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A method for analysis of maritime transportation systems in the life cycle approach – The oil tanker example

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HIGHLIGHTS

- We proposed a life cycle analysis method for examining systems providing services.
- We applied the method to evaluate life cycle carbon emissions of maritime transport.
- Findings suggest 12 knots as a reference speed for optimum energy/carbon efficiency.
- A reference range of life cycle carbon emission factors of oil shipping is reported.

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ABSTRACT

The International Maritime Organization considers decarbonizing international shipping an important and necessary step towards a sustainable global trade economy. There have been commendable studies focusing on nearly all stages of maritime transport from shipbuilding, to operation and maintenance, to engine performance optimization, to fuel options, and to dismantling and recycling, but the number of whole system level life cycle analyses (LCA) on maritime transport is far less than that on energy and goods production. This scarcity highlights the need for more independent studies to enrich the LCA literature on shipping. In response, we propose a method that adapts existing methods for the analysis of energy and goods producing systems. This approach provides crucial continuity in the serial development of a generic process chain analysis framework to ensure consistency in system and boundary formulations. Findings from the case study suggest that "slow-steaming" may not always be desirable and that 12 knots could be considered as a reference optimum speed for tankers of all size categories. Cruising at 12 knots over selected routes between top oil import and export countries, a reference range of life cycle carbon emission factors is found to be 6–9 mg of carbon dioxide for moving 1 tonne of crude oil over 1 km distance (mg-CO_2/t-km). These developments demonstrate the ability of the proposed method to provide independent assessments on the life cycle carbon emissions of maritime transport systems and to derive new and/or alternative insights on the decarbonizing measures conceived by earlier studies.

1. Introduction

The fifth assessment report published by the Intergovernmental Panel on Climate Change indicates that international and coastal shipping accounts for nearly 10% of global transport sector CO_2 emissions [1] or 2% of CO_2 emissions from fuel combustion [2,3]. According to the third International Maritime Organization (IMO) study on carbon emissions [4], maritime transport emits around 1000 million tonnes of CO_2 annually and is responsible for about 2.5% of global CO_2 emissions. Depending on future economic and energy developments, maritime transport carbon emissions are predicted to increase between 50% and 250% by 2050. A combination of operational and technological measures can help reduce ship's energy and hence carbon emissions by up to 75% [5]. Among the list of ten most effective measures in reducing energy intensity, and hence carbon emissions, speed reduction has ranked top of the list [6].

Studies in the literature generally employs life cycle analysis (LCA) or other analytical methods to explore the decarbonization potential of maritime transport or shipping. Existing studies on shipping tend to focus either exclusively on just the marine vessel or to provide a system view of the maritime freight over the vessel's lifetime. Those focusing on the marine vessel are further divided into studies on the complete life cycle of the vessel from manufacturing to end-of-life scrapping [7], shipbuilding [8], vessel operation [9,10], docking at ports [11], and

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Nomenclature

Country abbreviations

AO	Angola
BR	Brazil
CA	Canada
CN	China
DE	Germany
ES	Spain
IN	India
IQ	Iraq
IT	Italy
JP	Japan
KR	South Korea
KW	Kuwait
NG	Nigeria
PH	Philippines
RO	Romania
RU	Russia
SA	Saudi Arabia
SG	Singapore
TW	Taiwan
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America
VE	Venezuela
VN	Vietnam

Other abbreviations

DWT	deadweight tonnage
GHG	greenhouse gas
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle analysis
LCI	life cycle inventories
LWT	lightweight tonnage
PCA	Process Chain Analysis
SMCR	specific maximum continuous rating
tce	tonne of coal equivalent
ULCC	ultra large crude carrier
VLCC	very large crude carrier

Symbols

C_E	carbon emissions due to energy input
C_{NE}	carbon emissions due to non-energy input
C_{sys}	life cycle carbon emissions of the main system
$c_{e,i}$	carbon content of energy input
$c_{ne,i}$	carbon content of non-energy input
$d_{j,k}$	distance between two ports j and k
E_n	total energy input to the nth process of a system
$E_{n,i}$	energy input by type to the nth process of a system
E_{sys}	system energy input
e_i	energy input per unit of product produced
NE_n	total non-energy input to the nth process of a system
$NE_{n,i}$	non-energy input by type to the nth process of a system
NE_{sys}	system non-energy input
ne_i	non-energy input per unit of product produced
P_i	total engine power at a given ship speed
P	marine engine power
P_A	rated auxiliary engine power
P_M	rated main engine power
T	lifetime of the ship
v_0	maximum ship speed
v_i	actual ship speed
W	marine engine power output
W_i	total marine engine power output at a given speed over a fixed distance
σ	ship utilization rate
ϕ_A	auxiliary engine load factor
ϕ_M	main engine load factor

ship scrapping and recycling [12–16]. These studies can provide insights on specific stages of a larger maritime transport system, but they are unable to provide a holistic understanding of the life cycle system of shipping.

Those examining the larger system of maritime freight are further divided by focus areas and methods. Some studies focus on examining technical and operational measures for reducing carbon emissions such as [17–20]. Other studies focus on the development and/or use of LCA software to study the environmental impacts of shipping such as [21,22]. Relatedly, some studies tend to focus on the issues related to LCA methods, such as adaptation of LCA methodology to suit maritime transport, system boundaries selection, and life cycle inventories (LCIs) [23]. Although the existing literature has somewhat covered most aspects of LCA studies on shipping, the number of LCA studies on maritime transport is far smaller as compared to the number of LCA studies on energy systems. That has led to even smaller number of LCA studies addressing the critical issues related to system and boundary formulations to ensure consistent and unbiased results.

The scarce number of LCA studies is likely caused by the fact that all stages of shipping have already been studied in quite some detail. Furthermore, it is conceptually intuitive and has been demonstrated by existing studies that the shipping stage accounts for the majority of the life cycle carbon emissions. Since fuel typically accounts for around 40% of the total cost in shipping, freight business operators have a strong incentive to reduce transport speed [24]. However, the metrics used for evaluating the decarbonizing potential of speed reduction have not been thoroughly evaluated from a life cycle standpoint. Due to the lack of studies focusing on system, boundary and input-output definitions, many other similar issues as “speed reduction” require further independent assessment using alternative LCA methods. More importantly, the scarce number of LCA studies on shipping also highlights the need for further developments in LCA methodologies for analysis of systems providing services.

