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In-situ data vs. bottom-up approaches in estimations of marine fuel consumptions and emissions

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A B S T R A C T

Pollution by marine fuels and their influence on ecosystems and the human populace are growing concerns in the maritime industry. Consequently, emission regulations, alternate marine fuels and fuel efficiency enhancements are being pursued to ensure that marine emissions are curtailed within acceptable limits. Many strategic decisions related to these areas are taken based on cost and emission estimates which in turn depend on the accuracy of the estimation of marine fuel consumptions. The estimates are based on various methodologies which attempt to capture maritime fuel consumptions at local, regional and global levels. The bottom-up approach is the most predominant method to estimate emissions and thereby to assess compliance with the emissions regulations. The bottom-up methodologies rely heavily on average values of specific fuel consumptions and engine load factors. A case study which utilizes in-situ data is conducted to investigate the accuracy of the current approach and the results are compared with the estimates based on bottom-up approaches found in the literature. The findings revealed significant variations between the estimates and the actual fuel consumptions informing implications of unrealistic cost and emission estimates. As a solution the paper suggests a new concept in order to establish more reliable estimations of fuel consumptions and hence emissions predictions.

1. Introduction

Ocean is the highway for international maritime trade and shipping boasts to be the most efficient mode of carriage of goods in terms of fuel efficiency and emissions per tonne-mile (IMO, 2014; Merk, 2014). However, majority of ocean-going vessels consume high sulphur residual fuels. For the better part of last two centuries, the use of low quality marine fuels has contributed to accumulation of numerous pollutants in the atmosphere (Winebrake et al.; 2009; OECD/ITF, 2016) and major oil spills causing catastrophic consequences on planet's ecosystems. Marine emissions and their externalities on coastal populations and the environment have been a focal point of numerous studies (Joseph et al., 2009; Maibach et al., 2008; Starcrest Consulting Group, 2005; Corbett et al., 2007). Cumulative outcomes of such studies have resulted in strict marine emission regulations at local and international levels (Corbett et al., 2007; IMO, 2014; Dalsøren et al., 2009). International Maritime Organization (IMO) addresses pollution of atmosphere by marine emissions through Annex-VI of its convention for prevention of marine pollution (MARPOL). Since the declaration of Baltic Sea as an emission control area (ECA) in 2004, IMO has introduced stricter controls at a steady pace for the emissions of sulphur and nitrogen oxides (SO_X and NO_X). The recent declaration by IMO of 0.5% global sulphur cap, which is to take effect in 2020, is a stark reminder of an inescapable future of stringent emission regulations in the maritime industry. Presently, the industry is in continuous pursuit of potential alternatives to address present and future emission regulations. In this context, accurate estimations

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of marine fuel usage and their emission inventories are crucial to assess cost comparisons as well as emission inventories. Nevertheless, in the absence of comprehensive global data sets from individual vessels, maritime industry rely heavily on alternate methodologies to calculate approximate fuel usage and emission estimates. The paper discusses the basis and assumptions of such methodologies and their effectiveness. A case study is conducted to recognize the difference between results from such estimations and in-situ data collected over a 30 month period on a subject vessel.

1.1. *Estimating fuel consumptions for analysis of cost and emission components*

New emission regulations initiate the quest for compliance options, comparison of enduring economic feasibility between the alternatives and takes precedence in ultimate investment decisions. Be it calculating emission inventories and assessing external damages caused by marine emissions or carrying out emission/cost comparisons between alternative marine fuels, establishing accurate fuel consumptions are paramount for sound conclusions/strategies. Fuel consumptions are estimated using following approaches to determine fuel costs and emissions:

1.1.1. *Top-down approach*

This approach uses quantities of bunker supplies to a specific region to establish fuel consumptions of each vessel category (Tzannatos and Nikitakos, 2013; Merk, 2014). A major concern about this methodology is statistical difficulty in segregating fuel delivery to various vessel types in a region. Furthermore, since reporting of fuel bunker sales in some regions are not mandatory (Merien-Paul, et al., 2016), the figures from data bases may not always be representing accurate fuel consumption. Moreover, there is an inaccuracy of higher estimates for small countries which are key bunker supply hubs (Goldsworthy and Goldsworthy, 2015).

1.1.2. *Bottom-up or activity based approach*

Geospatial vessel traffic data is used to determine vessel movements (Algell et al., 2012; Psaraftis and Kontovas, 2009) and their respective estimated fuel consumptions to calculate fuel usage of vessels in a region (Merk, 2014; Goldsworthy and Goldsworthy, 2015). This approach (Fig. 4) involves assumptions and generalisations for the following parameters:

Fuel consumption of main engine:

- A bin category is assigned to a certain ship type and its dead weight range; a corresponding propulsion power in kilo watt (kW) is assigned to the vessel bin category.
- The operating load (engine load factor; as a percentage of maximum continuous rating or MCR) of the bin category is assumed as an average value based on vessel specifications obtained from a data base such as Lloyd's register fair-play (LRF). The operating engine load is further evaluated/changed according to slow-steaming or operating on reduced loads due to economic reasons.
- An average specific fuel oil consumption SFOC (in grams per kilo watt-hour or g/kWh) or a range is assigned to the given bin category based on available data from the vessel specifications (from a data base such as LRF).
- Operating period at sea is calculated from a data base of automatic identification system for ships (AIS) data or from a fleet data.
- Fuel consumption is calculated using above values a given ship type and its bin category.
- Fuel consumption of Main engine during manoeuvring periods are calculated assuming that engine load is to be a certain percentage of MCR and thereby using an average engine load factor or SFOC and aggregate time taken for manoeuvring.

Fuel consumption of auxiliary engines:

- The engine capacities of auxiliary engines (AE's) are considered as a percentage of installed main engine capacity depending on the vessel bin category (mainly based on vessel type).
- SFOC of AE's are taken as an average or a range from a data base.
- Auxiliary engine loads at sea, at anchorage and when in port (either idle or carrying out ballast/cargo operations) are assumed as average values from a common data base.
- Fuel consumptions of auxiliary engines are calculated with the above values for each mode of operation.

Fuel consumption of boiler:

- Fuel consumptions at sea, at anchor/port or during cargo operations are calculated in a similar manner as for AE's, using average boiler SFOC values from a common data base.

1.1.3. *Combined approach*

Some studies utilise a fusion of top-down and bottom-up approaches to establish fuel usage over a period of time for multiple regions where both methods may complement each other depending on availability of data. For example, IMO utilized top-down estimates in their initial studies from 2007 to 2011 and bottom-up approach in the latest GHG studies (IMO, 2014). While top-down methodology is considered to be less dependable as it rely on fuel sales in a region/country, bottom-up approach may produce overestimates consistently due to multitude of reasons (IMO, 2014).

1.2. Studies on fuel usage leading to cost estimates and comparisons

The feasibility of liquefied natural gas (LNG) filling infrastructure for north European ports has been studied by Danish Maritime Authority (2012). They allocated average SFOC's for vessel types and their sub-categories to estimate fuel consumptions based on vessel movements in the region. The estimated fuel consumptions were used to project future LNG demand in the region in order to determine infrastructure requirements and pertinent investments. They employed over 70 vessel sub-categories for their estimations probably with the intention of improving its accuracy. They also used direct energy conversion to estimate fuel consumptions between alternatives. This study, however, does not assess the accuracy of the results with comparison to any past or contemporary studies. Nor does it declare precise methodologies to describe how the concluding results were achieved.

Algell et al. (2012) assessed the feasibility of LNG fuelled propulsion in the Wider Caribbean region for four shipping segments and projected future LNG demand based on present fuel consumptions employing vessel traffic data from the regional marine pollution emergency information and training centre (REMPEITIC). The number of vessels in the study being limited to 90 and the project is IMO-initiated, access for actual fuel consumptions would not have been challenging for the authors. Therefore, the use of realistic data renders more legitimacy to their results. While the methodology they utilised was not discussed in detail, it appears that average fuel oil consumptions were converted to LNG energy equivalents. However, this raises the question for disregarding impact on energy requirements of individual fuels (for example, use of HFO onboard) and their processes on-board.

