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

By Eduardo Blanco-Davis[*,a] and Peilin Zhou[b]

[*]Corresponding Author. Tel. +44 (0) 151-231-2378, Email: E.E.BlancoDavis@ljmu.ac.uk

[a] Liverpool John Moores University, Engineering, Technology and Maritime Operations – LOOM Research Institute, James Parsons Building, Byrom Street, Liverpool, L3 3AF, United Kingdom.

[b] University of Strathclyde, Dept. of Naval Architecture, Ocean and Marine Engineering, Henry Dyer Building, 100 Montrose Street, Glasgow, G4 0LZ, United Kingdom.

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 described and also applied on two case study vessels, utilising them 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
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational 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
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).

Aside from the economic and social additions into the methodology, its application has grown into a widespread practice among different industries, and consequently has become internationally accepted within renowned environmental organisations, governmental departments, and research groups.

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).

This and other initiatives, such as the European Commission's Europe 2020, which among other goals aims to set rigid climate and energy targets by the year 2020 (EC, 2010), exert pressure on the public and the industry, not only aiming at creating a general awareness towards environmental wellbeing, but setting strict regulatory framework awaiting proper compliance.

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).

The prescriptive measures above, otherwise also categorised as energy efficiency metrics, while originally good in nature, have not been welcomed completely by all industry stakeholders. The last may be a reaction to some of the measures' shortcomings, such as their direct applicability to different sections of the fleet, e.g. newbuilds and existing vessels.

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 proposal 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).

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 and the SEEMP –and their implementation methodology–.

2.2.1.EEDI

The IMO defines the EEDI as "a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in specific ship design to the industry. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations" (IMO, 2011, 2012c).

The above summarises the EEDI as a measure that highlights a minimum energy efficiency requirement level for new ships –which actually depends on ship type and size–, while stimulating the continuous technical development of all the components which influence the fuel efficiency of a ship. This measure aims to reduce GHG emissions from newbuilds, by focusing on the energy efficiency improvement of ships, via design features and/or by the application of energy efficient technologies.

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, 2014a); thus, the CO_2 calculation is as simple as multiplying the fuel consumption by the carbon conversion factor (Kedzierski and O'Leary, 2012).

Following the above, the EEDI is understood as a measure which reflects the theoretical design efficiency of a newbuild ship –mostly based on assumptions regarding the specific fuel consumption of the engines compared to the power installed on the ship–, and ultimately provides an estimate of CO_2 emissions per capacity-mile (Kedzierski and O'Leary, 2012).

The full EEDI formula is specified by IMO (2014a), 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, 2012b), 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, 2012b). 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: 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

Once the *attained* EEDI is calculated, a two-stage verification process begins, which comprises the design stage and ultimately the completion of sea trials and commissioning (Lloyd's-Register, 2012b). The documents to be submitted for EEDI examination, and the different responsibilities by the classification society (as verifier), the shipbuilder, and the shipowner, are described by IMO (2012b).

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 (2012a) underscores that the purpose of the SEEMP is to establish a mechanism of performance improvement that while focused on ship-specific issues, is carried out as a broader corporate energy management policy, particular to companies that act as shipowners or operators.

