiency metrics, the European Commission has also decided to contribute with a regulation applicable to regulate CO_2 emissions within Europe –aimed at being applicable globally, however, if ultimately acknowledged–, establishing a regulation "on the monitoring, reporting and verification [MRV] of carbon dioxide emissions from maritime transport" (EC, 2013).

In its current form, the MRV regulation is applicable to all ships above 5000 GT calling into, out of, and in between EU ports, with an underlined entering-into-force date of July 1st, 2015, and with a reporting period starting on January 1st, 2018 (EC, 2013, 2015). The regulatory requirements highlight the monitoring of CO_2 emissions per voyage and on a yearly basis. It is relevant to point out as well that in the long term the MRV is aimed at addressing all emissions, including SO_x, NO_x and PM. The above can be similarly related to LCA, as a consolidated methodology that can offer a consistent account of GHG, SO_x, NO_x, and PM, among other emissions.

The problematic carried forward by the available performance measures underlines the issues of applicability within the different metrics (e.g. newbuilds and existing vessels), the incomparability or non-equivalency of the scores between them, the on-going discussion of a single metric approach, and their partial coverage and application, among other concerns. The last emphasises an evident prospect for a standardised alternative performance method –utilised as supplementary to the current regulatory measures–, and capable of not only highlighting energy efficiency but also serving as a widespread accepted environmental performance indicator, in order to strive to cover the inherited gaps of the regulatory metrics.

2.2. IMO energy efficiency regulatory measures

The following section includes a brief discussion into the actual regulatory metrics in place by IMO, i.e. the EEDI, the SEEMP and EEOI –and their implementation methodology–.

2.2.1.EEDI

The EEDI is based in the fundamental characteristic that fuel consumption is the most direct measure of energy use onboard. Similarly, CO_2 emissions are directly proportional to fuel consumption; therefore, as explained by Kedzierski and O'Leary (2012), the amount of CO_2 emitted by a ship can be calculated using the fuel consumption relative to that ship, and an emission factor relative to that fuel. Fuel mass to CO_2 conversion factors, additionally, have been established by the IMO for marine diesel, light and heavy fuel oils, liquefied petroleum and natural gas (IMO, 2014); thus, the CO_2 calculation is as simple as multiplying the fuel consumption by the carbon conversion factor (Kedzierski and O'Leary, 2012).

The full EEDI formula is specified by IMO (2014), and it includes various adjustment factors, applicable to specific types of ships and alternative configurations. The equation calculates the CO_2 produced as a function of the ship's transport-work performed (Lloyd's-Register, 2012), which is considered as the *attained* EEDI, and equates to a figure of grams of CO_2 over tonnes per nautical mile (gCO_2/tonne-nm).

By regulation, the attained EEDI shall be calculated for all ships of 400 gross tonnes (GT) and above (GL, 2013), defined by the types found in Table 1. A ship's attained EEDI must be equal to or less than the required EEDI for that ship type and size (Lloyd's-Register, 2012). The required EEDI – which is calculated for all ships using 100% of the deadweight (DWT) at summer load draft, except for passenger ships where GT is used (GL, 2013)–, is a function of the reference line value (see Table 1), defined by the following formula (see

Equation *3*): Required EEDI = a * (b)^(-c).

Table 1: Reference values for calculating the required EEDI (GL, 2013), as adapted from (IMO, 2013a, b)

Ship type	**a**	**b**	**c**
Bulk carriers	961.79	DWT	0.477
Gas carriers	1120.20	DWT	0.456
Tankers	1218.80	DWT	0.488
Container ships	174.22	DWT	0.201
General cargo ships	107.48	DWT	0.216
Refrigerated cargo ships	227.01	DWT	0.244
Combination carriers	1219.00	DWT	0.488
Vehicle/car carriers	$(DWT/GT)-0.7 \times 780.36$ where $DWT/GT < 0.3$; $(DWT/GT)-0.7 \times 1812.63$ where $DWT/GT \geq 0.3$	DWT	0.471
Ro-Ro cargo ships	1405.15	DWT	0.498
Ro-Ro passenger ships	752.16	DWT	0.381
LNG carriers	2253.7	DWT	0.474
Cruise passenger ships having non-conventional propulsion	170.84	GT	0.214

2.2.2. SEEMP and EEOI

The Ship Energy Efficiency Management Plan, in short SEEMP, is aimed at providing a potential approach for monitoring and optimising the ship and fleet –operational– efficiency performance over time (IMO, 2012). Although currently in voluntary form, IMO (2012) additionally promotes the use of the EEOI as a valid ship and/or fleet energy efficiency indicator, but also recognises other resources could be appropriate as supplementary. The last is of relevance, when considering LCA as a complementary tool underlined by an international standard, which could in turn support the EEOI implementation, as it will be underscored further in this paper.

Similarly to the EEDI, the EEOI is based on the principle that CO_2 emissions are directly proportional to fuel consumption. The main difference between the two metrics is that contrary to the EEDI, the EEOI does not measure design efficiency but the operational efficiency of ships. The operational efficiency is described by taking into account the *actual* ship fuel consumption (and emissions factor) under operational conditions, and the transport-work (i.e. cargo mass, number of passenger carried, etcetera) carried out. The effective EEOI formulation has been defined by IMO (2009), and its unit is expressed similarly to the EEDI in grams of CO_2 per tonnes per nautical mile (gCO_2/tonne-nm).

2.3. Relevant limitations and coverage gaps

As Faber et al. (2009) reiterate, the major difference between the EEDI and the EEOI is that the first assesses exclusively the design state of a vessel, while the latter strives to cover the operational phase of a particular ship.

Aside from the above-mentioned coverage differences, there is also a naturally inherent incomparability among some ship types when compared to others. The last is demonstrated by the different established EEDI reference values with regards to ship types (see Table 1). Therefore, it is rational to understand that a bulk carrier will have a different EEDI reference value from a containership, and that this in turn will produce a non-equivalent efficiency score among the two ship types. The last is equally applicable to the EEOI.

While the single performance metric approach would be ideal for a harmonised regulation across the entire fleet, the reality of the current regulatory measures' intrinsic shortcomings, prevents the use of one single metric to serve as a measure of overall efficiency for the entire fleet and different ship types. Taking into consideration the above, while also highlighting Ballou (2013)'s observation in favour of using supplementary metrics to support the current regulatory measures, an evident opportunity for the use of a standardised performance method –such as LCA–, is emphasised.

3. Life Cycle Assessment

3.1. Background and application

There are two current regulatory LCA standards, developed by the International Organization for Standardization (ISO), which define the concept and describe the methodology, respectively: the ISO 14040 and the ISO 14044 (ISO, 2006a, b).

Simply explained, the standardised LCA methodology is based on a process model assessment, which includes a thorough inventory of resource inputs and environmental outputs (i.e. input and output flows), while also calculates mass and energy balances, and evaluates potential environmental damage (Koch et al., 2013). Therefore, LCA offers an all-inclusive view by means of a holistic approach, and thus a more detailed representation of the actual environmental trade-offs related to a process, product, service or system.