In response, we propose a generic process chain analysis (PCA) methodology with reference to earlier developments in [25,26] to formulate an LCA methodology for analysis of maritime transport system. Building upon the reference methodologies, the key advantage of the proposed methodology lies with its flexible and yet strict system and boundary formulations, which are critical to ensure transparent, consistent, and unbiased LCA results. In addition, the proposed methodology can quantify the influence arising from a change in design considerations to the environmental sustainability of a system, also known as change impact analysis as described in [27]. A change impact analysis refers to “identifying the potential consequences of a change, or estimating what needs to be modified to accomplish a change” [28] or “the evaluation of the many risks associated with the change, including estimates of the effects on resources, efforts, and schedules” [29]. Most importantly, the serial developments from [25,26] and to the proposed methodology would establish a common PCA framework under which the conceptualized life cycle systems would be capable to evaluating systems producing energy, goods, and services. In turn, the same PCA framework could lead to the development of an alternative global energy systems modeling tool.

This paper is structured as follows to achieve the proposed developments. Section 2 describes the formulation of the methodology. Section 3 presents the data and assumptions employed in developing the case studies using crude oil tankers as examples. Section 4 presents the results of a base case conceptualized using a fixed set of assumptions. This is followed by change impact analyses on the size of tankers and tanker speed. The new insights are discussed in Section 5 and the conclusions and recommendation for future research are presented in the final section.

2. The methodology

Earlier developments of the LCA methodology have been primarily focused on energy producing systems, such as nuclear, coal, woody biomass, and solar photovoltaic [25,26,30,31]. The system representing maritime transport or shipping of commodities, such as crude oil and container cargo differs significantly from an energy producing system. Instead of energy production, the maritime transport system provides a service to attain profitability for a shipping business. Following the general system boundary conditions in earlier developments, a simplified maritime transport system can be conceived as shown in (Fig. 1). The system takes energy and non-energy inputs from the surroundings, and operates over a predetermined lifetime with carbon emissions released to the surroundings due to the usage of energy and non-energy inputs.

The three dimensions governing the system boundary formations remain valid. First, there is a boundary between the system and its surroundings. Next, there is a boundary between the Main System and its Sub-systems, which produce inputs for the Main System. Last, there are physical and temporal boundaries governing the formation of the life cycle Main System. The physical boundary governs the processes to be included in the life cycle system, and the temporal boundary governs the cradle-to-grave lifetime of the system [32].

In earlier developments, the process chain is assembled through the transformation of "products" across the Main System. The transformation of products refers to the movement of fossil or nuclear fuel, or fabrication of solar cells across the supply chain. The activities under each process utilize one or more forms of energy and or non-energy inputs to support product transformations. Only the direct conversion of the carbon content of the energy and non-energy inputs into carbon dioxide is accounted for when computing the life cycle carbon emissions of the Main System. Thus, a direct translation of "product" from an energy producing system to a maritime transport system can be potentially restricted to only the ship. As a result, the life cycle carbon emission is simply the total carbon emissions of building and decommissioning the ship.

The inclusion of ship operation and maintenance can be achieved by adjusting the concept of the "product". Using an oil tanker as an example for illustration (Fig. 2), the tanker picks up its cargo (crude oil) upon delivery of the ship to the oil exporting country. The tanker then delivers the crude oil to oil importing country. Subsequently, the tanker returns to the oil exporting country to reload crude oil for the next trip. In the process, the only useful energy output is the work done by the tanker's engine. As such, the life cycle system of maritime transport is effectively driven by the work output of the tanker's engine so as to provide freight service over the lifetime of the ship. In this study, the service refers to the tonnage of crude oil transported over the lifetime of the tanker.

It is noteworthy that the goal of an LCA study on maritime transport system differs from an LCA study on crude oil. The goal of an LCA study on the life cycle carbon emissions of crude oil would involve the construction of the oil drilling platform (onshore or offshore), pipeline construction or shipbuilding, pipeline operation (oil pumping) or tanker operation (oil delivery), the refinery process, and the consumption of all distillates over a predefined lifetime. The goal of an LCA study on the carbon emissions of maritime transport in this study refers to the total commercial service delivered over the lifetime of the ship, which does not account for the carbon emissions due to the production and consumption of the goods delivered. As such, the concept of "product" is slightly complicated in the maritime transport system although its definition remains exactly the same as that in earlier developments [25]. The "product" firstly refers to the ship just after the "Ship Delivery" process in Fig. 2. Upon commencement of business operations, symbolized by the "Loading" process in Fig. 2, "product" then refers to the freight services provided over the ship's lifetime.

Since the goal of a maritime transport system is to provide a service, the final output of crude oil transport system is effectively the equivalence of marine engine power output.

$$W = P \times T \times \sigma \qquad (1)$$

where W represents work done by the marine engine; P represents the marine engine power; T represents the lifetime of the ship; and σ represents the utilization rate of the ship.

The energy and non-energy input to each process of the system can be expressed respectively as

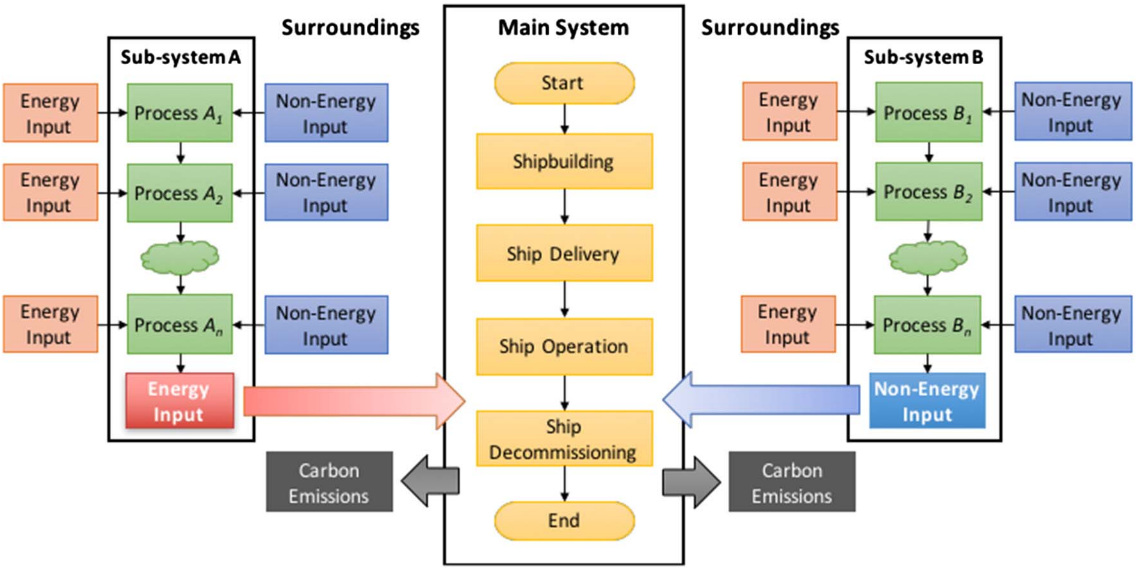

Fig. 1. Simplified system representation of maritime transport.