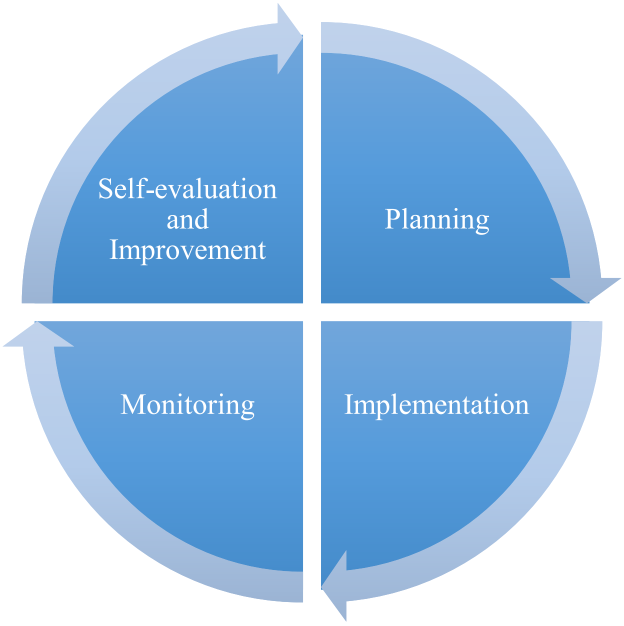

Figure 1: Structure of the SEEMP as adapted from IMO (2012a) and Lloyd's-Register (2012a)

Four main processes define the structure of the SEEMP: Planning, Implementation, Monitoring, and Self-evaluation and Improvement (see Figure 1). These however, will not be explained further herein, due to space constraints. It should be noted, nevertheless, that during the Monitoring phase, the tools that could provide a qualitative and quantitative basis for evaluation of the measures in place are defined (DNV, 2012), and significantly, that while IMO (2012a) leaves the choice of tools or Performance Indicators (PIs) up to the user, it advises that the energy efficiency of a ship should be monitored quantitatively by an established method, giving preference to indicators supported by an international standard.

IMO (2012a) additionally promotes the use of the EEOI as a valid ship and/or fleet energy efficiency indicator, but also recognises other tools 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.

The EEOI –which is currently a voluntary indicator–, is understood by IMO (IMO, 2014b) as a tool that enables operators to measure the fuel efficiency of a ship in operation, but additionally serves to gauge the effect of any of the changes brought about while implementing measures to improve energy efficiency onboard. Such measures include improved voyage planning, weather routeing, optimised ship handling, hull maintenance, and waste heat recovery, among others. Ultimately this is aimed at encouraging shipowners and operators alike, to consider new technologies and practices at each stage of the plan (DNV, 2012).

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). Nevertheless, the unit for the EEOI can also be expressed in tonnes of CO_2/tonne-nm, given that fuel consumption is commonly measured in tonnes, or additionally depending on the measurement of cargo carried or work done, e.g. tonnes of CO_2/TEU-nm, tonnes of CO_2/person-nm, etcetera (IMO, 2009).

IMO (2009) advises that the EEOI should be performed as a representative value of the ship's energy efficiency operation over a consistent period of time, which ultimately should also strive to represent the overall trading pattern of the vessel. This last is why the EEOI is finally presented as a rolling average, with various inclusive voyages depending on the defined period of time. Worthy of mention is that ballast voyages, i.e. voyages in which the vessel commonly sails without cargo, should also be included in the calculation.

Similarly to the EEDI, the SEEMP is verified by the vessel's assigned classification society. GL (2012) states that the verification of the requirement to have the SEEMP onboard shall take place at the first intermediate or renewal survey –whichever is first–, on or after January 1st, 2013, and is applicable to new and existing vessels of 400 GT and above.

2.3. Other relevant shipping efficiency metrics and the MRV

Aside from the regulatory energy efficiency measures presented previously in this section, other metrics are also available –voluntary in nature–, but nevertheless aimed similarly at improving the efficiency of the vessel, and ultimately of the fleet. Some of these are available commercially, while others are in-house developments used within owner and/or operator companies. They are however designed to assist users to properly comply with the current and upcoming regulatory framework.

The following includes a brief discussion with regards to the more popular voluntary metrics available; not with the aim of developing an inclusive listing, but in order to offer the reader a context in which it is underlined that alternative metrics are often used as supplementary tools, to assist with the implementation of the aforementioned regulatory measures.

For example, one of the most known optional metrics is the Existing Vessel Design Index (EVDI) –developed by the Carbon War Room and Rightship (2013) as a joint venture–, and aimed at being an attempt to formulate a single efficiency metric (Kedzierski and O'Leary, 2012); the last taking into consideration that it is allegedly applicable to both, newbuilds and existing vessels (Rightship, 2013). The EVDI formulation is based on the IMO's EEDI methodology, and can be calculated using the IHS Fairplay database, which is also IMO's database choice for reference lines computation (Kedzierski and O'Leary, 2012).