Currently, the methodology is commonly employed for two main purposes: to assess the potential environmental impacts of a certain product including the product's past history and forecast, in order to generate its environmental score; while the other purpose is to assess the product versus an alternative, making a pragmatic comparison among the available options (Blanco-Davis and Zhou, 2014).

More characteristics of LCA as well as deeper understanding of how LCA is spread and practised across academia and industry can be attained from: Guinée et al. (2002), Baumann and Tillman (2004), ISO (2006a), ISO (2006b), SAIC and Curran (2006), PE-International (2010), and the European Platform on Life Cycle Assessment by JRC (2013), which includes recent and complementary information.

Additionally, the doctoral thesis by Blanco-Davis (2015) provides a systematic discussion of the LCA application within shipping, shipbuilding and repair. In summary, the author reports the growing increase in application of life cycle perspective methodologies –and specifically LCA–, within the shipping and shipbuilding and repair industry.

3.2. Ships' life cycle model

When taking into consideration the lifetime of a ship –a period that usually spans from 25 to 30 years for a common commercial vessel–, there are various relevant phases which need to be underlined. These phases have been previously defined by Fet (1998), and are similarly portrayed by Figure 1.

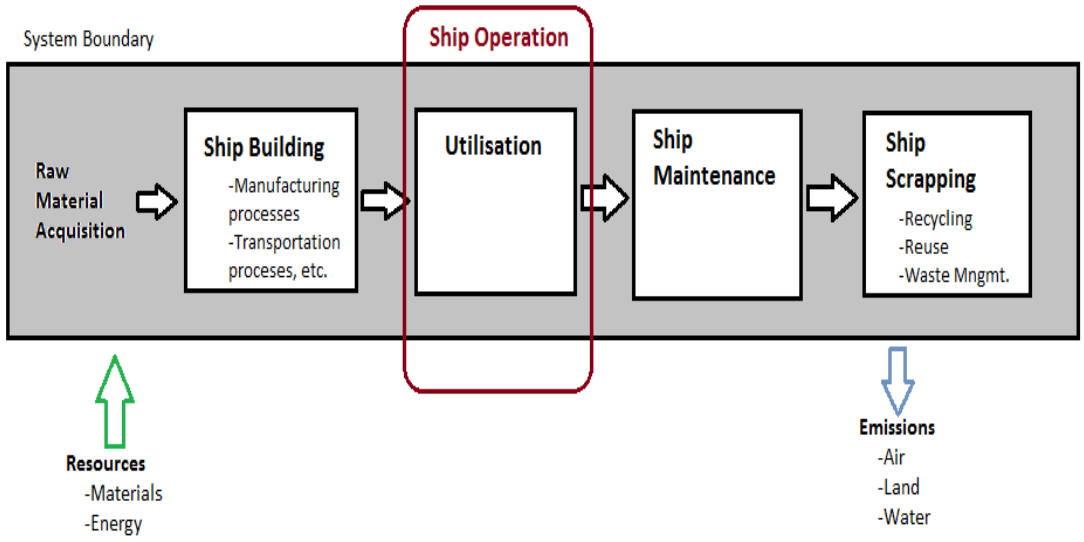


Figure 1: Main phases within the life cycle of a ship

In order to assess the potential resources consumed and the emissions emitted by a specific ship, a baseline LCA model is required. This model needs to feature the type and trade of the ship, and emphasise on the ship's most typical operations over a significant period of time (e.g. a year; this grants the possibility to extrapolate results to an assumed lifetime of e.g. 25 or 30 years, in order to assess the ship's whole life cycle). The last underscores that the operational profile of the ship – including its consumption parameters–, and any additional information from the construction phase to the assumed end-of-life scenario, proves ultimately essential to develop the ship's life cycle model.

Once the baseline LCA model is developed for a specific ship, the potential environmental impacts produced by the ship's operational profile can be assessed; this by accounting for the environmental history of the ship, as well as being able to extrapolate to potential future impacts. Any difference with regards to the most habitual behaviour within the operational profile of the ship, can now be assessed against the previously calculated baseline model (e.g. the switch to low-sulphur fuel) (Blanco-Davis, 2013a).

Significantly, the above comparison also offers the user the possibility of adjusting relevant operational inputs related to the original systems –or even applied retrofits–, in order to improve the calculated future environmental scores of the assessed system(s) (Koch et al., 2013). The above is also applicable to the building phase of a ship, in the case of ship re-design and system enhancement.

More information with regards to the model development and application is put forward by Blanco-Davis (2015); this work is openly available at the EthOs (e-theses online service) portal provided by the British Library.

3.3. Notes on impact assessment and carbon accounting

There are various impact categories within the LCA methodology, and furthermore, different damage approaches, e.g. midpoint and endpoint (see Figure 2); thus, the selection of the specific impact category or categories must be comprehensive in a way that they cover the significant environmental issues pertaining to the system under appraisal (JRC, 2010).

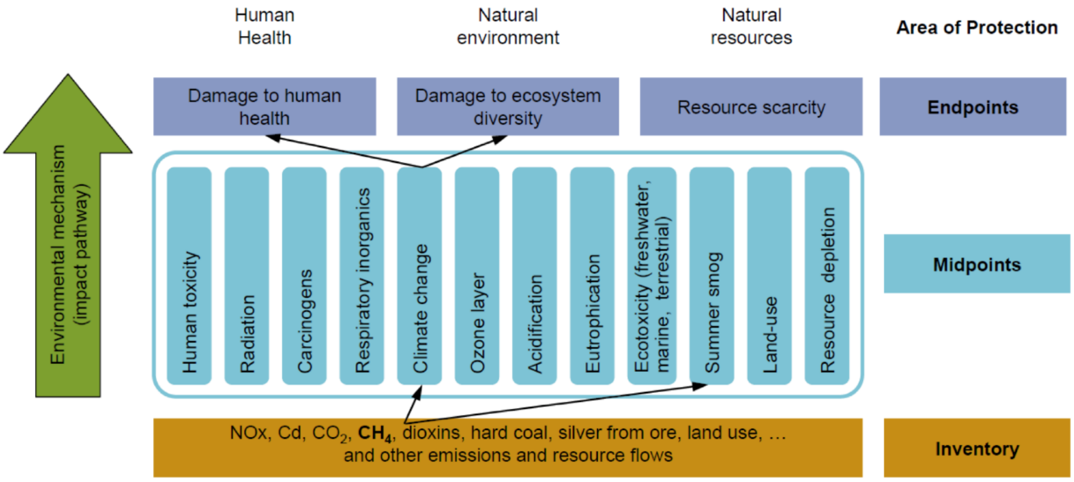


Figure 2: Schematic pathway from life cycle inventory to impact category endpoints (JRC, 2010)

For example, when a process or a system is appraised under the Global Warming Potential impact category in a 100 years, all emissions which contribute to this potential (meaning each emission with the radiative capability of a greenhouse gas) in the allotted period of time are collected, balanced, characterised –each using their own characterisation factor–, and ultimately presented under a unified carbon footprint or kg of CO_2eq score.