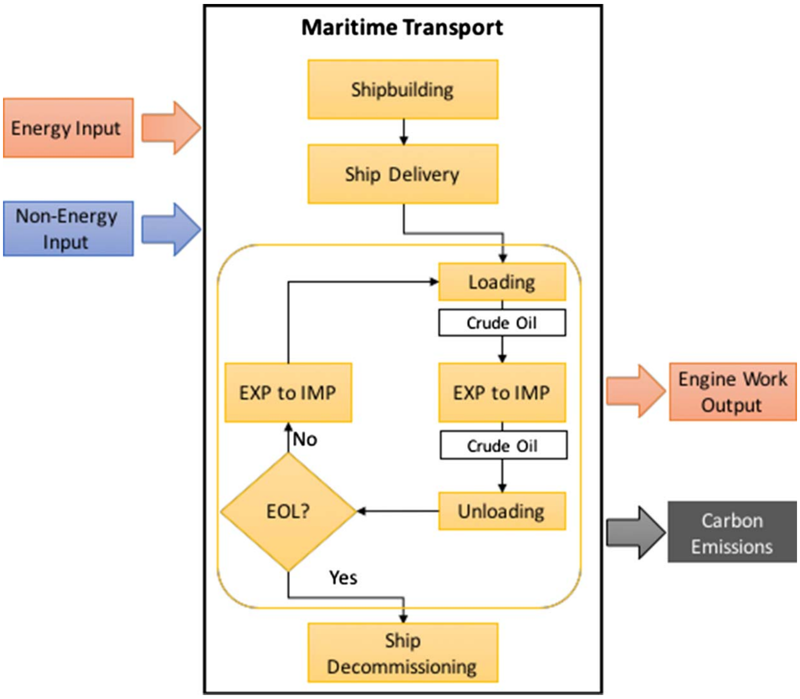

Fig. 2. Expansion of the ship operation process. IMP refers to import (country) and EXP refers to export (country).

$$E_n = \sum_{i=1,2,...} E_{n,i} \tag{2}$$

$$NE_n = \sum_{i=1,2,...} NE_{n,i} \tag{3}$$

where $E_{n,i}$ represents energy input by type such as diesel or electricity to each process (or nth process) of the system; and $NE_{n,i}$ represents non-energy input by type such as chemicals, metals, or other materials to each process (or nth process) of the system.

Since a maritime transport system comprises a number of processes, the total system energy and non-energy inputs can be expressed respectively as

$$E_{sys} = \sum_{n=1,2,...} E_n = \sum_{n=1,2,...} \left(\sum_{i=1,2,...} E_{n,i} \right) = \sum_{n=1,2,...} \left(p_n \times \sum_{i=1,2,...} e_i \right) \tag{4}$$

$$NE_{sys} = \sum_{n=1,2,...} NE_n = \sum_{n=1,2,...} \left(\sum_{i=1,2,...} NE_{n,i} \right) = \sum_{n=1,2,...} \left(p_n \times \sum_{i=1,2,...} ne_i \right) \tag{5}$$

where E_{sys} and NE_{sys} represents the total system energy and non-energy inputs respectively; p_n represents the product made by each process of the system; e_i represents energy input per unit of p_n produced; and ne_i represents the non-energy input per unit of p_n produced. The "product" only refers to crude oil transported by oil tankers since the temporal boundary of the system is restricted to only one tanker's lifetime.

The process carbon emissions due to energy and non-energy inputs can be expressed respectively as

$$C_E = \sum_{i=1,2,...} c_{ne,i} \times E_i = \sum_{n=1,2,...} \left(p_n \times \sum_{i=1,2,...} c_{e,i} \times e_i \right) \tag{6}$$

$$C_{NE} = \sum_{i=1,2,...} c_{ne,i} \times NE_i = \sum_{n=1,2,...} \left(p_n \times \sum_{i=1,2,...} c_{ne,i} \times ne_i \right) \tag{7}$$

where C_E represents carbon emissions due to energy input; C_{NE} represents carbon emissions due to non-energy input; $c_{e,i}$ represents the carbon content of energy input; and $c_{ne,i}$ represents the carbon content of non-energy input.

Following the physical system boundary conditions described in [25], the LCA main system is only responsible for carbon emissions due to the direct conversion of its inputs' carbon content such as the combustion of fossil fuel and other chemical/physical reactions. The carbon emissions due to the production of the inputs are excluded to ensure consistency with the boundary conditions. Since the LCA main system of shipping does not involve direct conversion of its non-energy inputs' carbon content, C_{NE} is removed from the final equation describing the life cycle carbon emissions of shipping as shown in Eq. (8).

$$\begin{aligned} C_{sys} &= C_E + C_{NE} + C_{Fuel} \\ &= \sum_{n=1,2,...} \left(p_n \times \left(\sum_{i=1,2,...} c_{e,i} \times e_i + \sum_{i=1,2,...} c_{ne,i} \times ne_i \right) \right) + C_{Fuel} \\ &= \sum_{n=1,2,...} \left(p_n \times \sum_{i=1,2,...} c_{e,i} \times e_i \right) + C_{Fuel} \end{aligned} \tag{8}$$

where C_{sys} represents the life cycle carbon emissions of the main system; and C_{fuel} represents the life cycle carbon emissions due to fuel consumption by ship operation.

The serial developments from [25,30] to [26] and to the present study have transformed a PCA methodology for analysis of energy producing system to product manufacturing systems, and to systems providing services. All transformations are achieved through the quantitatively formulated physical and temporal boundary conditions as described in [25]. The input and output exchange across the boundary always follows the elementary mechanisms such that only direct outputs as a result of corresponding inputs are accounted for in the analysis for the main system. Environmental impacts as a result of producing inputs by subordinating systems to the main system are always excluded by the physical boundaries.

3. Data and assumptions

This case study employs reference oil tankers of varying sizes, measured by deadweight tonnage (DWT) and manufacturing locations. The case study also considers wide-ranging oil export and import countries to examine the change in life cycle carbon emissions. In this case study, carbon emission only refers to CO_2 emissions.