The main difference between the two is data collection; whereas the EEDI utilises newbuild design data provided by the classification societies during certification, the EVDI exploits existing ship data from different sources, including the IHS Fairplay database, shipyards, owners, and classification societies (Kedzierski and O'Leary, 2012). While the data is eventually available for verification and correction by the shipowner or operator –once the service is commercially acquired–, the EVDI formulation is not publicly disclosed, proving difficult to assess its accuracy.

Another method of measuring ship energy efficiency has been put forward by Smith et al. (2013), using satellite automatic identification systems (AIS) data in order to analyse the global efficiency of the fleet. AIS data is combined with established naval architecture and marine engineering analysis techniques, resulting in estimates of the assessed ship's annual fuel consumption and consequently its CO_2 emissions.

A relevant variance to the method employed by Smith et al. (2013), in comparison to that of Rightship (2013), is that the former authors are not in favour of a single or simplified energy efficiency metric, designed for benchmarking the entire fleet. Actually, the AIS-based method is highly similar to that of the IMO's EEDI and EEOI, whereas the both offer separate formulations to assess design and operational efficiency, respectively.

Aside from the above-mentioned elective metrics, another measure worthy of reference is the European Commission's proposed regulation "on the monitoring, reporting and verification [MRV] of carbon dioxide emissions from maritime transport", which is targeted at regulating CO_2 emissions applicable to shipping transport within European waters (EC, 2013).

In its current form, the MRV proposal is applicable to all ships above 5000 GT calling into, out of, and in between EU ports, with a underlined entering-into-force date of July 1st, 2015 (EC, 2013, 2015). The regulatory requirements highlight the monitoring of CO_2 emissions per voyage and on a yearly basis, as well as having other parameters relative to energy efficiency metrics onboard expressed.

The MRV's CO_2 emissions calculation consists on using estimated fuel consumption figures and the appropriate emissions factor for the fuel type being consumed (Lloyd's-Register, 2013), similarly performed to obtain the EEOI. 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, in order to offer policy-makers the necessary information with regards to all affecting pollutants derived from maritime transport operations.

The above can be similarly related to LCA, as a consolidated methodology that aside from offering a consistent account of GHG, SO_x, NO_x, and PM, among other emissions, is also designed to provide improved reliability through its formulation, and even be utilised as a decision support tool as described by Blanco-Davis and Zhou (2014), Koch et al. (2013) and Hunkeler and Rebitzer (2005), among others.

2.4. Relevant limitations, criticism, 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. Table 2 shows the fundamental coverage differences between the EEDI and the EEOI, showing that while technical policy options are conceived to target mainly design measures in new ships, operational policy options, however, will in principle cover both design options in new ships and operational options in all ships (Faber et al., 2009).

Table 2: Comparison of areas which are covered by EEDI and/or EEOI (Faber et al., 2009)

<table>
<tr><th></th><th>Areas covered by EEDI</th><th>Areas covered by EEOI</th></tr>
<tr><td>Design (new ships)</td><td></td><td></td></tr>
<tr><td>Concept, speed & capability</td><td rowspan="3">Key aspects can be accounted for in the EEDI or technical standard.</td><td rowspan="9">All design and operational elements may implicitly be covered, as the resulting performance is the basis for the instrument.</td></tr>
<tr><td>Hull and superstructure</td></tr>
<tr><td>Power and propulsion systems</td></tr>
<tr><td>Low-carbon fuels</td><td rowspan="3">Capability can be included, but not necessarily used.</td></tr>
<tr><td>Renewable energy</td></tr>
<tr><td>Operation (all ships)</td></tr>
<tr><td>Fleet management, logistics & incentives</td><td>No</td></tr>
<tr><td>Voyage optimisation</td><td>No</td></tr>
<tr><td>Energy management</td><td>No</td></tr>
</table>

In addition to the apparent overlapping above, it is also noted that the majority of EEDI analyses presented up to its approval in 2011 were based on existing ships; this is possible since the data required to calculate an EEDI is available from a ship's technical documentation, which in turn is often supported by classification societies. Therefore, theoretically it is possible to calculate the EEDI for existing vessels (Faber et al., 2009).