Livanos et al. (2014) assessed suitability of alternative propulsion concepts for a roll-on roll-off ferry (Ro-Ro Ferry) vessel among following configurations: (a) running on LSFO in ECA and on HFO outside ECA, and (b) dual fuel engines continuously running on LNG. Fuel consumptions were estimated using SFOC's, engine load factors and propeller law, depending on projected annual operating profile of HFO fuelled vessels. LNG consumptions were estimated by using energy conversion factors. Since the standard SFOC's are expressed in ISO ambient conditions, they have apparently increased the SFOC values by 3% for more accuracy to represent realistic operational conditions. Engine load factors have been considered to be ranging from 50% to 100%, however, local and seasonal weather conditions and their effect on engine load is not discussed. Although operating modes for the vessel have been defined, but how the engine load was differentiated for the various operating modes have not been elaborated.

Brynolf et al. (2014) used life cycle assessment for weighing pros and cons among following alternatives with regard to their environmental performance: (a) HFO fuelled propulsion combined with SCR and an open loop scrubber, (b) LSFO fuelled propulsion with SCR and (c) LNG fuelled propulsion. Engine load factor is taken as 85% and the SFOC value is assumed according to the fuel in use. Their study has shown the importance of accurately estimating fuel consumptions for life cycle assessment of a fuel or an alternative compliance method during seagoing mode. However, citing an SFOC value from a data base may not realistically capture the tangible technical and operational conditions of a vessel. Moreover, they also use direct energy conversion to estimate fuel consumptions between alternatives (for example HFO vs. LNG). This approach excludes energy demand by an individual fuel and its unique processes which may increase/reduce total fuel consumption for a particular alternative. For example, the energy used for the generation, handing and the disposal of sludge, which are inherent within the use of HFO on-board have been excluded in this study.

OECD/ITF (2016) considered capital, operational and voyage costs to conclude effectiveness of a variety of compliance options to reduce marine sulphur emissions. Fuel consumptions were projected using average SFOC's and load factors using *Institute of Shipping Economics and Logistics* (ISL) data base for the respective vessels' particulars and movements. The study portrays how global sulphur cap would impact trade, policy, regulations and compliance in shipping. They concluded that upcoming global sulphur cap will result in 20–85% cost escalations for shipping and may diminish the level playing field. The significant uncertainty was found to be due to questions on availability of low-sulphur fuels post 2020. However, any uncertainties arising due to use of average engine load factors and SFOC's are not factored in or mentioned.

The study on the capacity utilization by Adland et al. (2016) suggests the use of admiralty coefficient for displacement and vessel speed, to determine fuel consumptions using AIS data and bottom-up approach. However, in their empirical model for calculating fuel consumptions, vessel speeds are excluded due unavailability of data for specific voyages in their entire sample. As a results, the vessel speeds are assumed to be fairly constant throughout the study period. This is somewhat a robust assumption considering the varying weather patterns encountered by deep-ocean-going vessels.

MAN (2013) carried out a cost/benefit study for five representative box-ship sizes assuming costs for key compliant technologies with comparison to a reference vessel. They concluded that the use of natural gas will invariably reduce marine emissions and would reduce costs depending on (a) pricing structure between HFO and LNG, operational time in ECA's and (b) investment cost of on-board storage systems for LNG. Being a reputed engine maker with decades of expertise it would be prudent to assume that their fuel consumption estimates were based on solid data. However, they assumed the auxiliary engine power to be a fraction of main engine power. This manifests the use of representative values from their data based on statistical generalisation and not resorting to actual data from individual vessels. DNV-GL (2013) carried out a joint industry project on natural gas fuelled coastal shipping in Australia and explored its viability in terms of pay back periods based on differential capital and operational expenditures against conventional fuel oils. The methodologies and assumptions employed in the project are not well articulated in the report available to the public.

1.3. Emission estimates/comparisons

Tzannatos (2010) evaluated external-costs of ships' emissions at port of Piraeus using an activity based (bottom-up) scheme. Engine load factors corresponding to each activity have been used in order to capture power outputs specific to a vessel activity (such as manoeuvring, at anchor or alongside) and respective emissions. Vessel specifications have been referred to from Lloyd's Register Fair-Play (LRF) to estimate average load factors of main engines. Power output of auxiliary engines have been simply assumed to be

27.8% of installed propulsion power citing (Starcrest Consulting Group, 2005). They comprised a list of engine load factors upon a survey with local ship operators and affirmed that engine load factors could result in significantly higher estimates. As a solution they attempt to capture seasonal changes and their influence in engine loads. Determining load factors for main and auxiliary engines during in-port ship activities represents an area of characteristic uncertainty especially if they are to be assigned based on operators' assumptions in the absence of sound technical basis or actual data. Moreover, fuel consumption of boilers and their load demand variations have not been specifically expressed, nor it is mentioned if they are apportioned to auxiliary engine loads.

Merk (2014) used a similar approach to estimate emissions by ocean-going vessels in major ports from 2011 to 2050; albeit with classifying and segregation of more vessel categories and allocating respective load factors according to various vessel types and their corresponding dead-weights (DWT) from Lloyd's maritime intelligence unit (LMIU). Engine load factors for auxiliary engines have been assumed to be comparative fraction of propulsion power. The premise here is that increased vessel categories enable employing more consistent engine load factors thus reducing their uncertainties, and main engine power corresponds to that of vessel's DWT (Source: EPA 2000). However, how the auxiliary engine power is assumed as a definite fraction of main engine is not justified. Furthermore, boiler consumptions in port is not included or mentioned. (Psaraftis and Kontovas, 2009) assessed CO_2 emissions for the world commercial fleet using a comparable approach and employed vessel bin-categories to differentiate ship types. Data of 375 vessels were collected from ship owners (Hellenic Chamber of Shipping), and then statistically cross-referenced for the world fleet of over 45,000 ships to assign averages for the assumed vessel bin-categories. Such generalisation of statistical cross-referencing from a relatively small sample to a larger population raises concerns of uncertainties which has not been adequately addressed in their study.

DNV-GL (2015) used activity based methodology utilising AIS data to estimate emissions from ships operating in Sydney's greater metropolitan area. They determined vessel speed every sixth minute and estimate engine load according to propeller law in order obtain higher resolution of emission inventories. In this study, engine load factors have been assigned referring to vessel data bases and pertinent vessel specifications to determine fuel consumptions (by use of SFOC's) and emission inventories for main engines. DNV-GL does not reveal the criterion for selection of their estimations/projections methodology and the reservations involved. For example, (a) combined influence of sea conditions and vessel's hull/propeller efficiency on speed, and their relevant uncertainties are not elaborated, (b) use of statistical generalisations in the absence of engine data of vessels and their influence on final results.

Goldsworthy and Goldsworthy (2015) estimated emissions in Australia for 2010/2011 for 7125 vessels. They used AIS data and propeller law (cubic equations of engine power and vessel speed) for each AIS movement to derive respective engine load factors. Lloyd's registry's "*Seaweb*" database provided vessel specifications for their study. They assume that main engines operated at 85% MCR while a vessel's observed speed is closer to its service speed. Installed auxiliary engine power has been listed as a fraction of installed main engine power. Moreover, due to complexities arising out of classifying the tangible power usage of the auxiliary engines in the different operating modes, an overall engine load factor is assigned. Auxiliary boiler usage in various modes and their relevant load factors are assigned in a similar manner. The equation for propeller law can only be applied to identical running conditions and the constant (c) used will vary from one vessel to another. Moreover, actual measurements indicate that engine power (P) does not always follow the cube relationship with the vessel speed (V) for varying vessel sizes at different speeds (MAN Diesl & Turbo, 2015). For example, it is more realistic to use; for large, high-speed ships such as container vessels; $P = c\ V^{4.0}$, for medium-sized, medium-speed ships; $P = c\ V^{3.5}$ and for low-speed ships like bulk carriers and tankers; $P = c\ V^{3.2}$ respectively. Furthermore, the power delivered to the propeller is less than the power produced by the engine due to losses during transmission. Therefore, determining actual power produced by an engine and its actual fuel consumption is quite complicated using generalised assumptions.

Specialised vessel such as dredging, dynamic positioning, offshore support and tugs may show very less or no speed at all while operating on near-full MCR. It is difficult to estimate fuel consumptions and emissions of these vessels by bottom-up methodologies.

Tzannatos and Nikitakos (2013) measured external damage caused by exhaust emissions due to use of HFO by domestic passenger shipping in Greece from 2001 to 2010 and compared with potential reductions which could be achieved by switching to LNG. A top-down, methodology based fuel sales was used to calculate average fuel consumptions of the fleet and thereby emission inventories and their external costs. While the fuel sales figures were at their disposal for the study, since the quantity of bunker deliveries to passenger ships also included supplies to coastal cargo ships, fishing and recreational vessels, how the fuel consumptions were distinguished for the passenger vessels alone has not been well defined. Similarly, the methodology does not allow for individual emissions from main, auxiliary engines and boiler to be determined. Moreover, as Psaraftis and Kontovas (2009) stressed, how the inherent unreliability of this methodology and accompanying inaccuracies were addressed in their prediction model are not emphasized.