3.1. Energy input data and assumptions

Information on shipbuilding are acquired through site interview with one of the top 10 shipbuilding companies in China. Table 1

Table 1
Shipbuilding energy consumption.

Department	Electricity (kWh/LWT)	Other energy (tce/LWT)
Production	104.60	0.03
Coating	1.53	< 0.001
Outfitting	0.04	0.06
Assembly	96.36	0.004
Production Support	0.96	–
Logistics	17.46	–
Total Energy Consumption	220.95	0.10

presents a detailed breakdown of energy consumption by department and fuel type in a typical shipyard based on per unit of lightweight tonnage (LWT) of ship constructed. All non-electricity energy consumptions are reported as tonne of coal equivalent (tce).

As of 2015, there are eleven major shipbuilding countries in the world as shown in Table 2. In the base case, China is selected as the shipbuilding location since it is the largest shipbuilding country by gross tonnage. This study also considers tankers constructed in other countries in the case study for completeness.

The operations during the lifetime of the ship upon completion of its construction employ the following assumptions in this study. Upon completion, we assume the oil tanker is delivered from the shipbuilding country to the oil exporting country for loading of crude oil. Once fully loaded, the tanker makes a non-stop trip from the oil exporting country to the oil importing country. Upon arrival at the oil exporting country, all crude oil onboard the oil tanker is fully unloaded. Upon emptying crude oil, the tanker makes a non-stop trip from the oil importing country back to the same oil exporting country. The return trips repeat the exact same route over the lifetime of the tanker taking into consideration time off duty for regular maintenance, harbor maneuvering and waiting time, and crude oil loading/unloading time. With reference to [20], the average downtime for maintenance is 33.89 days per year, the time for loading and unloading is 3 days per return trip, the time for maneuvering is 4% of the trip time per round trip, and the waiting time is 1 day per round trip.

The operation and maintenance energy consumption is calculated through the following assumptions. First, we assume that the operating conditions and hence energy use in the shipyard for ship maintenance are the same as those of a shipyard for shipbuilding. Thus, the average energy consumption for regular maintenance assumes 0.73 kWh/t-LWT and 0.0003 tce/t-LWT for every hour of maintenance. These are calculated based on the total energy consumption (electricity and tce in Table 1) over 304 working hours (equivalent to 10 months). The loading and unloading energy consumptions are assumed to be 1.035 kWh/t-oil for pump and 0.044 kWh/t-oil for ballast [33].

The fuel consumption during ship operation is calculated on the basis of engine power and speed. The main engine power is given as the SMCR (acronym for specific maximum continuous rating) as reported in [34] and the auxiliary engine power is given as a percentage of the main engine power as reported in [35] (summarized in Table 3). According to [9], the actual main engine power at a given speed can be calculating using the functional relationship as expressed in Eq. (9) and the energy required by the main engine and the auxiliary engine to travel between two ports can be obtained through Eq. (10).

Table 2
Major shipbuilding countries as of 2015.

Countries	Gross tonnage
China	25160000
South Korea	23272000
Japan	13005000
Philippines	1865000
Taiwan	749000
Romania	485000
USA	427000
Germany	384000
Vietnam	375000
Brazil	361000
Italy	219000

Table 3
Ship size and propulsion power demand.

Ship size (DWT)	Design speed (knots)	Main engine power (kW)	Auxiliary engine power (as percentage of main engine power)
85000	15	12300	23.0%
105000	15	13400	27.5%
115000	15	14300	15.0%
125000	15	15200	16.2%
150000	15	16000	19.2%
165000	15	16800	21.0%
260000	15.5	24100	33.9%
280000	15.5	25000	36.9%
300000	15.5	25900	39.9%
319000	15.5	27100	42.7%
360000	16	30600	6.9%
440000	16	34200	9.7%
560000	16	42200	13.8%

$$P_{M,i} = P_M \times \left(\frac{\nu_i}{\nu_0}\right)^3 \tag{9}$$

$$W_i = (P_{M,i} \times \phi_M + P_A \times \phi_A) \times \frac{d_{j,k}}{\nu_i} \tag{10}$$

where P_i represents the total engine power at a given ship speed; P_M represents the rated main engine power; ν_0 represents the maximum ship speed; ν_i represents the actual ship speed; P_A represents the rated auxiliary engine power; ϕ_M represents the main engine load factor; ϕ_A represents the auxiliary engine load factor; $d_{j,k}$ represents the distance between two ports j and k; and W_i represents the total work done by the main engine and the auxiliary engine when cruising at ν_i over distance $d_{j,k}$.

With reference to [36], we assume an average hourly fuel consumption rate of 206 g/kWh for the main engine and 221 g/kWh for the auxiliary engine, and an average main engine load factor of 0.8 and average auxiliary engine load factor of 0.5. The carbon emission factor of bunker fuel is generally around 3.1 t-CO_2/t-IFO.

Eq. (10) suggests that the distance of crude oil export–import routes could influence the life cycle carbon emissions of crude oil transport. In an attempt to cover most of the oil export–import routes, this study considers nine oil export countries, namely, Saudi Arabia, Russia, Iraq, United Arab Emirates, Canada, Nigeria, Kuwait, Angola, and Venezuela, and eleven oil import countries, namely, USA, China, India, Japan, South Korea, Germany, Philippines, Italy, Spain, United Kingdom, and Singapore. The distance between shipbuilding country to oil export country and the distance between oil export and import countries are presented in Tables 4 and 5 respectively. In the base case, we use Kuwait-Singapore as a reference freight route for analysis. The grid emission factors (GEFs) due to direct fuel combustion of all countries including shipbuilding, and oil export and import countries are taken from [2] for the year 2014 (data reported in Table 6).

At the end of the tanker's operational life, the tanker is scrapped for material recycling. With reference to [37], the energy use for tanker dismantling are presented in Table 7. We acknowledge that there could be other methods for ship dismantling and that recycling of scrapped materials require further energy input. Other dismantling methods as well as the recycling of scrapped materials are excluded from this case study since they are not the focus of this study.

Table 4
Port to port distance between shipbuilding and oil export countries (Unit: km).