The above has caused extensive debating within the IMO, as conflicting views of the applicability of both measures have generated supporters in favour of each, attempting to make a case for their own preferred policy acceptance (Faber et al., 2009). There are supporters which believe that the use of the EEOI, for example, should be encourage or mandated; and that this in turn will make the application of the SEEMP more effective, and additionally will involve more accurate and verifiable measurement of fuel consumption and resulting CO_2 monitoring (Bazari and Longva, 2011).

The discussion regarding the EEDI as applicable to existing vessels, in the other hand, can be related to the difficult task of striving to apply a single performance metric for different sections of the fleet, i.e. newbuilds and existing ships. The reality of the current regulatory metrics is that they are not only aimed at separate sections of the fleet, and that they measure efficiency differently, but they additionally produce scores that while may have the same unit, e.g. gCO_2/tonne-nm, are not originally designed to be equivalent within one another (i.e. EEDI $\neq$ EEOI).

Aside from the above-mentioned disadvantage, 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). ISO 14040 defines LCA as a method which "addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO, 2006a).

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). 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). In either of the two, the comprehensive view offered by LCA, strives to prevent the potential underestimation of overlooked impacts, commonly found in transportation and ancillary processes, among others.

Another relevant LCA benefit comprises the capability of quantifying exchanges to the environment, relative to each life cycle stage; this valuable information can also be linked to factors such as costs and performance data for a specific process or product, assisting in the design and enhancement of such (Blanco-Davis and Zhou, 2014).

A comprehensive review of the LCA methodology is out of the scope of this paper, and therefore the reader should refer to the following works for more information on its particulars: Guinée et al. (2002), 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. The above will provide the reader a historical reference of the methodology's development, as well as a context in which it is documented that LCA is widely accepted and practised, and additionally well referenced across academic and industry literature.

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 2.