Keeping in mind the above explanation with regards to LCA carbon accounting, it is of interest to reassess the way carbon accounting is done in turn for the EEDI and the EEOI. With the aforementioned difference that the former underscores design efficiency while the latter operational efficiency, both are meant to provide an estimate of CO_2 emissions per transport-work. The last is done by underlining the ship's fuel consumption and additionally using an emission factor relative to that specific fuel(s); therefore, CO_2 emission factors are utilised similarly as the characterisation factors above explained.

The first clear difference between the two methodologies, LCA and EEDI/EEOI, would be shown in the way of –not only the numerical distinction between factors–, but the fact that LCA encompasses additional substances in its carbon accounting through the GWP classification and characterisation, e.g. CO, CH_4, and CFCs among others emissions; the EEDI/EEOI carbon accounting is solely referenced to the quantities of CO_2 released per tonne of fuel consumed (or to be consumed), and does not emphasise on additional substances emitted through the operational phase –or other phases, for that matter– of the life of a ship. The last would seem to qualify LCA's carbon accounting as more comprehensive, indicating –at first instance–, its capability for properly underlining shipping environmental performance.

Another apparent difference between the two methodologies is what ultimately gives way to the measure of energy efficiency, i.e. the definition of transport-work. This is defined by the available capacity and the design speed in the case of the EEDI, and by the actual distance sailed and cargo transported in the case of the EEOI. As previously discussed, the two metrics are expressed in grams of CO_2 per tonnes per nautical mile (gCO_2/tonne-nm). Aside from being able to measure environmental performance, for the LCA to give proper indication that it could additionally be utilised to highlight energy efficiency, the methodology would have to encompass a suitable definition of transport-work, relative to a shipping context.

This is done in LCA by defining the *functional unit* of the system to be assessed. The functional unit is the quantified definition of the function of a product or system (PE-International, 2011). In the case of a ship, for example, the vessel's trade would be taken into consideration, in order to define its main function. Similarly as stated above in the case of the EEOI, a ship's quantified performance would usually be expressed in terms of cargo carried per distance sailed over a relevant period of time (e.g. a year); this description would also serve to define the functional unit of a ship appraised under an LCA.

The relevance of the LCA's functional unit is that ultimately all gathered results are linked to the chosen functional unit; e.g. a certain emissions estimate of kg of CO_2eq *per* tonne-mile per year. In this way, LCA results can be presented similarly as the EEDI/EEOI scores, i.e. an estimate of CO_2 emissions *per* transport-work. Although the above-discussed differences between the two methodologies are noteworthy, outcomes show that the results between the two are not only able to be similar, but also equivalent.

3.4. Adopted formulae

The following is the complete set of formulae utilised in the following section, in order to assess the different metrics against one another. Equations 1 and 2 belong to the original EEOI formulations.

Equation 1: Single trip EEOI as per defined by IMO (2009)

$$EEOI_{single\ trip} = \frac{\sum_j \left(FC_j \times C_{Fj}\right)}{m_{cargo} \times D}$$

Equation 2: Average EEOI as per defined by IMO (2009)

$$Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times\ C_{Fj})}{\sum_i (m_{cargo,i}\ \times\ D_i)}$$

Where:

- C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j
- D is the distance in nautical miles corresponding to the cargo carried or work done
- FC_j is the mass (grams) of consumed fuel j
- FC_{ij} is the mass (grams) of consumed fuel j at voyage i
- i is the voyage number
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- j is the fuel type.

Equations 3 to 5 are comprised within IMO (2014)'s most current EEDI guidelines.

Equation 3: Required EEDI as defined by IMO (2013a) and IMO (2013b)

$$Required\ EEDI = a \times b^{-c}$$

Where:

- b is DWT or GT as per defined by IMO (2013a) and IMO (2013b), and underlined in Table 1.
- a and c are reference values as per defined by IMO (2013a) and IMO (2013b), and underlined in Table 1.

Equation 4: EEDI equation, not including energy saving technologies applied to main engines and auxiliary power, as adapted from (IMO, 2014)

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right) + \left(P_{AE_{(i)}} \cdot C_{FAE_{(i)}} \cdot SFC_{AE_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

Where:

- *Capacity* as per defined by IMO (2014) in tonnes
- C_F is the conversion factor between fuel consumption and CO_2 emission
- P refers to power in kW
- SFC is the specific fuel consumption in g/kWh
- V_{ref} is the ship speed in knots
- $_{AE}$ refers to the auxiliary engines
- f_c is the cubic capacity correction factor
- f_i is the capacity correction factor
- f_j is correction factor for ship specific design elements
- f_l is the correction factor for general cargo ships equipped with cranes and other cargo-related gear
- f_w is the weather factor
- $_i$ is the index of summation
- $_j$ is the index of multiplication
- $_{ME}$ refers to the main engines.

Equation 5: Required auxiliary engine power supply in normal maximum sea load, applicable to ships with a total propulsion power of 10,000 kW or above, and not including shaft motors, as adapted from IMO (2014)

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}}\right)\right] + 250$$

Where:

- MCR is the maximum continuous rating of the engine(s) in kW
- P_{AE} is the power of auxiliary engines in kW
- $_i$ is the index of summation.

Equations 6 and 7 have been developed, while 8 to 10 have been put together in order to demonstrate the potential equivalency between the LCA formulation and the regulatory metrics; therefore, many of the equations' factors hold similarity to that of the factors of the previously documented EEDI and EEOI equations.

Equation 6: LCA energy efficiency CO_2 score

$$LCA_{eff_{CO_2}} = \frac{\sum_i gCO_{2_i}}{\sum_i (m_{cargo,i} \times D_i)}$$

Equation 7: LCA energy efficiency GWP score

$$LCA_{eff_{GWP}} = \frac{\sum_i gGWP_i}{\sum_i (m_{cargo,i} \times D_i)}$$

Where:

- D is the distance in nautical miles corresponding to the cargo carried or work done
- gCO_2 is the LCA CO_2 inventory aggregate in grams
- LCA_{effCO2} is the LCA energy efficiency CO_2 score in gCO_2/tonne-nm
- $gGWP$ is the LCA CO_2 inventory aggregate in grams comprising classification and characterisation of releases analogous to CO_2
- LCA_{effGWP} is the LCA energy efficiency GWP score in gCO_2/tonne-nm
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- $_i$ is the index of summation.

Equation 8: CO_2 emissions based on the direct relation of quantity of emissions released per consumed fuel

$$Quantity\ of\ released\ gCO_{2_{Ship\ propulsion}} = FC_{ME} \cdot C_{FME}$$

Equation 9: Carbon conversion factor based on the relation of CO_2 emissions factor per specific fuel consumption

$$C_{FME} = \frac{CO_{2_{emission\ factor}}}{SFC_{ME}}$$

Equation 10: Fuel consumption relative to the main engine(s) output power and designated specific fuel consumption

$$FC_{ME} = \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot SFC_{ME_{(i)}} \right) \cdot T$$

Where:

- C_{FME} is the conversion factor between fuel consumption and CO_2 emission
- FC_{ME} is the mass (grams) of consumed fuel by the main engine(s).
- SFC is the specific fuel consumption in g/kWh
- $_{ME}$ refers to the main engines.
- $\%Load_{ME}$ is the main engine(s) output power
- MCR_{ME} is the maximum continuous rating of the engine(s) in kW
- T is the duration in *hours* corresponding to period underlining the fuel consumption calculation, e.g. duration of the trip
- $_i$ is the index of summation.