Dalsøren et al. (2009) observed the movements of over 32,000 ships and attempted to validate suitability and accuracy of activity based model using geo-spatial data for estimation of ship emissions. Specifications of installed machinery were taken from Lloyd's Register Fairplay-2004 to allocate engine load factors for the respective vessels. Since the specifications of main engines for 17% of the vessels were missing, their power outputs were estimated statistically based on available 83% of vessels data. Similarly, as 45% of vessels did not carry data of the auxiliary machinery, their specifications have been derived by cross-referencing of available 55% data. Moreover auxiliary boiler consumptions/emissions are not included/mentioned in their study. However, they supposedly improve the model's accuracy by increasing ship-types, segments and size-brackets or "*bin-categories*" in the fleet with a breakdown on 105 ship types/sizes; improving upon approaches by Eyring et al. (2005). Although increased ship-segmentation may improve the model, the uncertainty arising due to; (a) use of average engine load factors and assumed average SFOC's, (b) assigning engine load factors and SFOC's for missing data by cross-referencing are not addressed. Moreover, as the results are compared against the estimates of previous studies based on similar assumptions, one could argue that only the methodology is improved and there is not comparison against realistic data.

Schrooten et al. (2009) presented a modified activity based methodology to capture shipping emissions in European coastal cities/

ports from 1980 to 2005. They used a segmental model comprising of; (a) the fleet module, which defines ship categories according to their dead-weight (DWT) and engine specifications. That is used for estimating fuel consumptions. (b) The transport module, which defines ship movements and their respective time periods at sea, at berth, idling at anchor, etc., based on traffic databases. (c) The emission module estimates energy use and resultant emissions combining information from first two modules. For estimating fuel consumptions, SFOC's have been considered as a range of values for each machinery type which were obtained from the Lloyd's Register Fairplay data base. Average engine load factors have been assigned for main and auxiliary engines during respective operating modes based on assumptions by Entec (2005). However the operation of auxiliary boilers in various operating modes are not cited. The SFOC's which are assigned for "auxiliaries" are probably for auxiliary engines only as the range is between 200 and 235 g/kWh whereas SFOC of an auxiliary boiler should typically fall well above 300 g/kWh (Goldsworthy and Goldsworthy, 2015).

Lindstad et al. (2012) investigated potential reductions in cost and emissions in shipping and found that significant reductions of emissions could be achieved through economies of scale. Their fuel consumption estimate equation encompasses all operating modes such as sea speeds during loaded and ballast passages, slow zone/manoeuvring, waiting periods, and loading/discharging. Propeller law is used for power calculation according to vessel's speed and Lloyd's Fairplay database has been utilized for obtaining vessel specifications. Their methodology appears to assume common SFOC across the board for all operating modes irrespective of engine load. Although it is assumed to be included in the model, how the consumptions and emissions for auxiliary engines and boilers were achieved is not explained explicitly. Moreover, engine load factors for bulk carriers were assumed to be 0.95 for cargo voyages and 0.80 for ballast voyages respectively. These assumptions would have resulted in higher estimates since engine load factors for bulk carriers are observed to be about 0.5 due to slow-steaming trend after the global financial crisis in 2009.

Corbett and Koehler (2003) used 132 sub-groups for the emission estimates for a world fleet of 88,660 ships using Lloyd's Maritime Information System (LMIS), 2002. They assumed respective engine load factors of 55% and 80% for low freight rates and normal rates for bulk carriers. A fleet-wide SFOC of 206 g/kWh was assigned for all cargo ships. Main engine operation was assumed to be 6500 h per annum and auxiliary engines were assumed to operate 3500 h per year on average at 50% load for their estimates. For ocean going ships, auxiliary engines typically operate continuously to support electrical and domestic requirements while main engines operate during manoeuvring and at sea. Therefore, assigning more operating hours for main engine compared to auxiliaries is a concern which has not been justified in their methodology. The typical SFOC for a slow speed diesel engine is about 165–195 g/kWh and that of a medium/high speed engine is about 213–227 g/kWh (USEPA, 2009; Starcrest Consulting Group, 2005; Starcrest, 2007). Thus, assigning a fleet-wide average of 206 g/kWh for all main/auxiliary engines is a significant issue which has not been reasoned with.

1.4. Summary of the above study; what is missing and what can be improved?

Technological advances such as AIS provide vessel movement and databases containing specifications of the world fleet continue to improve accuracies of estimations based on bottom-up methodologies. However, the influence of following key elements still remains to be the main factors for determining acceptable estimations of fuel consumptions.

- Assigning average engine load factors and average SFOC's directly from vessel databases or assigning average engine load factors and SFOC's based on fleet operator response and/or best estimates from cross-referencing/statistical representation.
- Use of propeller law or admiralty coefficient to determine engine power and fuel consumptions.

Hjelle and Fridell (2012) stressed the importance of representative engine load factors and accurate vessel speeds for achieving convincing estimates and carrying out comparative analysis. The general tendency for achieving more accuracy is to increase bin-categories for vessel types and assigning different average engine load factors for respective operating modes. The basic assumption here that such practice would near-represent actual fuel consumptions/emissions. As Corbett and Koehler (2003) noted, engine load factors and days at sea remain the most sensitive input parameters to activity based modelling; Dalsøren et al. acknowledged that their study had not made any fundamental improvements on these factors. The fundamental reason for this predicament could be due to the accuracy of these estimates are compared against previous estimates based on the same methodology, but not against actual data obtained from individual vessels. When estimates based on similar assumptions are compared against each other, the deviations may normally fall within their assumed boundaries giving a sense of self-fulfilling accuracy. Therefore, such estimates should be pitted against results based on actual data for a realistic comparison. However, such comparisons are absent in contemporary literature. As an attempt to address this knowledge gap, a case study is conducted using data collected over a 30 month period on a bulk carrier. The actual data is then compared against hypothetical estimates based on activity based modelling found in literature. Such a comparison will provide importance of cross-checking bottom-up estimates with in-situ data and impetus for further studies of this nature for more vessel categories. Section 2 explore the issues/challenges involved in using average engine load factors and SFOC's in activity based modelling in practice. Section 3 involves the case study and the relevant hypothetical estimates and comparisons followed by findings and discussion in Section 4, and conclusion/future work in Section 5.

2. Drawbacks of using average engine load factors and SFOC's for estimation of fuel consumptions

2.1. Estimation of fuel consumptions

A common feature of top-down, bottom-up methodologies is the fact that they allocate average values for specific fuel

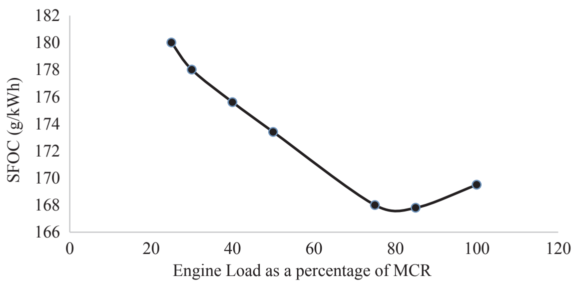

Fig. 1. SFOC vs. Main Engine load.
Source: From in-situ data, Engine: MAN B&W 6S 70MCC, 16,700 kW.

consumptions (SFOC's) and engine load factors for the vessels involved to estimate fuel consumptions. The average SFOC's are obtained from data bases such as LRF, maritime shipowners online data-base (IHSF), Seacrest's vessel boarding program (VBP), International comprehensive ocean-atmospheric data set (ICODAS) and Automated mutual-assistance vessel rescue system (AMVER) for respective vessel categories to establish fuel consumptions for various phases of a vessel's activities (IMO, 2014; Tzannatos, 2010; Merk, 2014; Corbett et al., 2007). Due to a combination of reasons, i.e. utilisation of average fuel consumptions and bottom-up and top-down methodologies, there are significant variances (overestimates and underestimates) in the outcomes of these two approaches. Therefore they tend to predict either significantly high or low fuel consumptions which consequently result in erroneous estimates of operational expenditure and emissions. The outcomes are often presented as a range of values from low, mid to high or with sensitivity values to represent the uncertainties (Bradley, 2017). Such uncertainties reflect and influence on the accuracy of cost-benefit outcomes and emission externalities. IMO (2014) found a difference of 78 million tonnes between annual aggregate fuel consumption estimates deduced by two approaches from 2007 to 2012, which was a substantial difference of 24% of the higher value.