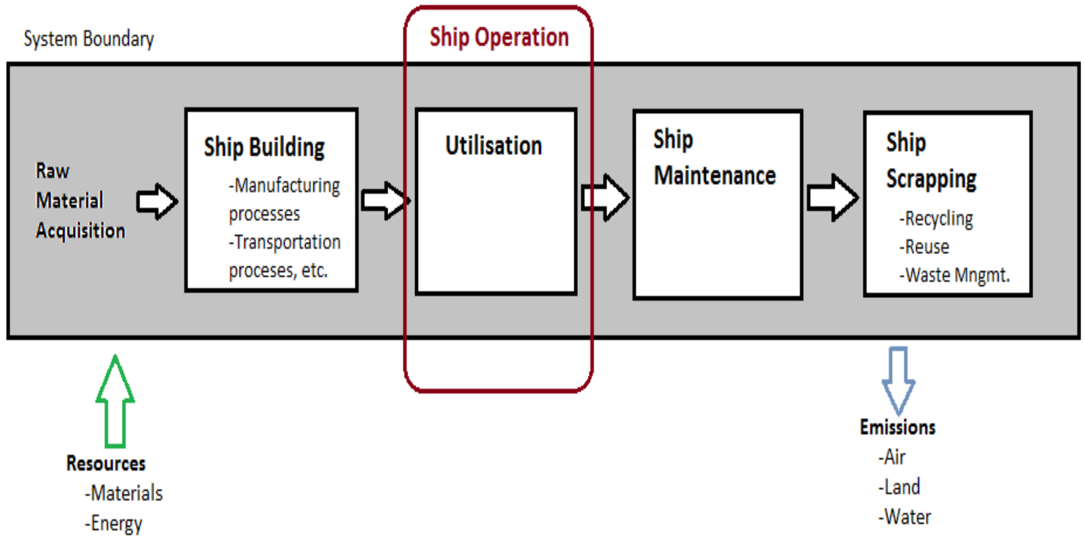

Figure 2: Main phases within the life cycle of a ship

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 end-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 developed impact categories within the LCA methodology, and furthermore, different damage approaches, e.g. midpoint and endpoint (see Figure 3); 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). In relation to the shipping industry, the focus gathers mainly on climate change –specifically highlighted under the Global Warming Potential impact category–, or additionally known or described as carbon footprint analysis.

Impact categories are usually based on a reference substance. Global Warming Potential (GWP), for example, is based and calculated in kilograms of carbon dioxide equivalents (CO_2eq), meaning that for each emission with the radiative capability of a greenhouse gas, a characterisation takes place in order to define its potential under a common unit and substance, i.e. kg of CO_2-equivalents.

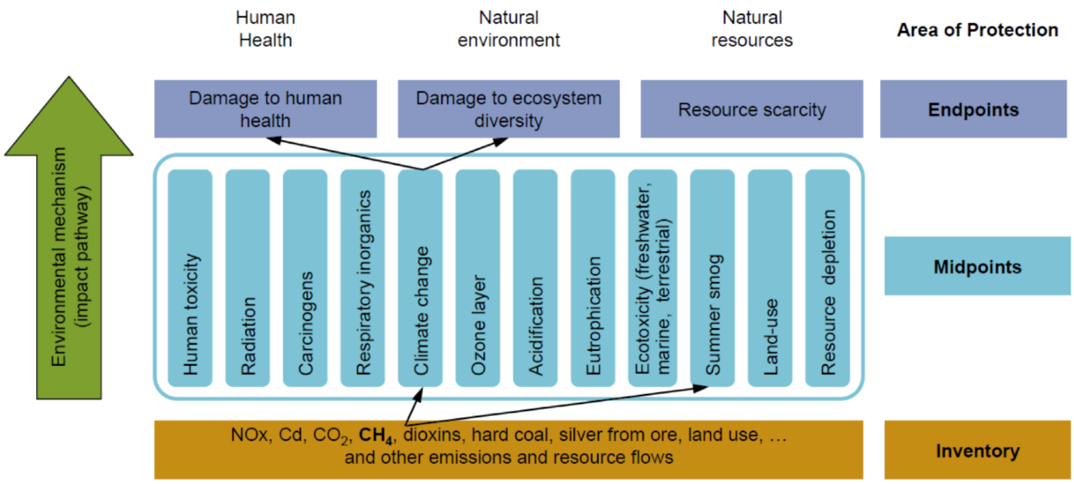

Figure 3: Schematic pathway from life cycle inventory to impact category endpoints (JRC, 2010)

In summary, when a process or a system is appraised under the Global Warming Potential impact category in a 100 years, for example, all emissions which contribute to this potential 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. carbon monoxide, methane, 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), that additionally serves as the unit of comparison which assures that products being compared (e.g. ships) provide an equivalent level of function or service (SAIC and Curran, 2006). 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.

Lastly, it is worth mentioning that an LCA can encompass past CO_2 emissions into the accounting of SO_x, NO_x and PM, and other contaminants, whether in individual form –i.e. during the life cycle inventory aggregation–, or by ways of impact assessment, and consequently the substance classification and characterisation within a specific impact category (e.g. SO_x within the Acidification Potential impact category). Furthermore, LCA aside form accounting CO_2 emissions, can encompass any other substance or emission produced during the life of a ship that has a warming potential analogous to CO_2, comprehensively covering all releases under this category.

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.

Nevertheless, a comprehensive description of the case studies and their model development is not included herein, nor the LCA characteristics and factors holding similitude to the factors found in the formulation of the EEDI and EEOI, aiming at keeping this particular account as a succinct practical depiction. The most relevant results, however, are comprised in this section, 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. 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.