4. Results and discussion

The doctoral work by Blanco-Davis (2015) comprises two case vessels which are utilised to validate the LCA methodology and previously mentioned model, in order to assess LCA in comparison to the EEDI and EEOI, respectively. In addition, one of the case vessels encompasses a relevant retrofit application (FRC paint scheme over conventional A/F), in order to enrich the above mentioned comparison, and allows for the appraisal of the before and after phases of the retrofit among the different metrics and LCA.

A summarised description of the one of the case studies, and the LCA characteristics and factors holding similitude to the factors found in the formulation of the EEDI and EEOI, is included in the following section. The most relevant results, additionally, are comprised herein, in order to underline positive conclusions as to the helpful application of LCA in the shipping and shipbuilding and repair industry, as well as describing LCA as a tool to complement the implementation of the current shipping efficiency regulatory framework.

4.1. Case study introduction

The case vessel proposed is a capesize bulk carrier, which has a worldwide operation and often transports grain. Table 2 lists the ship's main particulars.

Table 2: Bulk Carrier vessel particulars

Type of vessel:	Bulk carrier	**Deadweight (DWT):**	84,607 tonnes
Year of built:	2009	**Gross tonnage (GT):**	51,255 tonnes
Length overall (LOA):	229.2 metres		
Length between perpendiculars (LBP):	222.0 metres	**Hull materials:**	Naval A grade steel
Breadth:	38.0 metres	**Hull connections:**	Welded
Draft:	14.9 metres	**Power (main engine):**	14,280 kW at 105 rpm

4.1.1. Goal and scope of the study

The goal of the study is to validate the LCA methodology as a fitting environmental indicator supplement to the EEDI and EEOI metrics, while additionally being able to underline energy efficiency outcomes. It should be noted that the case ship will be assessed using the previously summarised ships' LCA model, but the scope of the study will only comprise the operational phase of the Bulk Carrier (rather than the whole life cycle).

4.1.2. Operational profile

The Bulk Carrier was built in 2009, and operates cargo routes from Europe to Africa, and across Western Asia, whilst also being able to call on ports differing from the above routes. The last proves as a difficulty for developing an operational profile that ultimately accommodates a regular yearly schedule. For this reason, the voyage profile considered herein has been summarised in order to provide a simpler calculation and comparison between the different metrics. Nevertheless, this should be underscored as a potential limitation, and should be listed further to enhance future appraisals.

The voyage profile considered for the purpose of the study, highlights the vessel travelling from Port Kirkenes, Norway, to Port Said, Egypt, and back. Considering the two different locations, the average distance between the two is 5808 miles. Additionally, the vessel undertakes a loaded voyage to arrive to its destination, while coming back unloaded, i.e. a ballast voyage. Since the vessel's service speed is 12 knots, then the average sailing time for each trip or voyage is 484 hours (20.17 days). Lastly, it is assumed the vessel carries out 10 trips per year, resulting in 4840 hours of operation a year while using its main engine; the rest of the time is either spent at port loading and unloading cargo, and performing maintenance while using shore power and having its main engine offline.

4.1.3. Function of the system

The function of this type of vessel is to transport unpackaged cargo in bulk, such as grains, ore, cement, coal, and etcetera. Therefore, its main defined function would be the transportation of maximum mass, i.e. cargo. It is worthy to mention that the environmental scores obtained from this appraisal are only comparable to scores to that of similar types of ships, with the same functional performance.

4.1.4. Functional unit

Based on the consideration that the system's main function is the transportation of maximum cargo, thus the functional unit should be defined as:

- (Cargo transported × distance) per year between the two port destinations.

Moreover, the ship's maximum carrying potential amounts to 100,300 cubic meters. Assuming that in average 85% of this capacity is reached, and additionally that the vessel undertakes transport of grains of wheat –with a density of 790 kg/m^3–, then the total transported cargo per trip would amount to:

- (100,300 m^3 × .85 × 790 kg/m^3) ÷ (1/1000 tonne/kg) = 67,351.45 tonnes/trip.

Considering the above, the functional unit of the system is defined as **tonne × nm transported per trip** between the two port destinations, with a functional performance of 67,351.45 tonnes/trip × 5808 nautical miles = 3.91×10^8 tonne-nm per loaded trip.

4.1.5. Assumptions and limitations

The following list of assumptions is associated to the operational phase:

1. Consumption and emission factors are taken from MAN-Diesel (2009) and Moldanová et al. (2012), respectively. These factors are used to define the 'ship propulsion & generation' process (found in the original LCA appraisal, see Blanco-Davis (2015)), *with the exception* of the CO_2 emission factor. This last amounts to 520.1 g/kWh; this is so that there is consistency while using IMO's carbon conversion factor for HFO (i.e. 520.1 g/kWh ÷ 167 g/kWh SFC_{ME} = 3.114)(IMO, 2009).
2. In order to account for the complete life cycle of the vessel, the lifetime of the ship has been assumed to be that of 25 years for the original model. Nevertheless, to assist the comparison between LCA scores and the EEDI/EEOI –instead of using results extrapolated to 25 years–, results for one trip of operation will be utilised against the EEDI, while results for one year of operation (10 trips) will be used versus the EEOI. This is done because neither of the regulatory metrics is designed to carry out lifetime appraisals.
3. Engine performance is assumed constant, disregarding operation of the engines at port, if any.
4. The auxiliary generators are disregarded through the LCA modelling and EEOI, although the EEDI formulation does account for the auxiliary engine power. The current LCA modelling does however supplement the aggregate score with additional emissions, other than the ones obtained during the operational phase, underscoring releases generated during the refinery production of the ship's utilised HFO.

4.2. Evaluation of the LCA application as an energy efficiency metric (Bulk Carrier)

Table 3 includes some of the inputs respective to the operational profile of the Bulk Carrier. Some of these inputs have been utilised for the calculation of the EEDI and EEOI scores, while the majority have been recorded for the modelling phase relative to performing the LCA appraisal.