Shipbuilding countries	Oil export countries								
	SA	RU	IQ	UAE	CA	NG	KW	AO	VE
CN	11064	20711	10342	9414	20889	17651	10112	15766	18903
KR	12638	22285	11849	10988	19277	19337	11719	18007	17292
JP	11331	22126	11690	10829	19524	19166	11560	17837	17538
PH	9230	20026	9590	8773	20637	16851	9460	15522	19642
TW	10210	21005	10569	9753	20522	18076	10436	16746	18537
RO	7904	8747	8264	7447	9358	9803	8130	10858	10538
USA	15035	7775	15394	14577	537	8971	15260	10029	4234
DE	13142	1335	13501	12684	6286	9093	13368	10156	8703
VN	8051	18846	8410	7854	19457	15990	8280	14660	20063
BR	15659	13314	16018	15462	10103	7377	15888	7095	6495
IT	7908	2713	8267	7712	7245	7690	8138	8745	8393

Table 5
Port to port distance between oil export and import countries (Unit: km).

Oil import countries	Oil export countries								
	SA	RU	IQ	UAE	CA	NG	KW	AO	VE
USA	15035	10234	3461	12210	11490	12388	9338	7556	9527
CN	9879	15031	8006	17007	16286	7232	14134	2580	5838
IN	15696	10593	2939	12570	11849	12747	9697	7921	11353
JP	15014	11508	2384	12014	11293	12192	9141	7365	10797
KR	3254	20302	14970	14970	19277	5982	20744	7343	5256
DE	9282	19542	12658	12658	19337	8340	16972	7788	6945
PH	15868	11934	3691	3691	11719	12618	9567	7791	11223
IT	10342	18213	11329	11329	18007	9403	15642	8843	8008
ES	3254	17850	16118	16118	16825	8228	19198	8491	7030
UK	15035	10234	3461	12210	11490	12388	9338	7556	9527
SG	9879	15031	8006	17007	16286	7232	14134	2580	5838

3.2. Cost data and assumptions

This study covers five categories of tankers by DWT, namely, Panamax, Aframax, Suezmax, very large crude carrier (VLCC), and ultra large crude carrier (ULCC). The indicative new building prices are taken from [38] for new tankers built in 2011 and the tanker freight rates are taken as the average values of the freight rates reported in [39] (data presented in Table 8). All monetary values are reported in 2015 US Dollar values.

With reference to studies, such as [40,41], the tanker freight rates are somewhat correlated to the crude oil prices. As such, we extrapolated a times series freight rates based on the changes in the projected crude oil prices from 2017 to 2046. The levels of the extrapolated tanker rates are within the range of values predicted by experts as reported in [42]. The data for long-term crude oil price forecasts is taken from the projections made by the United States Energy Information Administration [43]. The bunker fuel price for IFO380 is taken as the

Table 6
Grid emission factors of countries selected in this study in alphabetical order.

Country	Grid emission factor (g-CO_2/kWh)
Angola	363
Brazil	414
Canada	145
China	680
Germany	474
India	813
Iraq	1177
Italy	331
Japan	556
Kuwait	702
Nigeria	416
Philippines	604
Romania	320
Russia	380
Saudi Arabia	711
Singapore	441
South Korea	517
Spain	255
Taiwan	581
United Arab Emirates	643
United Kingdom	413
USA	486
Venezuela	243
Vietnam	355

Table 7
Ship decommissioning energy use by fuel type.

Fuel type	MJ/DWT
Liquefied propane gas	753.62
Diesel	130.78
Electricity	0.9

Table 8
New building prices and tanker freight rates.

DWT by class	New building prices (2015 M$)	Tanker rate (2015 Thousand $/Day)
Panamax 60000–80000 t	37.91	26.55
Aframax 80000–120000 t	46.73	37.95
Suezmax 120000–200000 t	53.59	46.71
VLCC 200000–320000 t	67.31	64.85
ULCC 320000–550000 t	67.31	64.85

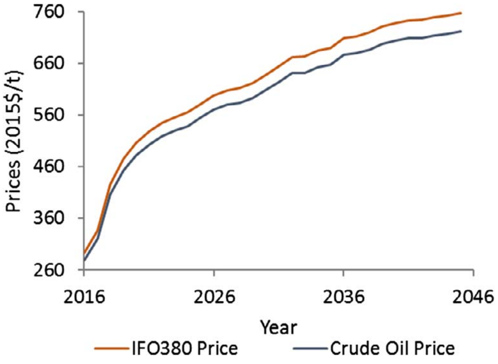

Fig. 3. Crude oil and IFO380 price projections.

Table 9
Annual operating expenditure of oil tankers.

Tanker size	USD per year
Handysize	2884208
Panamax	3149286
Aframax	3042436
Suezmax	3448243
VLCC	3853305
ULCC	3853305

average price in 2016 as reported in [44]. The subsequent annual average IFO380 prices are projected based on the annual growth rate of crude oil prices. The crude oil and IFO380 prices are plotted in Fig. 3.

The operation and maintenance cost, collectively named as operating expenditure (OPEX) includes crew members' salaries, spare parts and repair costs, and other expenses enlisted in Table 9 (information extracted from [45]).

The tanker is assumed to be scrapped at the end of its lifetime. With reference to [46], the average scrap value is assumed to be 532.88 $/LWT. This study is unable to solicit sufficient evidence on ship decommissioning cost and an appropriate discount rate for lifetime cost/revenue calculation. For illustration purposes, decommissioning cost and the discount rate are assumed to be the same as large scale projects, such as power plants as seen in [43,47]. As such, the cost of oil tanker decommissioning is assumed to be 15% of the CAPEX including dismantling, scrappage handling, and other technical and management related costs. The discount rate and decommissioning cost have minor influence on the lifetime cost values, but they are not expected to have a strong influence on the overall results.

4. Case study results

4.1. Validation

As reviewed earlier, studies in the literature generally show that majority of the life cycle carbon emissions of crude oil transport is contributed by the combustion of IFO380 during transport. Using a 260000 DWT tanker built in China and traveling between Kuwait and Singapore for oil import-export, findings from our study are consistent with those reported in the literature as shown in Fig. 4. For further validation, we reduced the ship speed from 15 knots to 8 knots in steps of 1 knot and found that the life cycle carbon emissions of crude oil transport reduce as the ship speed reduces. We acknowledge that oil tankers are unlikely to cruise at 8 knots unless under specific circumstances. Experimenting with 8 knots ship speed is only meant to show that our method is robust enough to accommodate extreme cases when used by others. The life cycle carbon emission of crude oil transport is found to be 30.1 kg of CO_2 per tonne of crude oil transported (kg-CO_2/t-oil) at 15 knots and 20.3 kg-CO_2/t-oil at 8 knots. At 8 knots, ship operation remains the major contributor to the life cycle carbon emissions at 81.8%. Although the exact values of the life cycle carbon emissions are different from those reported in the literature, these results are generally within the range of values reported in the literature. In other words, the methodology as well as the data used in this LCA study are considered to have been validated.