Table 3: 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

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 3 recapitulates the EEDI results for both vessels, and additionally their respective LCA obtained scores ($LCA_{eff-CO2}$ which includes only CO_2 aggregation, and $LCA_{eff-GWP}$ which includes additional aggregation of substances with GWP); 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.

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 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 3 and Table 4).

Table 4: 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 Passenger Vessel	1 trip A/F	257.658	296.843	304.664
	1 trip FRC	218.178	251.671	258.302
	150 trips A/F & FRC	237.918	274.257	281.483
Bulk Carrier	1 trip $_{loaded}$	6.892	7.628	7.851
	10 trips $_{(5 loaded \& 5 ballast)}$	13.463	15.256	15.702

Table 4 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 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. Ultimately this translates into the following: as the number of voyages rises and the amounts of cargo differ significantly, the higher this difference may become. The last also underscores noted improvements to the model, which are ultimately highlighted by Blanco-Davis (2015).

Lastly both regulatory metrics, the EEDI and EEOI, as well as the LCA formulation, presented 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 3), 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 capable of 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 end-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

Of relevance is the emphasised aim of supporting the single performance metric approach by some industry stakeholders, as an ideal tool for a harmonised regulation across the entire fleet. Nonetheless, it has been documented that the reality of the current regulatory measures' intrinsic shortcomings, prevent the use of one single metric to serve as a measure of overall efficiency for the entire fleet and different ship types. Therefore, 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 etcetera), 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.

Several advantages towards LCA's conjoint application along the regulatory metrics have also been highlighted while summarising the results section. Although not discussed further herein, another benefit worthy of mention is LCA's ability to be linked to other technical performance and cost indicators, as demonstrated by Blanco-Davis and Zhou (2014) and Blanco-Davis et al. (2014), among others.

It is 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 monitor 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.

The work presented herein has briefly described a doctoral thesis by Blanco-Davis (2015), which underlines the widespread environmental problematic caused by human-generated detrimental emissions, and additionally highlights how the shipping industry is related to this global problematic, while lastly mentioning how the IMO has reacted by establishing methods aimed at striving to get shipping emissions under control.

In addition, Blanco-Davis (2015) has also 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.