Table 3: Bulk Carrier vessel relevant operational profile inputs

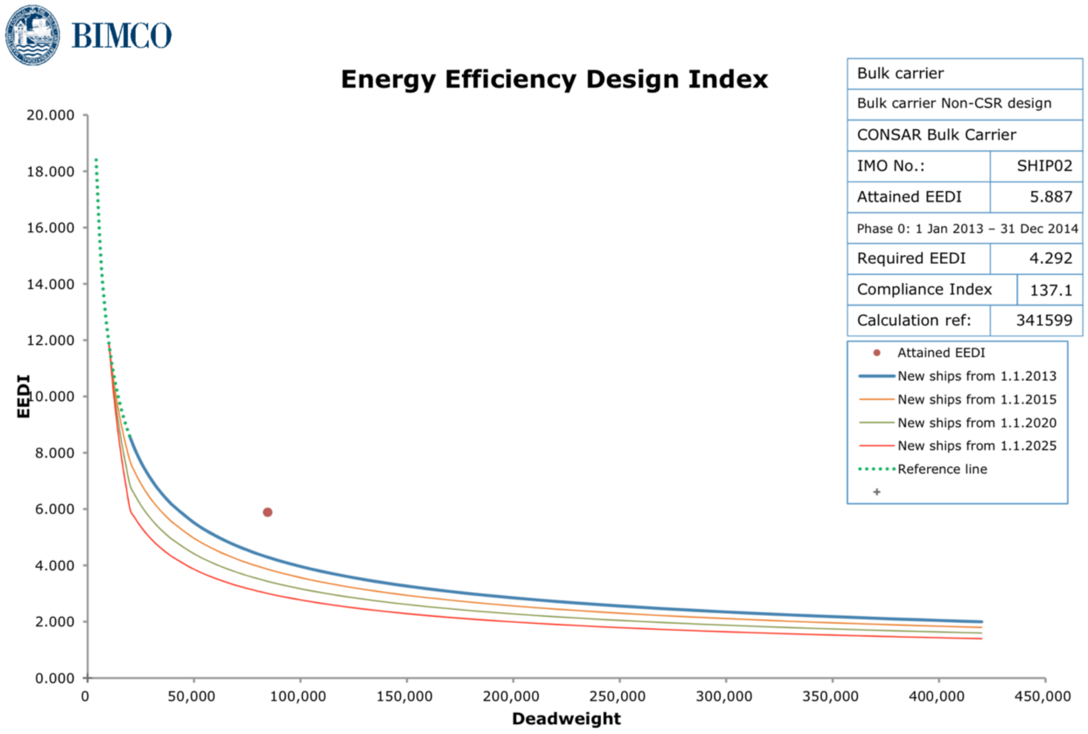
MCR_{ME}:	14,280 kW	**V_{ref}:**	12 knots
SFC_{ME}:	167 g/kWh	**Cargo (transported / trip):**	67,351.45 tonnes
CO_2 emission factor:	520.1 g/kWh	**Cargo (transported / year):**	336,757.25 tonnes
T (time / trip):	484 hours	**Capacity (DWT):**	84,607 tonnes
# Trips per year:	10	**D (distance):**	5,808 miles
T (time / year):	4,840 hours	**SFC_{AE}:**	215 g/kWh
$\%Load_{ME}$:	75%	**C_F (IMO factor for HFO):**	3.1144 $gCO_2/gFuel$

Recalling Table 1: Reference values for calculating the required EEDI (GL, 2013), as adapted from (IMO, 2013a, b), and

Equation 3 for obtaining the required EEDI value, while also recalling IMO (2014)'s 2014 EEDI guidelines which define that for bulk carriers deadweight should be used as capacity, the following is calculated:

$$Required\ EEDI = a \times b^{-c} = (961.79) \times (84{,}607)^{(-0.477)} = 4.292$$

Therefore, the required EEDI for phase 0, which runs from January 1st, 2013 to December 31st, 2014, is equal to 4.292 gCO_2/tonne-nm for the Bulk Carrier, with a deadweight capacity of 84,607 tonnes. Figure 3 shows the plotted reference lines for the Bulk Carrier case ship, the required EEDI score, and additionally the plotted result for the calculation of the attained EEDI (5.887 gCO_2/tonne-nm).



Bulk carrier	
Bulk carrier Non-CSR design	
CONSAR Bulk Carrier	
IMO No.:	SHIP02
Attained EEDI	5.887
Phase 0: 1 Jan 2013 – 31 Dec 2014	
Required EEDI	4.292
Compliance Index	137.1
Calculation ref:	341599

Figure 3: Bulk Carrier case vessel EEDI plot result, screenshot from BIMCO (2011) calculator

Prior to recalling Equation 4 for the calculation of the EEDI, the required auxiliary power should be calculated as per defined by IMO (2014) using Equation 5.

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}}\right)\right] + 250$$

$$P_{AE} = [0.025 \times (14{,}280\ kW)] + 250 = 607\ kW$$

Having calculated the auxiliary power, and recalling that the main engine power input (P_{ME}) required for the EEDI formulation is considered to be 75% of the aggregated rated installed power ($\Sigma MCR_{ME(i)}$), and additionally emphasising on the carbon conversion factor (C_F) and SFC for both main and auxiliary engines, the capacity, and the reference speed –all listed in Table 3–, and lastly assuming that the power correction factor (f_j), the cubic capacity correction factor (f_c), the capacity correction factor (f_i), the cargo-related gear correction factor (f_l), and the weather correction factor (f_w) are all equal to one (1.0), the following underlines the calculation for the vessel's attained EEDI:

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right) + \left(P_{AE_{(i)}} \cdot C_{FAE_{(i)}} \cdot SFC_{AE_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

$$Attained\ EEDI = \frac{(1)(10{,}710\ kW \cdot 3.1144 \cdot 167\ g/kWh) + (607\ kW \cdot 3.1144 \cdot 215\ g/kWh)}{1 \cdot 1 \cdot 1 \cdot 84{,}607\ tonnes \cdot 1 \cdot 12\ knots}$$
$$= 5.887\ gCO_2/tonne \cdot\ mile$$

Although the above-obtained result is relatively close to the phase 0 reference line, it is still under compliant of the regulatory framework as it is clear that the required EEDI is lower (4.292 gCO_2/tonne-nm). Nonetheless, this ship is currently not required to comply with the EEDI, having been built in 2009; thus the above is purely a hypothetical exercise to review what would the ship's environmental design efficiency seem like at the time of construction.

With the above logic in mind, it would also be interesting to evaluate the outcomes resulting from the LCA appraisal, and to compare these with the above result, in order to assess if the scores have any degree of equivalency. The LCA energy efficiency scores are calculated by using Equation 6 and

Equation *7*; the difference between them is that the first calculates the energy efficiency using the LCA CO_2 inventory aggregate, while the latter supplements this result with the contribution by ways of classification and characterisation of releases analogous to CO_2 (i.e. GWP)[1]. Additionally, the denominator in these equations is nothing more than the stated functional performance, relative to the previously defined functional unit of the system.

Table 4: Bulk carrier CO2 and GWP aggregate 1-trip results, attained EEDI, and respective LCA energy efficiency scores while using DWT capacity (84,607 tonnes)

	ΣCO_2 (gCO_2)	**ΣGWP (gCO_2eq)**	**EEDI (gCO2/tonne-nm)**	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
1 trip	2.98E+09	3.07E+09	5.887	6.072	6.250

With regards to the LCA energy efficiency scores, Table 4 already encompasses the gathered values, while additionally including the LCA CO_2 inventory aggregate and the GWP results for the Bulk Carrier ship in grams for 1 trip, and lastly the attained EEDI result. It is interesting to note that the obtained LCA energy efficiency scores are rather close to the attained EEDI.

$$LCA_{eff_{CO2\ (1\ trip\ A/F)}} = \frac{2.98 \times 10^9 gCO_2}{(84{,}607\ tonnes\ \times\ 5{,}808\ nautical\ miles)} = 6.072\ \ gCO_2/tonne \cdot nm$$

The LCA efficiency score for the CO_2 aggregate result in Table 4 can be calculated recalling Equation 6, the CO_2 aggregate value displayed in the same table, the capacity utilised for the EEDI calculation, and the single trip distance found in Table 3.