4.2. Size matters

The engine power is correlated to the size of the ship (measured by DWT) and hence the size of the ship influences the life cycle carbon emissions of crude oil transport. When measured by the absolute quantity, the life cycle carbon emissions of crude oil transport increase as the size of the ship increases from 85000 to 319000 (Fig. 5). The discontinuity is caused by the sudden change in the auxiliary engine power from 319000 to 360000 as specified in Table 3. This trend completely reverses when the life cycle carbon emissions are measured on a per unit crude oil transported basis (kg-CO_2/t). The life cycle carbon emission factor of crude oil transport drastically reduces as the size of the ship increases. In other words, crude oil transport using larger tankers would result in significantly less carbon emissions when measured on the basis of the life cycle carbon emissions over the total

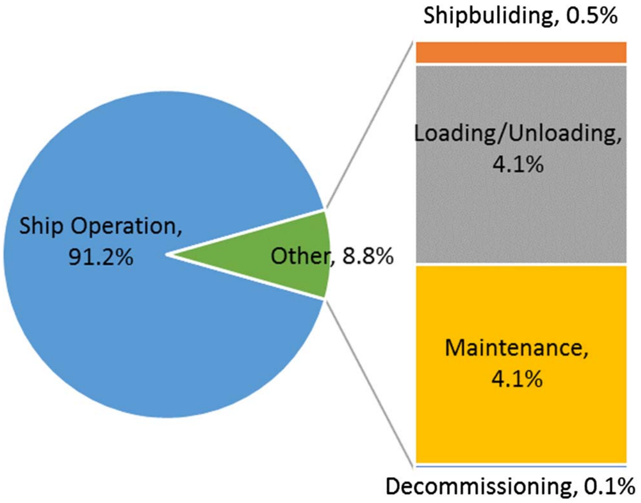

Fig. 4. Percentage contribution of carbon emissions by each process of the life cycle system for crude oil transport.

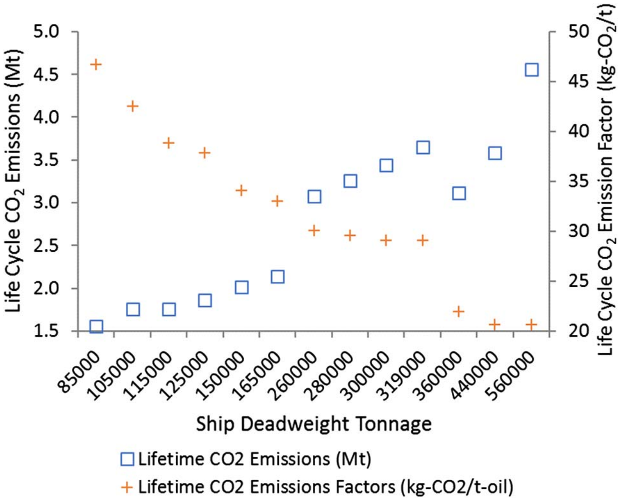

Fig. 5. Influence of ship size on the life cycle carbon emissions of crude oil transport at 15 knots ship speed.

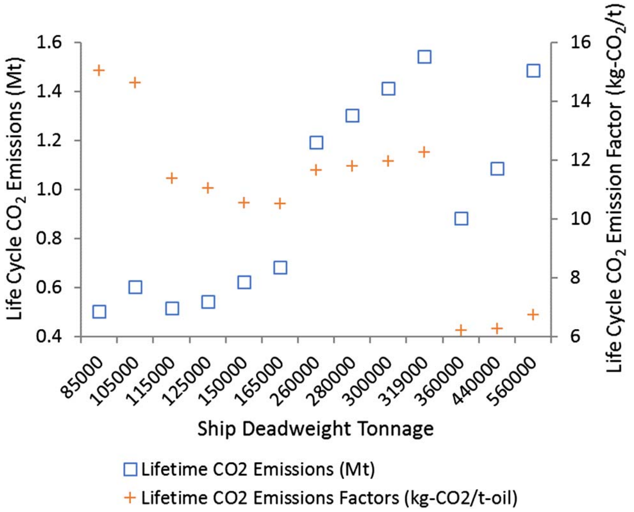

Fig. 6. Influence of ship size on the life cycle carbon emissions of crude oil transport at 8 knots ship speed.

amount of crude oil transported over the entire service life of the ship.

The results are further changed when the ship speed is reduced to 8 knots. The general trends in the total quantity of life cycle carbon emissions remain the same when comparing the results shown in Figs. 5 and 6. The life cycle carbon emission factors exhibit a near U-shaped trend when the size of the ship increases from 85000 to 319000 DWT (Fig. 6b). The life cycle carbon emission factors of large-sized tankers remain the lowest. In addition, we note that the life cycle carbon emissions and the life cycle carbon emission factors have both significantly reduced when the ship speed reduces from 15 to 8 knots.

The U-shaped trajectory suggests that speed may have a varying degree of influence on the life cycle carbon emission factors of tankers of different sizes. The varied influence of ship speed on the life cycle carbon emission factors of crude oil transport by ships of varying DWTs demonstrated here suggests a challenge to the much-alluded benefits of "slow-steaming" in decarbonization. As such, further deliberation on the selection of the physical unit for measuring the carbon intensiveness of crude oil transport is needed.

4.3. *"Slow-steaming" the way to go?*

Based on the cost information, we can compute the levelized cost of crude oil transport taking into consideration the main cost components such as shipbuilding, operation and maintenance, fuel, and dismantling costs. The result from levelizing these cost components over the lifetime of the ship gives the average cost of crude oil transport incurred by the shipping company. The levelized cost of crude oil transport can also be calculated from the perspective of crude oil merchants or brokers taking into consideration scheduled payments based on daily tanker rates. Using a 260000 DWT tanker as an example, the levelized cost of crude oil transport is $0.362/t for the shipping company and $0.415/t for the merchant if the average ship speed is set at 15 knots.