2.1.1. *Specific fuel oil consumption (SFOC) and its fluctuations in practice*

SFOC refers to amount of fuel oil consumed by an engine in grams for one kilo-Watt hour of energy produced. SFOC's for an engine is first measured at a test-bed to determine respective values at different engine loads; this procedure is commonly referred to as "*Shop Trials*". Results of the shop-trials, i.e. SFOC values, are then corrected to ISO[1] conditions for standardisation.

It should be noted that SFOC values differ not only between different engine makers, but amongst different engine models from the same maker, and also within a series of same models with same power output rating. Furthermore, SFOC follows a polynomial correlation (Fig. 1) with engine load and therefore cannot be interpolated using a reference value to determine values for idling, slow-steaming and cruising for main engines. Similarly those of auxiliary engines will differ from idling at anchor, operating at port or used at sea. Vessel speed reduction due to charter party requirements or owners policies are carried out in order to optimize fuel consumption and maintain competitiveness. Since different vessel speeds are achieved at different main engine loads (engine load factors), respective SFOC's and therefore daily fuel consumptions will differ.

Apart from the design perspective, there are other factors that will influence SFOC and daily fuel consumptions of an engine. Thus, appointing common load factors based on vessel types (their installed power and respective dead-weights) irrespective of the explicit characteristics of their engines and the conditions in which the vessels are operated will yield significant uncertainties. For example, SFOC of a vessel at a certain load will differ significantly over time due to its condition of hull and propulsion machinery. Such deviations of SFOC measured at 85% of MCR over a 30 month period are shown in Fig. 2.

Moreover, ocean current, wind, swell conditions and other natural phenomena affecting engine load cannot be determined by AIS data. They will be reflected upon individual daily fuel consumptions of a given vessel. For example, if vessel's speed is used to calculate main engine power output based on propeller law or admiralty coefficient, the basic assumption is that the vessel operates in ideal sea conditions. However, when the vessel's speed changed due sea conditions and/or efficiency of hull/propeller, the resulting calculations will lead to under or over estimations of fuel consumptions. A representation of factors which affect SFOC and daily fuel consumptions are summarized in Fig. 3.

DNV-GL (2015) emphasized the significance of uncertainties arising due to use of averages in their disclaimer which insinuated that there is a significant difference between "*estimated*" values and "*actual*" values and stressed the need for comparing results of estimations with those obtained from in-situ measured data. Similarly, EPA NSW (2015) stressed the importance of improving "*evidence base*", upon which calculations/estimations of fuel consumptions and ship emissions are modelled. The reliability of the models and their estimates are to be verified continuously with actual data. Such verifications should be followed by modifications to the model as and when required so that its estimations/calculations will be more rational and dependable.

In the absence of in-situ data and practical difficulties in collecting a vast amount of data required from thousands of vessels, present studies tend to rely heavily on activity based (bottom-up) modelling for estimates. Moreover, there have been attempts to improve top-down methodologies (IMO, 2014; Dalsøren et al., 2009) to refine the processes in order to achieve reliable accuracies. It is obvious that the lack of access to specific data and fuel consumptions for each individual vessel and its trading patterns, loading

[1] ISO: International Standards Organisation. ISO conditions are pre-determined ambient conditions for shop-trials of marine engine installations as defined by respective ISO standards.

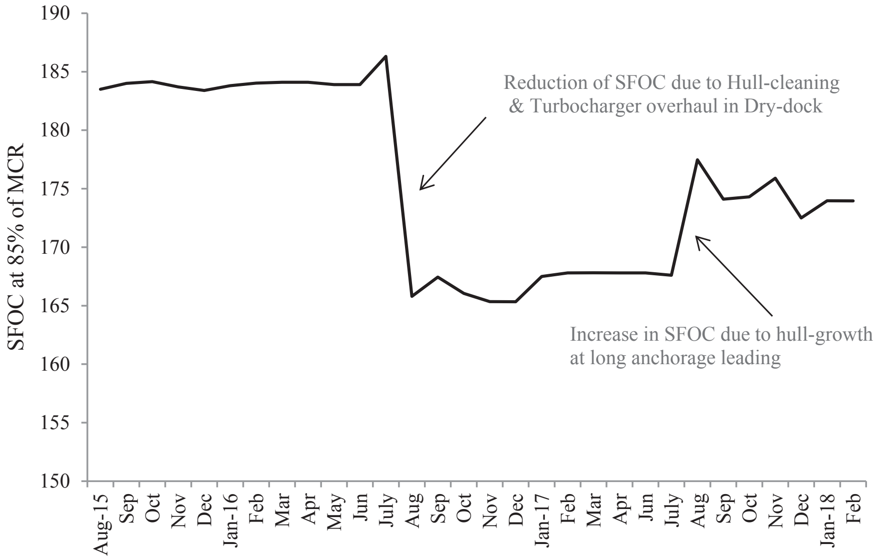

Fig. 2. Variation of SFOC at 85% of MCR measured over 30 months.
Source: from in-situ data, Engine: MAN B&W 6S 70MCC, 16,700 kW.

characteristics of main and auxiliary engines would necessitate resorting to obtain acceptable range of average values from a representative data base.

3. The case study

3.1. Goal, scope and methodology

This study endeavours to emphasize the importance of using in-situ data for calculating fuel consumptions of marine machinery during various operation modes of a vessel. A comparison between in-situ data and fuel consumption estimates produced by bottom-up methodologies which are found in literature is carried out. A comparison between actual (in-situ) and estimated consumptions are presented and the findings are analysed/discussed in preceding sections. Such an approach will facilitate estimation of accurate emission inventories as well as cost comparisons.

Fuel consumption data of a bulk carrier which plies between Australia and Far-East is collected over 30 months for the case study for each operational mode. The main characteristics of the chosen ship are indicated in Table 1.

The chosen vessel is engaged in international voyages, in which it crosses equator and encounters varying weather patterns and seasonal changes in the oceans. A period over 30 months represents winter, summer and relevant changes in sea conditions in which the vessel operates. Such variations will be represented by the vessel's fuel consumption and speed over time. Moreover, this period allows capturing influence on fuel consumption due to deterioration of hull and machinery conditions over time and their respective improvements gained during dry-docking of the vessel as indicated in Fig. 2. Moreover, the number of cape-size bulk carriers in the world fleet and their distribution represent a considerable portion of fuel consumption and emission inventories.

Using the actual operational times and technical specifications of vessel's machinery, fuel consumptions are estimated/calculated using assumptions and methodologies discussed in literature. Only the bottom-up (or activity based) methodology is compared with the findings from the actual data. Top-down or methodology based on bunker fuel sales are not considered for the study as the approach is found to be highly unreliable (Goldsworthy and Goldsworthy, 2015; IMO, 2014) for estimates of emissions and cost related studies.

3.2. In-situ data

In-situ data refers to actual data collected on-site on a continuous basis for all operating modes. When such data are collected on a ship, the variations of vessel's engine load factors, SFOC's and their influence on fuel consumptions will be captured over a period of time for all operating modes.

3.2.1. Main engine

Table 2 represents time duration and fuel consumptions by main and auxiliary machineries for respective operational modes. The seagoing mode represents 12,894 h; which is about 58% of the total operational hours. Calculated actual SFOC was found to be 178.70 g/kWh, for an average engine load factor of 51.21% of MCR for the sea-going mode. However, if shop-trial data are referred, the corresponding SFOC should read as 172.8 g/kWh at 51.21% of MCR.