Equation *7* can be utilised similarly to calculate the LCA energy efficiency score for the GWP aggregate result. The reader should note that having the CO_2 and GWP aggregate results in scientific format, might influence the precision of the LCA energy efficiency scores.

Both of these aggregate emission results, CO_2 and GWP, are comprised of the contribution of releases from the HFO production process, as well as emissions from the ship propulsion process (both resulting from the LCA appraisal). Prior to highlighting the sole CO_2 contribution of the main engine's emissions, likewise as mostly emphasised on the EEDI formulation, the following are the

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[1] Both the LCA CO_2 inventory aggregate and the GWP values have been previously calculated in the doctoral thesis by Blanco-Davis (2015).

differences that have been addressed to enable a more parallel comparison between the EEDI and LCA results:

1. Engine MCR is regarded as 14,280 kW for the EEDI, as well as for the LCA modelling.
2. Main engine output power relative to the EEDI calculation is 75% of the rated installed power (MCR), as well as for the LCA modelling.
3. The carbon conversion factor used for the EEDI calculation is equal to 3.1144, as correspondingly utilised for the LCA modelling.

Perhaps the most significant of the above-mentioned issues is the carbon conversion factor, as the regarded MCR and utilised per cent load are not uncommon to the current ship's operational profile and consequent LCA modelling. Thus, the emphasised model input underlines the vessel's CO_2 emission factor, in order to have an equivalent conversion value to that utilised by IMO on both, the EEDI and EEOI formulations (see the following calculation, while recalling

Equation 9).

$$C_{FME} = \frac{520.10\ g/kWh}{167\ g/kWh} = 3.1144\ \ gCO_2/gFuel$$

Therefore, underlining the previously proposed equivalency between the two formulations –the EEDI and the defined LCA emissions release function for the ship propulsion process (see Equation 8)–, in theory the aggregate releases generated by the main engine under the LCA process definition while recalling the functional performance of the vessel, should equal the attained EEDI result minus the auxiliary power contribution.

Recalling Equation 6, the CO_2 separate ship propulsion contribution result from the LCA appraisal (2.69 x 10^9 g of CO_2), the capacity utilised for the EEDI calculation, and the single trip distance found in Table 3, the following denotes the LCA energy efficiency score solely for the CO_2 emissions generated by the ship's propulsion plant:

$$LCA_{eff_{CO2\ (1\ trip\ S.P.)}} = \frac{2.69 \times 10^9 gCO_2}{(84{,}607\ tonnes\ \times\ 5808\ nautical\ miles)} = 5.486\ \ gCO_2/tonne \cdot nm$$

Lastly, assuming that the auxiliary power is removed from the EEDI equation –due to the formerly highlighted fact that the current LCA model formulation does not include releases from auxiliary engines–, the following would be the theoretical attained EEDI exclusively for the main engine's emissions:

$$Attained\ EEDI_{(w/o\ aux\ pwr)} = \frac{(1)(10{,}710\ kW \cdot 3.1144 \cdot 167\ g/kWh)}{1 \cdot 1 \cdot 1 \cdot 84{,}607\ tonnes \cdot 1 \cdot 12\ knots}$$
$$= 5.486\ gCO_2/tonne \cdot\ mile$$

The above is merely an exercise in order to demonstrate the type of flexibility, which could allow the end user to adapt the LCA formulation –not only to be applied alternatively to the IMO efficiency metrics–, but also implemented in parallel to them when the need for further environmental efficiency information was required. While it is true that further work is necessary with regards to the LCA formulation explained herein –e.g. the inclusion of parameters allowing the simulation of releases related to auxiliary engines–, the present work is intended to demonstrate the possibility and advantages of the LCA application as a tool for highlighting shipping energy efficiency, as satisfactorily as the regulatory metrics.

With regards to the EEOI –although also holding similitude to the EEDI formulation–, its equation is less complex, focusing mainly on the fuel consumed per voyage, and the actual distance and cargo transported. Thus, the main differences with regards to the EEDI formulation is that auxiliary power is not considered specifically, there is no specific input or variable for energy saving technologies, and there are no specified correction factors for weather or different ship types. Additionally, the EEOI uses a variant of the $D=V_{ref}\times T$ relation; i.e. instead of using the reference speed, it uses the distance factor. The EEOI is calculated using Equation 1 for a single trip, and

Equation *2* for a rolling average comprising a number of trips.

It should be noted that the following calculations are in accordance to the assumption that the bulk carrier transports a constant quantity of cargo per year –and thus per trip–, as per defined by section 4.1.4. Nonetheless, the bulk carrier's assessment will comprise the inclusion of loaded, as well as ballast voyages (see section 4.1.2), with the aim of underlining any differences between the EEOI and LCA valuations.

The EEOI score for a single loaded trip is calculated by recalling Equation 1 as mentioned previously, as well as the values for the carbon conversion factor, the single trip distance, and the quantity of cargo carried per trip –all found in Table 3–, and additionally recalling

Equation *10* for the fuel consumption, and adjusting accordingly for the number of engines, the MCR, the weighted average load, the SFC, and the trip duration (i.e. 1 engine, 14,280 kW, 75% load, 167 g/kWh, and 484 hours). Table 5 gathers the EEOI single loaded trip result.

$$EEOI_{1-trip\ (loaded)} = \frac{\left(8.66\times 10^{8} g\ of\ Fuel \cdot 3.1144\ {}^{gCO_2}/_{gFuel}\right)}{(67{,}351.45\ \text{tonnes}\cdot 5{,}808\ nautical\ miles)} = 6.892\ gCO_2/tonne\cdot\ mile$$