Recent studies suggest that "slow-steaming" could be a sensible option to reduce operating costs as well as carbon emissions due to reductions in fuel consumption. We then reduced the ship speed from 15 knots to 8 knots in steps of 1 knot to compute the levelized cost of crude oil transport at each ship speed using the same 260000 DWT ship as an example. As shown in Fig. 7, the levelized cost of crude oil transport to the shipping company is reduced as the ship speed reduces while the levelized cost to the merchant remains almost exactly the same. We acknowledge that the reference calculation only focuses on the shipping stage and does not account for instantaneous changes in crude oil price and commercial practices for maximizing profitability through trading. Since the levelized cost to the merchant is effectively the revenue to the shipping company, it is sensible for the shipping company to reduce ship speed as much as possible so as to achieve higher profit margin.

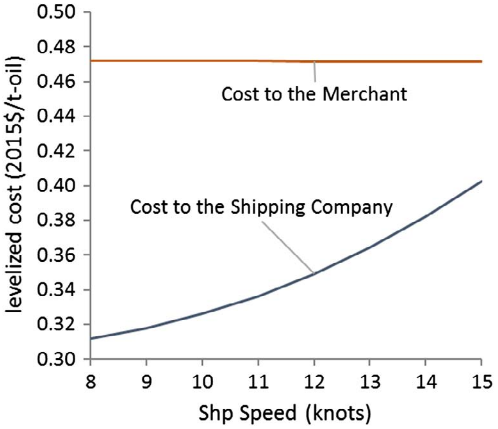

Fig. 7. Influence of ship speed on the levelized cost of crude oil transport (260000 DWT tanker).

Although slow-steaming seems to bring higher profit margin to the shipping company, we find that indiscriminate reduction in ship speed could be undesirable when viewed from a life cycle energy/carbon efficiency perspective (Fig. 8). In Section 4.2, the measurement unit for carbon intensiveness of crude oil transport is kg-CO$_2$/t, which connotes the average amount of carbon emissions released for every tonne of crude oil shipped during the lifetime of tanker. The use of kg-CO$_2$/t is appropriate and likely more accurate for quantifying the life cycle carbon emission factor of crude oil transport when the exact conditions in the life cycle system are known and fixed. As such, the unit of kg-CO$_2$/t tends to be case-specific and is not suitable for comparing among different tankers of varying DWT and/or cruising at different speed.

Revisiting the formulation of the life cycle system, the effective output of the system is the shipping service delivered by the system. Although crude oil is ultimately the commercial good delivered from the exporter to the importer, the fuel consumed for enabling the shipping service is meant to move the cargo over a given distance. In that sense, a more accurate unit for reflecting the carbon intensiveness of crude oil transport would be the amount (in milligram) of carbon emissions released when moving one tonne of crude oil over a 1 km distance (mg-CO$_2$/t-km). This measurement unit of mg-CO$_2$/t-km resembles the same concept of the fuel economy of heavy duty vehicles, which is usually measured by the amount of fuel used for moving one tonne of goods over 1 km distance (liter-diesel/t-km).

The use of mg-CO$_2$/t-km would be more flexible and can enable fair comparisons among tankers of different DWT and or cruising at different speeds. The total fuel consumption during transport is primarily dependent on engine power, ship speed, and distance. Once the ship DWT is fixed, the total distance traveled and the total amount of crude oil transported over the fixed lifetime of the tanker are only dependent on ship speed. Since the tanker's fuel consumption is entirely dependent on speed, the unit of mg-CO$_2$/t-km can be considered a generic representation of the carbon intensiveness at different ship speed.

The life cycle carbon emission factor of crude oil transport when measured by mg-CO$_2$/t-km unveils new findings. Intuitively, Fig. 8a would have led to continuously decreasing trajectories of the life cycle carbon emission factors. On the contrary, the life cycle carbon emission factors computed here for all tanker sizes show a U-shaped trajectory when the ship speed reduces from 15 to 8 knots (Fig. 8b). These U-shaped trajectories suggest that there is an optimum ship speed for each DWT at which the carbon intensiveness of crude oil transport is the lowest. When grouped according to tanker class, we find the optimum speed is 11 knots for Panamax, 10–11 knots for Aframax, 11–12 knots for Suezmax, 12–13 knots for VLCC, and 9–11 knots for ULCC. On

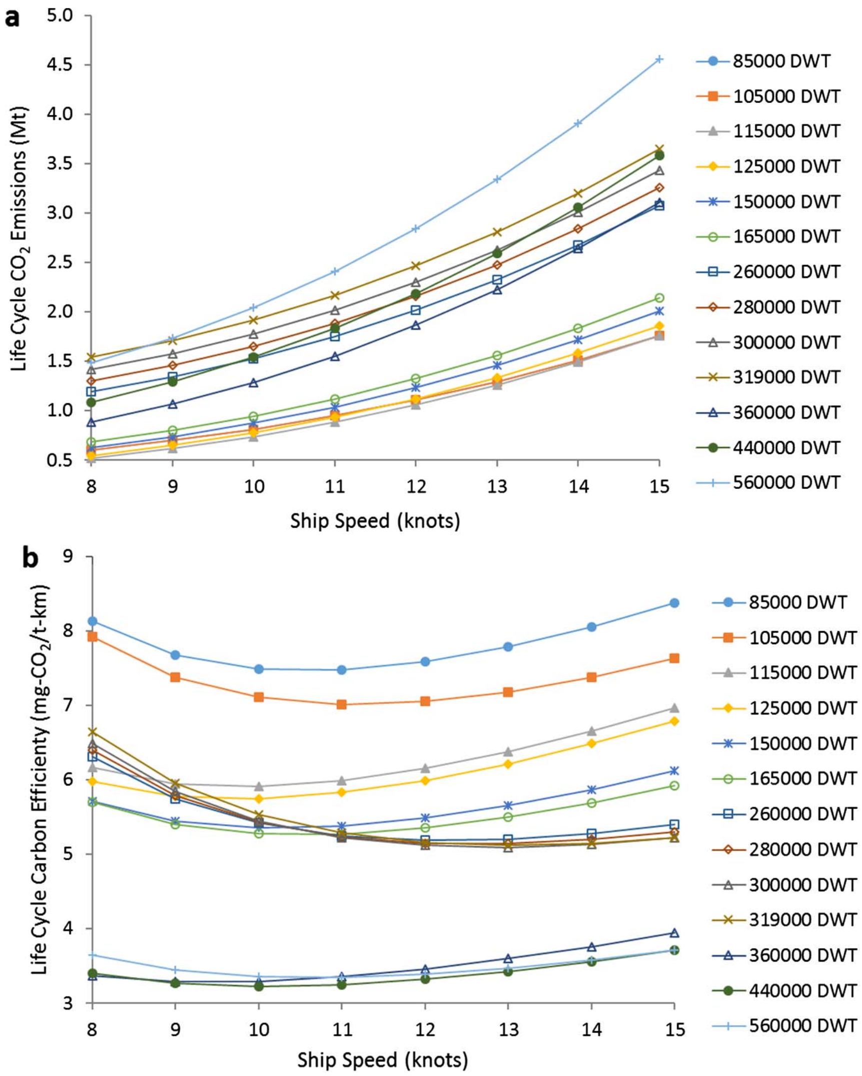

Fig. 8. Influence of ship speed on the life cycle carbon emission factors of crude oil transport by ship DWT.