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7. References

Alkaner, S., Zhou, P., 2006. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. Journal of Power Sources 158 (1), 188-199.
Ballou, P.J., 2013. Ship Energy Efficiency Management Requires a Total Solution Approach. Marine Technology Society Journal 47 (1), 83-95.
Bazari, Z., Longva, T., 2011. Assessment of IMO mandated energy efficiency measures for international shipping: estimated CO2 emissions reduction from introduction of mandatory technical and operational energy efficiency measures for ships. Report. Lloyd's Register & DNV.
BBC, 2014. UN: 'Massive shift' needed on energy, News: Science & Environment, http://www.bbc.co.uk/news/science-environment-27007486.
Bengtsson, S., Fridell, E., Andersson, K., 2012. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Policy 44, 451-463.
Blanco-Davis, E., 2013a. Eco-REFITEC Life Cycle Assessment Tool and User Manual: Guidelines to the Ship's Life Cycle's data gathering and LCA prototype modelling. EC-FP7 Project Deliverable 3.3, http://eco-refitec.eu/.
Blanco-Davis, E., 2013b. LCA for Eco-REFITEC selected cases: Report of implementation of LCA for shipyards, including owner costs and results of case ships. EC-FP7 Project Deliverable 5.1, http://eco-refitec.eu/.
Blanco-Davis, E., 2014. LCA impact assessment of greening existing fleet: Potential environmental impact of the technological eco-innovation for greening existing fleet. EC-FP7 Project Deliverable 5.2, http://eco-refitec.eu/.
Blanco-Davis, E., 2015. An investigation into LCA as a complementary utility to regulatory measures of shipping efficiency, Naval Architecture, Marine and Ocean Engineering. University of Strathclyde, Glasgow, p. 279.
Blanco-Davis, E., del Castillo, F., Zhou, P., 2014. Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry type ship. The International Journal of Life Cycle Assessment 19 (10), 1705-1715.
Blanco-Davis, E., Zhou, P., 2014. LCA as a tool to aid in the selection of retrofitting alternatives. Ocean Engineering 77 (0), 33-41.
Cabezas-Basurko, O., Mesbahi, E., 2012. Methodology for the sustainability assessment of marine technologies. Journal of Cleaner Production, 1-10.
DNV, 2012. The how, why and what of SEEMP. Brochure. Det Norske Veritas AS, Norway. http://www.dnv.com/binaries/1108-052_seemp_bro_12_preprint%20(2)_tcm4-472602.pdf.
EC, 2010. Europe 2020 A strategy for smart, sustainable and inclusive growth. Report. Brussels: European Commission.
EC, 2013. Regulation of the European Parliament and of the Council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and amending Regulation (EU) No 525/2013, COM(2013) 480 final report. European Commission, Brussels.
EC, 2015. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. Official Journal of the European Union.
Ellingsen, H., Fet, A.M., Aanondsen, S., 2002. Tool for Environmental Efficient Ship Design, International Conference on Marine Science and Technology for Environmental Sustainability, Newcastle Upon Tyne.
Faber, J., Markowska, A., Nelissen, D., Davidson, M., Eyring, V., Cionni, I., Selstad, E., Kågeson, P., Lee, D., Buhaug, Ø., Lindtsad, H., Roche, P., Humpries, E., Graichen, J., Cames, M., Schwarz, W., 2009. Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport. Report. CE Delft.
Fet, A.M., 1998. ISO 14000 as a Strategic Tool for Shipping and Shipbuilding. Journal of ship production 14, 155-163.
Fet, A.M., Margrethe Aspen, D., Ellingsen, H., 2013. Systems engineering as a holistic approach to life cycle designs. Ocean Engineering 62 (0), 1-9.

Fet, A.M., Michelsen, O., 2000. Life Cycle Assessment of transport systems, The Fourth International Conference on EcoBalance, Tsukuba, Japan, pp. 31.10-32.11.
GL, 2012. Information on the International Energy Efficiency Certificate (IEEC), GL Focus - Regulatory and Technical Update, http://www.gl-group.com/pdf/GL_Focus_News_IEEC.pdf.
GL, 2013. Energy Efficiency: Guidelines for Determination of the Energy Efficiency Design Index, Rules for Classification and Construction, VI Additional Rules and Guidelines. Germanischer Lloyd SE, Hamburg, Germany.
Guinée, J., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future†. Environmental Science & Technology 45 (1), 90-96.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., 2002. Handbook on life cycle assessment.
Hunkeler, D., Rebitzer, G., 2005. The Future of Life Cycle Assessment. The International Journal of Life Cycle Assessment 10 (5), 305-308.
IMO, 2009. MEPC.1/Circ.684 (Issued on 17 August 2009): Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI). International Maritime Organization, London.
IMO, 2011. Main events in IMO's work on limitation and reduction of greenhouse gas emissions from international shipping, http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Historic%20Background%20GHG.aspx.
IMO, 2012a. Annex 9 Resolution MEPC.213(63) (Adopted on 2 March 2012): 2012 Guidelines for the development of a ship energy efficiency management plan (SEEMP).
IMO, 2012b. Annex 10 Resolution MEPC.214(63) (Adopted on 2 March 2012): 2012 Guidelines on survey and certification of the energy efficiency design index (EEDI).
IMO, 2012c. Marine Environment Protection Committee (MEPC), 63rd session, 27 February to 2 March, MEPC Meeting Summaries, http://www.imo.org/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-63rd-session.aspx.
IMO, 2013a. Annex 14 Resolution MEPC.231(65) (Adopted on 17 May 2013): 2013 Guidelines for calculation of reference lines for use with the energy efficiency design index (EEDI).
IMO, 2013b. Annex 17 Resolution MEPC.233(65) (Adopted on 17 May 2013): 2013 Guidelines for calculation of reference lines for use with the energy efficiency design index (EEDI) for cruise passenger ships having non-conventional propulsion.
IMO, 2014a. Annex 5 Resolution MEPC.245(66) (Adopted on 4 April 2014): 2014 Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships.
IMO, 2014b. Technical and Operational Measures, Air Pollution and GHG Emissions, http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Report.
ISO, 2006a. 14040:2006(E) Environmental management - Life cycle assessment - Principles and framework, Geneva, Switzerland.
ISO, 2006b. 14044:2006(E) Environmental management - Life cycle assessment - Requirements and guidelines, Geneva, Switzerland.
JRC, 2010. General Guide for Life Cycle Assessment – Detailed Guidance, ILCD Handbook. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Luxembourg.
JRC, 2013. LCA Info Hub, in: European Commission, J.R.C., Institute for Environment and Sustainability (Ed.), European Platform on LCA. European Commission, Joint Research Centre, Institute for Environment and Sustainability, http://lca.jrc.ec.europa.eu/lcainfohub/provider.vm?pid=471.
Kedzierski, A., O'Leary, A., 2012. Energy Efficiency of Ships: what are we talking about?, Publications - Year 2012, http://www.transportenvironment.org/sites/te/files/publications/2012_12_Ship_efficiency_briefing.pdf.
Koch, T., Blanco-Davis, E., Zhou, P., 2013. Analysis of Economic and Environmental Performance of Retrofits using Simulation, in: Bertram, V. (Ed.), Conference in Computer and IT Applications in the