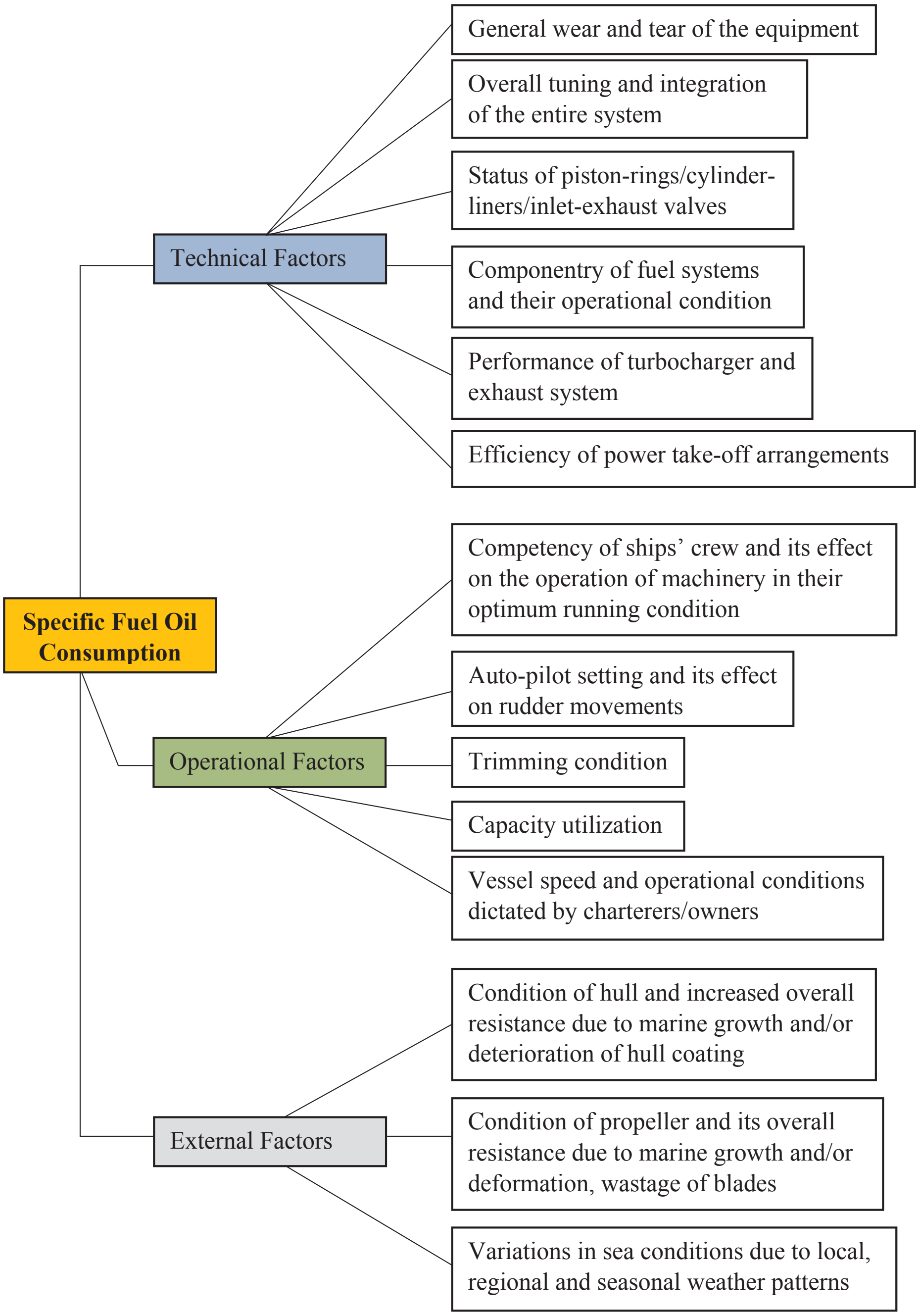

Fig. 3. Factors affecting SFOC.
Source: Authors' industry experience, MAN Diesel (2015), Adland et al. (2016), Prakash et al. (2016).

3.2.2. Auxiliary engines and boiler

The subject vessel has three generator engines with an aggregate output of 1800 kW. The average load at sea was found to be 360 kW. This corresponds to an engine load factor of 0.6 at sea with a corresponding SFOC of 232.5 g/kWh based on in-situ data. However, as per shop-trial results, SFOC at 60% engine load factor should be 216.67 g/kWh.

3.3. Hypothetical fuel consumptions based on bottom-up (activity based) methodologies

Fig. 4 illustrates the conceptual approach involved in bottom-up (activity based) methodology. The core concept of the approach is to; (a) obtain installed power of the main engine and assign load factors for its operational modes at sea, and (b) assign auxiliary

Table 1
Characteristics of the subject vessel.

Ship Type		Cape-size Bulk carrier of Dead weight (DWT): 181,381 tonnes		
Dimensions		Length Overall	Breadth	Depth
		291.98 m	45 m	24.7 m
Speed		MCR	NSR[*]	Slow-steaming
	Laden	N/A	15 Knots	10 Knots
	Ballast	N/A	16 Knots	11 Knots
Main Engine		MCR (100% load)	NSR (85% Load)	Slow-steaming (51% load)
		16,700 kW at 87 RPM[a]	14,195 kW at 82.4 RPM	8517 kW at 69 RPM
Fuel Consumption				
"In-situ" Data	Tonnes/day	N/A	56.4–63.5	36.5
	SFOC	N/A	165.4–186.3 g/kWh	178.7 g/kWh
"Shop-Trial Data"	Tonnes/day	67.6	56.4	35.3
	SFOC	168.7 g/kWh	165.7 g/kWh	172.8 g/kWh
Auxiliary Power		**Generator Engines**	**Oil Fired Boiler**	
		(03 × 600) kW total	1300 kW at 0.6 MPa	
Fuel Consumption				
"In-situ" Data	At Sea	2.9 tonnes/day	N/A	
	Drifting	1.9 tonnes/day	1.3 tonnes/day	
	Port	2.5 tonnes/day	1.4 tonnes/day	
	Anchor	1.9 tonnes/day	1.4 tonnes/day	
	SFOC	232.5 g/kWh at 360 kW		
"Shop-Trial Data"	SFOC	216.7 g/kWh at 360 kW		

[a] MCR: maximum continuous rating, NSR: normal service rating, RPM: Revolutions per minute.

Table 2
Fuel consumption data collected from the subject vessel for 30 months.

Operational mode	Time (h)	HFO (tonnes)			DO (tonnes)	
		Main engine	Aux. engine	Boiler	Aux. engine	Boiler
At Sea	12,894	18,718	1581	N/A	41	N/A
Drifting	473	N/A	37	25	1	N/A
At Port	3682	N/A	389	212	29	3
At Anchor	4326	N/A	348	245	16	N/A
Manoeuvring	551	438	62	15	2	N/A
Total	21,926	19,156	2417	497	89	3

engine power based on assumed installed main engine power. If propeller law/admiralty coefficient is used for estimating main engine power at sea, a load factor for sea-going mode is assigned to estimate total installed main engine output (Goldsworthy and Goldsworthy, 2015; Lindstad et al., 2012). We apply frameworks/assumptions adopted by following authors to the conceptual approach for calculating hypothetical fuel consumptions for the 30 month case study period of the chosen vessel.

1. Merk (2014)
2. Dalsøren et al. (2009)
3. Schrooten et al. (2009)
4. Goldsworthy and Goldsworthy (2015)
5. Corbett and Koehler (2003)

The assumed installed powers, SFOC's and load factors are presented in Tables 3 and 4 for respective machineries. Thereafter, calculated hypothetical fuel consumptions are compared against the in-situ data in Table 5.

Merk (2014) estimated emissions of shipping within port by using bottom-up methodology adopted by Joseph et al. (2009). In view of their assumptions, installed horsepower of main engine for a bulk carrier is assumed to be:

$$P_{me} = (0.0985.\ DWT) + 6726 \tag{1}$$

where P_{me} is installed main engine horsepower, DWT is the dead weight of the subject vessel.