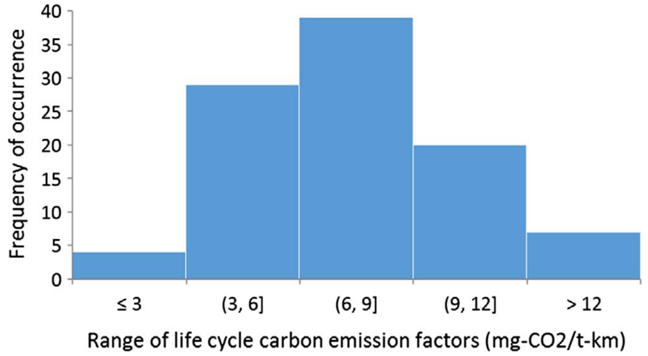

Fig. 9. Reference range of life cycle carbon emission factors of crude oil transport.

average, a 12 knots ship speed appears to be a reasonable average among the optimum speeds obtained for each class.

For completeness, we computed the life cycle carbon emission factors of crude oil transport for all possible routes between oil export and import countries using the average optimum ship speed of 12 knots (results shown in Fig. 9). The export-import routes and distances are obtained using Table 5. We have also computed the life cycle carbon emission factors for tankers built in different countries and ship delivery routes and distances as reported in Table 4, but the influence of varying shipbuilding locations on the life cycle carbon emission factor of crude oil transport is almost negligible and is thus not discussed. Based on the results shown in Table 10, the life cycle carbon emission factors of crude oil transport vary between 2.65 and 13.15 mg-CO_2/t-km with an average value of 7.63. The majority of crude oil export-import routes can expect a life cycle carbon emission factor of 6–9 mg-CO_2/t-km (Fig. 9). The results are expected to change according to the proportionality shown in Fig. 8b when the size of the tanker increases or decreases from the 260000 DWT used in obtaining Fig. 9.

5. Discussion

Crude oil transport or shipping in general contributes to global warming even though the consumption of crude oil distillates from the refinery contributes significantly more carbon emissions. When measured by life cycle carbon emission factors, larger tankers tend to be more carbon efficient in transporting crude oil than small ones. However, carbon efficiency does not necessarily correspond to less carbon emissions. When measured by the absolute quantity of life cycle carbon emissions, large tankers tend to produce a lot more carbon emissions than smaller tankers within the same 30-year lifetime as shown in Fig. 8a. The differences in the life cycle carbon emissions between larger and smaller tankers suggests that reducing dependence on crude oil imports remains the most effective way of reducing carbon emissions, especially when the entire crude oil life cycle from production to final consumption is considered.

Table 10
Life cycle carbon emission factors of crude oil transport over selected routes between top oil import and export countries (Unit: mg-CO_2/t-km).

		Oil importing countries										
		USA	CN	IN	JP	KR	DE	PH	IT	ES	UK	SG
Oil producing countries	SA	9.95	7.12	3.17	8.27	7.84	8.36	6.57	5.45	6.61	8.08	4.99
	RU	6.72	9.81	5.69	10.95	10.52	5.16	9.26	2.41	4.29	5.22	7.76
	IQ	10.62	7.57	3.06	8.74	8.29	8.83	7.01	5.88	7.94	8.90	5.47
	UAE	9.89	7.85	2.55	8.12	7.68	8.21	6.42	5.31	7.33	8.27	4.91
	CA	2.75	12.76	9.66	9.61	12.13	4.32	13.01	5.09	3.89	3.81	11.51
	NG	6.38	12.50	8.45	8.39	12.34	5.82	10.96	5.46	4.99	5.85	9.73
	KW	10.44	8.13	3.30	3.23	7.97	8.49	6.71	5.59	7.61	8.56	5.18
	AO	6.98	11.67	7.63	7.58	11.51	6.42	10.13	6.06	5.55	6.45	8.91
	VE	2.79	11.38	10.39	10.34	10.75	5.68	12.16	5.80	4.93	5.32	12.24

Slow-steaming has been much alluded to as a cost-effective means of reducing bunkering energy consumption and hence carbon emissions. Findings from our study have brought new insights with the discovery of optimum ship speed for each weight class. In general, speed reduction can help reduce the absolute quantity of the life cycle carbon emissions, but indiscriminate reduction in ship speed could hinder the energy and carbon efficiency of crude oil transport when measured by mg-CO_2/t-km. As such, we recommend the establishment of a new benchmark following the physical unit of mg-CO_2/t-km for maritime energy efficiency improvement and decarbonization.

6. Conclusion

We have demonstrated two key contributions in this study. The first and most important contribution is the further development of a PCA method for analyses of life cycle systems providing services. This is a significant and concluding step for the serial developments of the PCA method developed in 2014. The serial developments up to the present study have transformed a generic PCA method for analysis of energy producing systems to manufacturing systems, and to service providing systems. The serial developments and particularly the developments presented in this study have demonstrated the advantages of the quantitative formulations in deriving the system and boundary conditions. More importantly, this study represents the completion of the first stage of a larger study for the development of a global LCA model, which is recommended as future research works.

The next contribution lies with the new insights we have derived from the case study. Findings from this study show that indiscriminate speed reduction is not always desirable. Although the absolute quantity of the life cycle carbon emissions is reduced with reductions in ship speed, the total amount of crude oil transported over the tanker's life time is also reduced. In effect, the energy and carbon efficiency of crude oil transport is also lowered if the ship speed is too low. When measured by the amount of carbon emissions released as a result of moving one tonne of crude oil over a distance of 1 km (mg-CO_2/t-km), findings from this study suggest 12 knots as a reference speed at which the life cycle energy and carbon efficiency of crude oil transport is optimized. Using the reference optimum speed of 12 knots, we find that 5–10 mg-CO_2/t-km can be used as a reference range of life cycle carbon emission factors for crude oil transport.

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