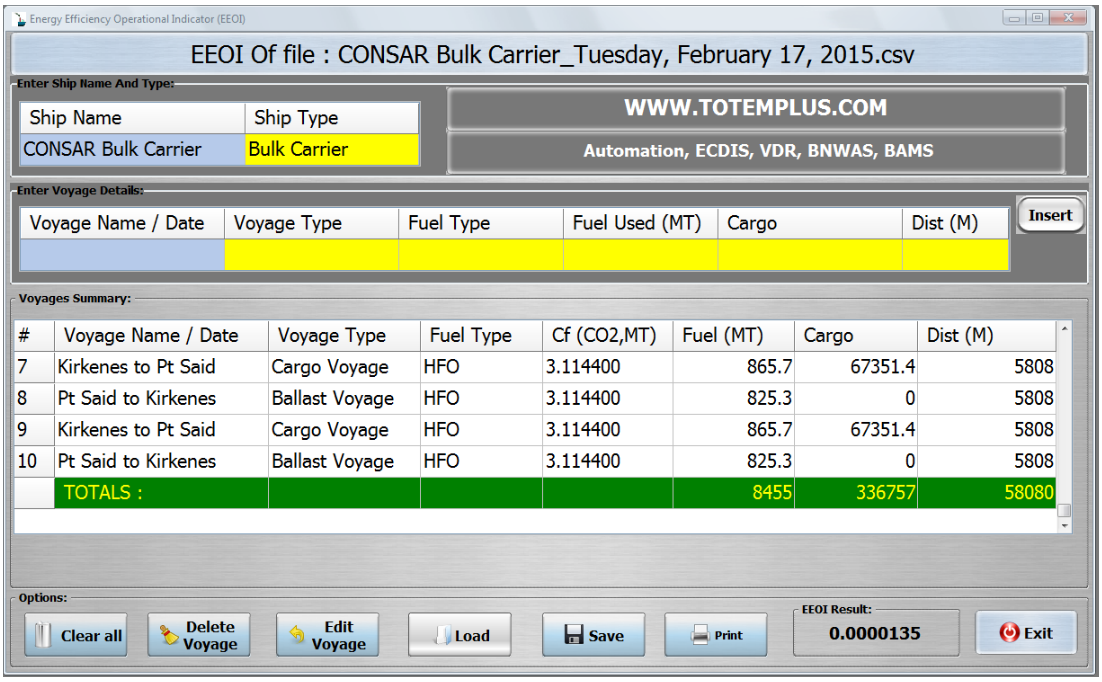
It is relevant to note that the resulting fuel consumption for the single loaded trip averages 865.67 tonnes per trip. The ship consumes on average 2 tonnes of fuel less per day during a ballast voyage, according to records supplied. Recalling that each voyage lasts 20.17 days, the fuel consumption relative to a ballast voyage totals 825.33 tonnes per trip.

$$Yearly\ Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)}$$

$$Yearly\ Average\ EEOI\ =$$

$$= \frac{3.1144\ {}^{gCO_2}/_{gFuel}\,[(8.66\times 10^{8} gFuel\cdot 5\ trips) + (8.25\times 10^{8} gFuel\cdot 5\ trips)]}{5{,}808\ \text{nautical miles}[(67{,}351.45\ tonnes)\cdot(5\ trips) +\ (0\ tonnes)\cdot(5\ trips)]}$$
$$= 13.463\ {}^{gCO_2}/_{tonne\cdot nm}$$

Figure 4 shows a screenshot of the Totem-Plus (2012) calculator, representing the resulting average EEOI score for a total of 10 trips (1 year), including the rounded fuel consumption for loaded as well as ballast voyages. The converted result totals 13.463 gCO_2/tonne-nm (see Table 5).



EEOI Of file : CONSAR Bulk Carrier_Tuesday, February 17, 2015.csv

Enter Ship Name And Type:

Ship Name	Ship Type
CONSAR Bulk Carrier	Bulk Carrier

Enter Voyage Details:

Voyage Name / Date	Voyage Type	Fuel Type	Fuel Used (MT)	Cargo	Dist (M)

Voyages Summary:

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
7	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
8	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
9	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
10	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
	TOTALS :				8455	336757	58080

Options:

EEOI Result: 0.0000135

Figure 4: Bulk Carrier case vessel EEOI result, screenshot from Totem-Plus (2012) calculator

Table 5 comprises both EEOI results –1 and 10 trips–, as well as the resulting LCA energy efficiency scores for the CO_2 and GWP aggregate results found in Table 4, and relative to the ship's functional performance for 1 and 10 trips, respectively.

Table 5 evidences that the resulting LCA energy efficiency scores are not numerically far off with regards to the obtained EEOI values. These LCA scores are procured similarly to the previously demonstrated results in the EEDI section; the following is a sample calculation for one of the scores, recalling Equation 6 and the inventory aggregate for CO_2 emissions during that period (2.98 x 10^9 gCO_2), as well as the resulting cargo transported and distance travelled found in Table 3.

$$LCA_{eff_{CO2\,(1\,trip)}} = \frac{2.98 \times 10^9\ gCO_2}{67{,}351.45\ tonnes \cdot 5{,}808\ nautical\ miles} = 7.628\ \ gCO_2/tonne \cdot mile$$

The above LCA energy efficiency CO_2 value is relative to 1 operational trip, and takes into consideration the inventory aggregate for CO_2 emissions during that period (2.98 x 10^9 gCO_2), which in turn is comprised of emissions from the ship propulsion and generation process, as well as contributing releases from the production of HFO.

Similarly as with the aforementioned EEDI values, the difference from the EEOI results to the LCA energy efficiency scores is minimal (see Table 5), understanding that the latter's formulation is rather analogous to the EEOI's. Nevertheless, both LCA efficiency scores are slightly higher in comparison to that of their EEOI's counterpart; the last is clearly due to the additional contribution that each LCA category, CO_2 and GWP, inherently supplies.

Table 5: Bulk carrier vessel EEOI and respective LCA energy efficiency scores, 1 trip and 10 trips (1 year) results

	EEOI	**LCA$_{eff(CO2)}$**	**LCA$_{eff(GWP)}$**
	(gCO2/tonne-nm)	**(gCO2/tonne-nm)**	**(gCO2eq/tonne-nm)**
1 trip loaded	6.892	7.628	7.851
10 trips (5 loaded & 5 ballast)	13.463	15.256	15.702

With the above in mind, it is also interesting to note that the resulting LCA energy efficiency score solely for the CO_2 ship propulsion contribution outcome (2.69 x 10^9 gCO_2), calculated using the single trip distance and cargo carried values –found in Table 3–, totals 6.892 gCO_2/tonne-nm, equalling the EEOI single loaded trip result (as mentioned previously, having the CO_2 aggregate result in scientific format, influences the precision of the LCA energy efficiency score). The last underlines once again the equivalency between both formulations, EEOI and LCA, and additionally the potential of using each other optionally.

$$LCA_{eff_{CO2\,S.P.(1\,trip)}} = \frac{(2.69 \times 10^9\ gCO_2)}{67{,}351.45\ tonnes \cdot 5{,}808\ nautical\ miles} = 6.892\ \ gCO_2/tonne \cdot mile$$

Lastly, it is relevant to point out that a correction for the LCA energy efficiency scores relative to various voyages –comprising loaded and ballast fuel consumption results– would be required when the need for more precise amounts is underscored. Currently, although still generating similar values to that of the EEOI, the LCA formulation only takes into account the fuel consumption procured during loaded voyages. This difference may become higher when the number of voyages rises, and the amounts of cargo differ significantly.

A solution to address this is to add supplementary parameters within the LCA processes' definition, correspondingly to that of variables regarding specific trip fuel consumption and cargo transported, for example. The should be highlighted subsequently as another issue worthy of revision for the improvement of the model formulation.

4.3. Relevant case studies' results

The previous sections have underlined that the LCA formulation shows indication of compliance to both IMO regulatory metrics (i.e. EEDI and EEOI), not only as a practical environmental indicator, but also as a tool able to highlight energy efficiency, by ways of underscoring the amount of transport-work obtained through the ship's consumed energy.