Maritime Industries (COMPIT). Technische Universität Hamburg-Harburg, Cortona, Italy, pp. 225-237.
Lloyd's-Register, 2012a. Implementing a Ship Energy Efficiency Management Plan (SEEMP): Guidance for shipowners and operators, Documents and publications, http://www.lr.org/Images/LR%20SEEMP%20Guidance%20Notes%20for%20Clients%20v2_tcm155-240651.pdf.
Lloyd's-Register, 2012b. Implementing the Energy Efficiency Design Index (EEDI): Guidance for owners, operators, shipyards and tank test organisations, Documents and publications, http://www.lr.org/Images/EEDI%20Guidance%20Notes%20for%20Clients%20v3.0_tcm155-240648.pdf.
Lloyd's-Register, 2013. European Union Proposal for Regulation on Monitoring, Reporting and Verification of CO2, Documents, http://www.lr.org/Images/LR%20EU%20MRV%20Proposed%20Legislation%20Report%20v1_0_tcm155-247872.pdf.
PE-International, 2010. Handbook for Life Cycle Assessment: Using the GaBi Education Software Package, Leinfelden-Echterdingen.
PE-International, 2011. GaBi Paper Clip Tutorial: Handbook for Life Cycle Assessment, Using the GaBi Software. PE International GmbH and Universität Stuttgart.
Rightship, 2013. Calculating and Comparing CO2 Emissions from the Global Maritime Fleet. Report.
Rightship, 2014. Environmental Ratings, Shipowners, http://site.rightship.com/ship-owners/environmental-ratings/.
SAIC, Curran, M.A., 2006. Life-cycle Assessment: Principles and Practice. Report. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.
Smith, T., O'Keeffe, E., Aldous, L., Agnolucci, P., 2013. Assessment of Shipping's Efficiency Using Satellite AIS data. Report, Low Carbon Shipping - A Systems Approach. UCL Energy Institute.
Utne, I.B., 2009. Life cycle cost (LCC) as a tool for improving sustainability in the Norwegian fishing fleet. Journal of Cleaner Production 17 (3), 335-344.
Weidema, B., 2006. The Integration of Economic and Social Aspects in Life Cycle Impact Assessment. The International Journal of Life Cycle Assessment 11 (0), 89-96.