Applying these assumptions to subject vessel, the hypothetical installed power for the main engine is obtained as 18,252 kW instead of actual main engine output of 16,700 kW. Since they assume that total power of auxiliary engines is to be 22.2% of the installed main engine output, the hypothetical auxiliary power would be 4052 kW instead of actual 1980 kW. Auxiliary engine loads

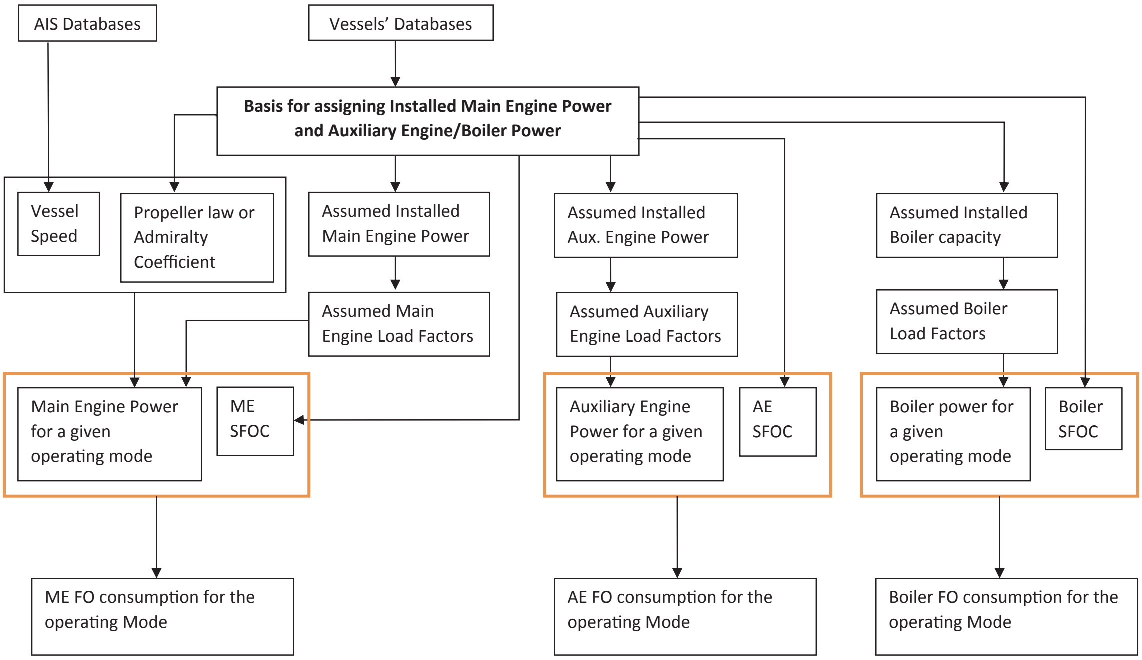

Fig. 4. Conceptual approach for calculating fuel consumptions in bottom-up methodology.

Table 3
Assumed SFOC's and engine load factors for main engine.

Authors	Main engine			
	SFOC (g/kWh)	Installed power (kW)	ELF at sea	ELF manoeuvring
Merk (2014)	N/A	18,252	N/A	N/A
Dalsøren et al. (2009)	196	16,700	0.70	**
Schrooten et al. (2009)	188	16,700	0.80	0.0765
Goldsworthy and Goldsworthy (2015)	195	16,700	0.70	0.2
Corbett and Koehler (2003)	206	16,700	0.55	N/A

** Incorporated into "at-Sea" mode.

Table 4
Assumed SFOC's and engine load factors for auxiliary engines.

Authors	AE Engines						Boiler	
	Assumed Power (As a % of ME)	ELF[a] At Sea	ELF Manvrng.	ELF Anchor	ELF Port	SFOC (g/kWh)	Estimated (kW)	SFOC (g/kWh)
Merk (2014)	22.2	0.22	0.1	0.1	0.1	216.67	N/A	N/A
Dalsøren et al. (2009)	15	0.15	0.2	0.2	0.2	222	N/A	N/A
Schrooten et al. (2009)	30	0.3	0.5	0.4	0.4	210	N/A	N/A
Goldsworthy and Goldsworthy (2015)	22.2	0.17	0.45	0.22	0.22	227	109	305
Corbett and Koehler	N/A	0.55	N/A	N/A	N/A	206	N/A	N/A

[a] ELF: engine load factor.

for port/anchor/manoeuvring activities were assumed to be 10% of the installed main engine power; therefore the hypothetical loads would be 1825 kW for respective activities instead of actual 1670 kW. As the SFOC for auxiliary engine are referred to data bases, the shop trial figure of 216.67 g/kWh is assumed hypothetically. Once the average auxiliary power for an operating mode and the total time duration are known, the fuel consumption is calculated by;

$$Fuel_{Con} = Power_{Av}.\ Time_t.\ SFOC \tag{2}$$

where $Fuel_{Con}$ is the total fuel consumption for a given activity, $Power_{Av}$ is the average auxiliary power (in kW) for the activity, $Time_t$ is the total time duration for the activity in hours and SFOC is the specific fuel oil consumption in g/kWh for auxiliary engines taken

Table 5
Actual fuel consumptions vs. hypothetical estimates in tonnes.

		In-situ data	Merk (2014)	Dalsøren et al. (2009)	Schrooten et al. (2009)	Goldsworthy and Goldsworthy (2015)	Corbett and Koehler (2003)
Main Engine	At Sea	18,718	N/A	30,806	32,386	29,393	30,747
	Manoeuvring	438	N/A	N/A**	132	359	N/A
Aux. Engines	At Sea	1581	N/A	1122	4070	1845	811
	Manoeuvring	62	218	46	290	209	N/A
	Port	389	1457	410	1550	682	N/A
	Anchor	348	1711	482	1821	801	N/A
	Drifting	38	N/A	85	149	68	N/A
Boiler	Manoeuvring	15	N/A	N/A	N/A	18	N/A
	Anchor	245	N/A	N/A	N/A	144	N/A
	Drifting	25	N/A	N/A	N/A	16	N/A
	Port	212	N/A	N/A	N/A	122	N/A

N/A** (included in "at-Sea" estimates as per respective assumptions by Dalsøren et al., 2009).

from a vessel data base.

Dalsøren et al. (2009) assumed main engine load at sea to be 70% of the installed power, and auxiliary engine power to be 15–20% of installed propulsion power. Since vessel data bases are used for reference, installed main engine power is taken as 16,700 kW. However, as the assigned SFOC's according to their vessel categorisations, SFOC of the main engine is taken as 196 g/kWh and that of auxiliary engine was taken as 222 g/kWh respectively (Tables 3 and 4). Such assumptions would result in estimations of 2505–3340 kW of auxiliary power for the subject vessel. They did not estimate fuel consumption of main engine for manoeuvring mode and instead included them in the respective sea-going leg by default. As a result, the hypothetical fuel consumption for seagoing mode of the subject vessel for 30 month period is calculated as:

$$Fuel_{me}^{sea} = ELF_{me}^{sea}.\ P_{me}.\ Time_{sea}.\ SFOC_{me} \tag{3}$$

where $Fuel_{me}^{sea}$ is fuel consumption of main engine at sea for 30 months, ELF_{me}^{sea} is the main engine load factor at sea, $Time_{sea}$ is the time spent at seagoing mode in hours and $SFOC_{me}$ is the assumed specific fuel oil consumption for main engine in g/kWh. In a similar manner, hypothetical fuel consumptions are calculated for auxiliary engines for respective activities.

Schrooten et al. (2009) declared a range of SFOC's between 157 and 218 g/kWh for slow speed marine engines and range of 185–235 g/kWh for medium to high speed marine engines respectively. The load factor of main engine was assumed to be 80% of installed power during sea passage. Citing Starcrest Consulting Group (2005), they used engine load factors of 3.7–11.6% for manoeuvring of bulk carriers. Other relevant load factors have been utilised from engine load factor table indicated in European Commission (2005) for their calculations. This study has derived average SFOC's for main engine, 188 g/kWh and for auxiliary engine, 210 g/kWh for hypothetical estimates based on above ranges. Installed main engine power for the subject vessel was taken as actual of 16,700 kW as they referred to vessel databases. Auxiliary power was assumed to be 30% of the main engine installed output; resulting a hypothetical figure of 5010 kW instead of actual total auxiliary engine power of 1800 kW.

Goldsworthy and Goldsworthy (2015) assigned a bin category for bulk carriers above 75,000 gross tonnage and assumed load factors/SFOC's from a number of sources for auxiliary engines and boilers. SFOC of main engine for the subject vessel's bin category was assumed to be 195 g/kWh. Engine load factors for main engine operation have been calculated using AIS data and cubic law equations (propeller law) for a ship using fixed pitch propeller;

$$p = c.\ u^3 \tag{4}$$

$$LF = p/p_{max} = (u/u_{max})^3 \tag{5}$$

where p is power delivered to the propeller, c is a constant, u is vessel's speed, LF is the engine load factor, p_{max} is the power at the maximum continuous rating (MCR) and u_{max} is the speed at MCR. Fuel consumption at sea is then estimated as;

$$Fuel_{me}^{sea} = ELF.\ p_{max}.\ Time_{sea}.\ SFOC \tag{6}$$

where $Fuel_{me}^{sea}$ is fuel consumption of main engine at sea for 30 months, ELF is the main engine load factor at sea, $Time_{sea}$ is the time spent at seagoing mode in hours and $SFOC$ is the assumed specific fuel oil consumption for main engine in g/kWh.