In the case of the EEDI, for example, it is important to note it has been demonstrated by Blanco-Davis (2015) that it is possible for LCA results to be used against already established reference lines for the different ship types, by implementing similar corrections to the LCA scores. Table 6 recapitulates the EEDI results for both vessels, and additionally their respective LCA obtained scores; the values are provided in order to summarise the outcomes between both, the EEDI and LCA valuations, and not to compare the environmental results between the different ships, as due to their distinctive functional performance, these values are not equivalent.

Table 6: EEDI results for both case vessels, and respective LCA energy efficiency scores

		EEDI (gCO2/tonne-nm)	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
Ro-Ro Passenger Vessel	1 trip A/F	32.679	35.015	38.441
	1 trip FRC	-	29.662	32.568
Bulk Carrier	1 trip	5.887	6.072	6.250

Nevertheless, it is relevant to conclude that the LCA energy efficiency scores procured for both vessels, are numerically close to their respective EEDI outcomes. The last keeping in mind the differences in ship types; the Ro-Ro Passenger vessel, for example, required a correction due to its multipurpose design, while the Bulk Carrier's dispensable ship functionality correction provided for a more straightforward calculation.

The above numerical difference among the EEDI and LCA scores can be further refined, in order to generate closer outcomes to that of the EEDI. This type of flexibility on the LCA part was also validated when certain model definitions were modified for the Bulk Carrier LCA appraisal (see Blanco-Davis (2015)), ultimately generating closer LCA efficiency results to both, the EEDI and EEOI scores for the Bulk Carrier vessel (see Table 6 and Table 7).

Table 7: EEOI results for both case vessels, and respective LCA energy efficiency scores

		EEOI (gCO2/tonne-nm)	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
Ro-Ro	1 trip A/F	257.658	296.843	304.664
Passenger	1 trip FRC	218.178	251.671	258.302
Vessel	150 trips A/F & FRC	237.918	274.257	281.483
Bulk Carrier	1 trip $_{\text{loaded}}$	6.892	7.628	7.851
	10 trips $_{\text{(5 loaded \& 5 ballast)}}$	13.463	15.256	15.702

Table 7 gathers the EEOI results for both case ships, and their respective LCA energy efficiency scores. Similarly as explained previously for the EEDI outcomes, the LCA results herein are considered satisfactorily close to their respective EEOI values. Worthy of mention, however, is that the LCA efficiency scores are the least similar to their EEOI counterparts for the Ro-Ro Passenger vessel; this last entails the significant difference by contribution of additional CO_2 and GWP substances, in their respective columns.

The above table (Table 7) also underlines the Bulk Carrier's inclusion of loaded as well as ballast voyages for the EEOI calculation, which turned out to be an interesting comparison among the EEOI and LCA valuations. The last emphasised that while values procured by the LCA were rather similar to that of the EEOI, the LCA formulation only took into account the fuel consumption procured during loaded voyages. The last also underscores noted improvements to the model, which are ultimately highlighted by Blanco-Davis (2015).

Lastly, although not presented herein due to space constraints, both regulatory metrics, the EEDI and EEOI, as well as the LCA formulation, showed evidence of being able to incorporate the FRC retrofit in their respective calculations, and produce relative outcome savings. In the case of the EEDI, while the savings procured where not calculated (see Table 6), Blanco-Davis (2015) documented that such a retrofit can be implemented by establishing the reduction in power and evaluating the impact on speed, and re-running the EEDI calculation with the obtained power and speed.

The LCA appraisal was able to efficiently highlight the savings procured by the FRC retrofit, not only on resulting CO_2, NO_x, SO_x or emissions contributing to global warming (i.e. GWP), but additionally the savings generated through less consumption of energy and material inputs (not described herein), such as crude oil and fresh water. The Life Cycle Assessment was also able to pinpoint these savings to their respective processes, satisfactorily addressing the before and after phases of the proposed retrofit.

In summary, this brief account of results is meant to emphasise on the characteristic flexibility of LCA to ultimately address the user's needs, and produce a formulation generating values equivalent to that of the regulatory metrics (i.e. EEDI and EEOI) –not only to be applied alternatively to the IMO efficiency indicators–, but also capable of being implemented in parallel to them when the need for detailed environmental information was essential.

Although future work has been described by Blanco-Davis (2015) as necessary for the LCA formulation, such as the inclusion of additional parameters which would allow for detailed modelling, the work depicted herein is aimed at evidencing the possibility for the LCA tool to emphasise shipping energy efficiency, as satisfactorily as the current IMO-approved metrics.

5. Conclusions

Due to the current regulatory measures' intrinsic shortcomings, preventing the use of one single metric to serve as a measure of overall efficiency for the entire fleet and different ship types, an evident opportunity for the use of a flexible standardised performance method is accentuated. LCA could serve as an alternative environmental performance metric, while showing indication of parallel compliance and support to the current regulatory framework.

It has also been documented that the LCA formulation briefly described herein, shows indication of compliance to IMO's regulatory metrics. In the case of the EEDI, is important to note that it is possible to use the already established reference lines for the different ship types, by similarly implementing corrections factors to the LCA efficiency outcomes if necessary.

The above could represent an added benefit for the LCA formulation whilst used in parallel with the EEDI, as the regulatory framework is already in place; for example, LCA could supplement consumption and emission factors relative to other phases not included within the EEDI methodology (construction, maintenance, and end-of-life), and assess further potential emissions based on theoretical fuel consumption and added releases relative to other ship phases, ultimately generating more comprehensive results than the actual EEDI. The last could entail redefinition of existing ship emission baselines and reference lines, but would strive to implement better emission control throughout the life of the vessel, rather than only the operational stage.

It is also relevant to note that LCA utilises fuel consumption and the proper emissions factor relative to the fuel assessed, as directly as the EEOI and MRV formulation does. Furthermore, it is interesting to underline the EC's emphasis on developing a harmonised MRV methodology, which is able to provide consistent data with regards to GHG emissions from shipping. Underlining the already emphasised advantages of being able to generate micro pollutants as well as NO_x and SO_x outcomes, the implementation of LCA could be considered as a potential aid for the MRV's application. LCA could serve to assess and report maritime transport emissions with a widely accepted methodology, capable of consistent application across not only shipping divisions, but additionally across industry sectors as a common performance metric.

Although not mentioned herein, Blanco-Davis (2015) has described significant limitations and encountered difficulties, that should be underlined in order to improve the LCA formulation as a tool to assist the current regulatory metrics. Furthermore, the author has listed recommendations for future work and research into the improvement of the LCA methodology for this particular intended use, such as encompassing different type of retrofits into the LCA/EEDI/EEOI comparison (e.g. optimised propeller designs, hull air lubrication systems, waste heat recovery systems, the utilisation of wind or solar power, and etcetera).

Lastly, LCA's potential should not be neglected as a complementary tool –applicable to both newbuilds and existing vessels–, and which in parallel to the implementation of the regulatory metrics, is able to offer reliability and accessibility of information, aside from providing efficient reporting and verification of environmental scores and energy efficiency.

6. Acknowledgements

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