Installed main engine power was taken as 16,700 kW since they used for Lloyd's database for reference. An average main engine load factor of 0.7 was used for hypothetical estimates. Using USEPA (2009) as reference, Auxiliary engine power has been assumed to be 22.2% of the installed main engine output. For the manoeuvring mode where main engine load is below 20%, they adopted low-load adjustment factors for calculations (Tables 3 and 4). Boiler is assumed to be operating with an SFOC of 305 g/kWh with a 109 kW energy demand for all modes except the sea-going leg where waste heat recovery system is in operation.

Corbett and Koehler (2003) assigned a fleet-wide SFOC of 206 g/kWh for commercial ships and 6500 operating hours/annum at an engine load factor of 0.55 for low freight rates for bulk carriers. Auxiliary engines were assumed to be operating 3500 h/annum at an engine load factor of 50%. For example, the hypothetical fuel consumption of main engine for the subject vessel for 30 month period is calculated as:

$$Fuel_{ME} = ELF_{ME}.\ P_{ME}.\ Time_{sea}.\ SFOC_{ME} \tag{7}$$

where $Fuel_{ME}$ is fuel consumption of main engine at sea for 30 months, ELF_{ME} is the main engine load factor at sea, $Time_{sea}$ is the time spent at seagoing mode in hours and $SFOC_{ME}$ is the assumed specific fuel oil consumption for main engine in g/kWh. In a similar manner, hypothetical fuel consumptions are calculated for auxiliary engines for the respective period.

Fuel consumed by oil-fired boilers during the respective activity modes are not indicated/mentioned separately in above literature (except for Goldsworthy and Goldsworthy, 2015). We may assume that fuels consumed by boilers are included in the estimations of consumptions by auxiliary engines (or auxiliary power). Accordingly, estimates of boiler consumptions are carried out only for Goldsworthy's approach. All studies have assumed the auxiliary power installed on the vessel category to be a fraction of total propulsion power installed. A combined representation of the assumptions of SFOC's engine power outputs and engine load factors are illustrated in Tables 3 and 4

4. Findings

The in-situ data and respective hypothetical fuel consumption estimations for a capesize bulk carrier (189,000 DWT) based on bottom-up methodologies are tabulated in Table 5.

Schrooten et al. (2009) assigned engine load factor of 0.8 for main engine at seagoing mode and an SFOC value of 188 g/kWh compared to 0.51 for engine load factor and SFOC value of 178.7 g/kWh from in-situ data. The main culprit here for the deviation is assuming a higher engine load factor accompanied by a higher SFOC value. Similarly, Dalsøren et al. (2009) and Goldsworthy and Goldsworthy (2015) allocated an engine load factor of 0.7 for seagoing mode and higher SFOC values of 196 g/kWh and 195 g/kWh respectively for their estimates.

Merk (2014) assigning installed power based on DWT which gives installed power of 18,252 kW instead of actual power of 16,700 kW. As auxiliary power is assumed to be 22.2% of installed power, hypothetical auxiliary power is taken as 4052 kW in place of actual auxiliary power of 1800 kW. Auxiliary power and fuel consumptions calculations for each operating modes are based on the inflated hypothetical values, where the final estimates deviate considerably from those of in-situ data. Many vessels have opted to operate on reduced load (slow-steaming) after the financial crisis in 2008. Especially, bulk carriers follow the practice of super slow-steaming where main engine load is reduced to 50% of MCR or even lower to remain competitive. Even though Corbett and Koehler (2003) assigned a low engine load factor of 0.55 considering reduced freight rates during economic downturn, since they assigned a fleet-wide SFOC of 206 g/kWh instead of actual values. Consequently, significant deviations of estimates are observed in comparison to in-situ data. Therefore, although the estimates may be substantiated as indicated by Dalsøren et al. (2009), by comparing with one another based on similar methodology, they should be further verified with in-situ data. Over 90% of fuel consumption is observed at sea (Fig. 4) use average values for SFOC's and engine load factors which invariably tend to result in inconsistent estimates.

4.1. HFO consumptions by main engine

The estimates by Schrooten et al., Dalsøren et al. (2009), Corbett and Koehler (2003) and Goldsworthy and Goldsworthy (2015) are found to be, 73%, 65%, 64% and 57% higher compared with the fuel consumptions of in-situ data as shown in Fig. 5. The fuel consumptions by bottom-up estimates range between 29,393 and 32,386 tonnes, which are close to each other as the data bases and conceptual assumptions on which their approaches are built upon are reasonably similar. Nevertheless, when compared with the key values obtained from in-situ data, the source of such significant deviations can be comprehended.

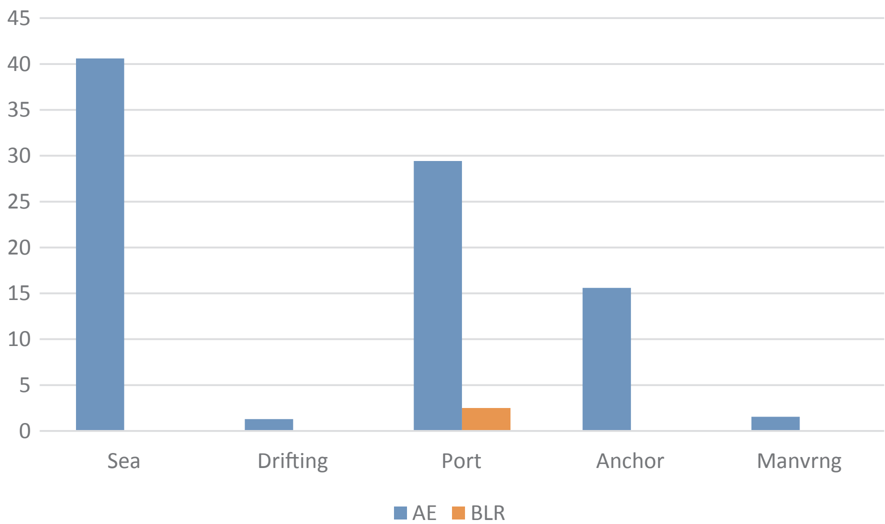

Fig. 5. MDO consumptions by Auxiliary Engines and Boiler (from in-situ data).

4.2. HFO consumptions by auxiliary engines

For all operational modes, estimates based on assumptions by Schrooten et al. are noted to be significantly higher compared with in-situ data for “at sea” mode. The estimates by Corbett and Koehler (2003) are found to be lowest due to their assumed annual operating hours for the auxiliary engines. The discrepancies between in-situ data and estimates for the operational modes do not follow a similar pattern to that of at-sea mode. This is probably due to larger variations in assumed auxiliary power outputs in relation to installed propulsion power and subsequent load factors for operational modes (Table 3). Bulk carriers typically experience lengthy anchorage and port durations resulting significant fuel consumptions by their auxiliary engines. Therefore, sizable variances in assumed load factors between estimation approaches are likely to affect aggregate fuel consumptions produced by their estimates.

4.3. HFO consumptions by auxiliary boiler

It is assumed that fuels consumed by boilers are included in consumptions by auxiliary machineries. However, such inclusions and their methodologies are not elaborated in the studies. Considering that boilers are extensively in use while vessels are at anchor and alongside in port, their fuel consumptions and emissions cannot be neglected. It is noted that fuel consumed by boiler at port and in anchorage are significantly higher for in-situ data compared with estimations by Goldsworthy and Goldsworthy (2015) (Table 5).

4.4. Marine diesel oil (MDO) consumptions found by in-situ data

During the 30 month study period, 88.49 tonnes and 2.5 tonnes of MDO have been consumed by auxiliary engines and boiler respectively (Fig. 5). The use of MDO is required by auxiliary engines during their starting, stopping operation and/or during maintenance of HFO feed systems. This aspect has not been considered in the current literature and in their estimates except for Corbett and Koehler (2003) who assigned average consumption rates based on vessels categories and their engine types, and Goldsworthy and Goldsworthy (2015) based on engine size. Moreover, such use of MDO cannot be incorporated in bottom-up methodology assumptions as vessel specifications may not always include relevant information. Considering the cost of MDO and the potential inventory of emissions, the aggregate of 90.99 tonnes shown in Fig. 5 is a significantly non-negligible quantity.

5. Conclusion and future work

In response to concerns of steady growth of maritime transportation leading to ever increasing fuel usage and emissions, numerous regulatory, operational and technical strategies are in place for limiting harmful effects of marine emissions. Therefore, accurate estimation of fuel consumptions/emissions is essential for assessing effectiveness of such strategies. This study investigated the fuel consumption of a ship through a case study considering a capesize bulk carrier of 186,000 DWT using in-situ data against the commonly used estimates from bottom-up approaches. Noting that there were 1437 bulk carriers similar to that of subject vessel category in service as of 1st January 2016, wherein their aggregate fuel consumptions/emissions represent a substantial quantity.

It is noted that use of fleet-wide averages for engine load factors and SFOC’s in conjunction with generalised assumptions to estimate fuel consumptions (using bottom-up methodologies) produced significant deviations for the subject vessel when compared with in-situ data. For the seagoing mode, the estimates by bottom-up approaches are found to be 57–73% higher in comparison to in-situ data. Considering the significant amounts of fuel consumed by this vessel category at sea, when fuel consumptions are estimated using bottom-up methodologies for emission inventories and cost estimates, the resulting discrepancies are substantial. Hence, it must be emphasized that future decisions of emission strategies and operational expenditures based on such estimations should be revisited and thoroughly scrutinised against actual data. In view of a future where emission regulations are becoming more stringent and right compliance options are to be chosen for long-term cost effectiveness, improvements have to be made constantly to achieve better and more accurate estimates with available data.

Considering and acknowledging the discrepancies and their influence on outcome of potential cost comparisons and emission estimates, use of vessel-specific activities and direct vessel observations to the greatest practical scope should be the way forward. A combination of bottom-up approach using geo-spatial inputs and in-situ data will present an accurate dynamic picture of real fuel consumptions and emission dispersions for a vessel’s position and its operations. However, further studies/comparisons are needed to be carried out for different vessel types and their respective sub-categories using in-situ data. Recent European Union mandates under Regulation EU-2015/757 and, IMO requirements under Regulation 22A (MEPC70) which enforced mandatory vessel reporting are a step in the right direction for computing accurate fuel consumptions and emission dispersions. European scheme intends to publicise data collected on vessels in their territorial waters while the IMO’s data collection system encompasses the global fleet, but will only publicise anonymised data. Therefore, these two regulations may need to evolve to be more transparent and comprehensive to produce reliable and publicly available data in order to calculate fuel consumptions and accomplish accurate cost and emission-dispersion estimates. Although it would require more sophistication and additional resources, fuel consumption and emission estimates would reach accuracy only if they are based on individual ships, their movements and corresponding fuel consumptions.

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References

Adland, Roar, Jia, Haiying, Strandenes, Siri P., 2016. The determinants of vessel capacity utilization: the case of Brazilian iron ore exports. Transport. Res. Part A: Policy Pract.

Algell, Johan, Bakosch, Alexandra, Forsman, Björn, 2012. IMO Feasibility Study on LNG Fuelled Short Sea & Coastal Ships in Wider Caribbean Region. IMO.

Bradley, Stuart, 2017. Targeting a 30% Improvement in Fuel Efficiency for Marine Vessels. Energy Technologies Institute.

Brynolf, Selma, Magnusson, Mathias, Fridell, Erik, Andersson, Karin, 2014. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transport. Res. Part D: Transp. Environ. 28, 6–18.

Corbett, James J., Koehler, Horst W., 2003. Updated emissions from ocean shipping. J. Geophys. Res.: Atmos. 108 (D20).

Corbett, James J., Winebrake, James J., Green, Erin H., Kasibhatla, Prasad, Eyring, Veronika, Lauer, Axel, 2007. Mortality from ship emissions: a global assessment. Environ. Sci. Technol. 41 (24), 8512–8518.

Dalsøren, S.B., Eide, M.S., Endresen, Ø., Mjelde, A., Gravir, G., Isaksen, I.S.A., 2009. Update on emissions and environmental impacts from the international fleet of ships. Atmos. Chem. Phys. 9, 2171–2194.

Danish Maritime Authority, 2012. Nort EU Ports LNG filling Station Infrastructure Feasibility Report.

DNV-GL, 2013. JIP on LNG Bunkering in Australia DNV & Partners 2013.

DNV-GL. 2015. Emissions from Ships Operating in the Greater Metrolitan Area-NSW DNV-GL study. In: NSW EPA Ship Emissions Study. NSW.

Entec, UK, 2005. Ltd. European Commission Directorate General Environment: Service Contracts on Ship Emissions: Assignment, Abatement and Market-Based Instruments. Entec UK Ltd, Newcastle-Upon-Tyne, UK.

EPA NSW, 2015. Diesel and Marine Emissions Management Strategy. Government of NSW, Sydney.

European Commission, 2005. Service Contract on Ship Emissions: Assignment, Abatement and Market based Instruments. European Commission, UK.

Eyring, V., Köhler, H.W., Lauer, A., Lemper, B., 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. J. Geophys. Res.: Atmos. 110 (D17). http://dx.doi.org/10.1029/2004JD005620.

Goldsworthy, Laurie, Goldsworthy, Brett, 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data–an Australian case study. Environ. Modell. Softw. 63, 45–60.

Hjelle, Harald M., Fridell, Erik, 2012. When is short sea shipping environmentally competitive? In: Environmental Health-Emerging Issues and Practice. InTech.

IMO, 2014. 3rd IMO GHG Study 2014. IMO.

Joseph, Joshy, Patil, R.S., Gupta, S.K., 2009. Estimation of air pollutant emission loads from construction and operational activities of a port and harbour in Mumbai, India. Environ. Monitor. Assess. 159 (1), 85–98.

Lindstad, Haakon, Asbjørnslett, Bjørn E., Strømman, Anders H., 2012. The importance of economies of scale for reductions in greenhouse gas emissions from shipping. Energy Policy 46, 386–398.

Livanos, George A., Theotokatos, Gerasimos, Pagonis, Dimitrios-Nikolaos, 2014. Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. Energy Convers. Manage. 79, 640–651.

Maibach, Markus, Schreyer, C., Sutter, D., Van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., Bak, M., 2008. Handbook on Estimation of External Costs in the Transport Sector. CE Delft.

MAN Diesl & Turbo, 2015. Basic Principles of Propulsion. MAN Diesel & Turbo, Denmark.

MAN, GL, 2013. Costs and Benefits of LNG as Ship Fuel for Container Vessels. GL and MAN, Germany.

Merien-Paul, Rumesh H., Enshaei, Hossein, Jayasinghe, Shantha Gamini, 2016. Guessing to prediction – a conceptual framework to predict LNG Bunker demand profile in Australia. In: IAMU AGA 2016. Vietnam Maritime University, Haiphong, Vietnam.

Merk, O., 2014. Shipping Emissions in Ports. International Transport Forum Discussion Papers, No. 2014-20. OECD Publishing, Paris Google Scholar.

OECD/ITF, 2016. Reducing Sulphur Emissions Shipping; The impact of International Regulation. Paris.

Psaraftis, Harilaos N., Kontovas, Christos A., 2009. CO2 emission statistics for the world commercial fleet. WMU J. Marit. Affairs 8 (1), 1–25.

Schrooten, Liesbeth, De Vlieger, Ina, Panis, Luc Int, Chiffi, Cosimo, Pastori, Enrico, 2009. Emissions of maritime transport: a European reference system. Sci. Total Environ. 408 (2), 318–323.

Starcrest, 2007. Port of Los Angeles inventory of air emissions for calendar year 2005. In: Starcrest Consulting Group, LLC, Poulsbo, WA.

Starcrest Consulting Group, 2005. Port of Long Beach Air Emissions Inventory. Port of Long Beach.

Tzannatos, E., Nikitakos, N., 2013. Natural gas as a fuel alternative for sustainable domestic passenger shipping in Greece. Int. J. Sustain. Energy 32 (6), 724–734.

Tzannatos, Ernestos, 2010. Ship emissions and their externalities for the port of Piraeus-Greece. Atmos. Environ. 44 (3), 400–407.

USEPA, 2009. Current methodologies in preparing mobile source port-related emission inventories. In: Final Report for US Environmental Protection Agency.

Winebrake, James J., Corbett, J.J., Green, E.H., Lauer, A., Eyring, V., 2009. Mitigating the health impacts of pollution from oceangoing shipping: an assessment of low-sulfur fuel mandates. Environ. Sci. Technol. 43 (13), 4776–4782.