Real Time Energy Efficiency Operational Indicator (EEOI): Simulation Research from the Perspective of Life Cycle Assessment

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Abstract. In order to evaluate the effect of CO2 emissions during ship building, maintenance and scrapping on energy efficiency, a real time EEOI definition was put forward, a life cycle assessment calculation framework was established, and a ship propulsion model with main diesel engine was built. A bulker carrier YUMING was taken as the case ship. CO2 emissions during ship building, maintenance, and scrapping were calculated. Main engine revolution and real time EEOI value with other parameters were obtained by simulating in different ship draft. The results show that life cycle assessment result will explicitly increase the real time EEOI value especially in lower engine speed and lower ship draft. It means that slow steaming may bring less environmental benefit if the life cycle assessment result is involved.

Keywords: Merchant Ship; Slow Steaming; EEOI; Life Cycle Assessment.

1. Introduction
It is predicted that annual CO2 emissions from the international shipping industry may increase by 1.5–3.5 times by 2050 [1]. For operating ships, applying operational measures is more attractive for reducing CO2 emissions measures than using alternative technologies [2]. Therefore, the Energy Efficiency Operational Indicator (EEOI) is used more and more common [3]. EEOI and fuel consumption are directly depended on ship speed under the conditions that transport volume is constant. Shipping industry has introduced energy efficiency into ship schedule and routing optimization. Dongping Song et al introduced the shipping emission as one of the three objectives in optimization of liner planning [4]. The improved non-dominated sorting genetic algorithms were used. Inge Norstad et al optimized the ship speed for ship schedule and routing optimization [5]. Shuaian Wang et al also used optimized ship speed for container liners schedule and routing [6]. Slow steaming can apparently reduce fuel consumption as well as CO2 emissions [7]. The research conducted by Haakon Lindstad pointed out that slow steaming can reduce emissions by 28% with a zero abatement cost [8]. However, there is an “energy efficiency gap” difference between the actual lower level of the implementation of energy efficiency measures and the higher level that would appear to be from the consumers or firms point of view based on techno-economic analysis [9]. There are many reasons leading to the difference, such as split incentives, informational problems, hidden costs, and so on. Among these reasons, the life cycle cost is an obvious and important one.
Life cycle assessment (LCA) method had been used in the marine context. Chatzinkolaou et al established a holistic framework for researching ship gas emissions in life cycle view [10]. Eduardo Blanco-Davis et al suggested that life cycle assessment could be used as a regulatory measure for improving shipping energy efficiency [11]. EEOI was taken as the metric during the phase of ship operation. Life cycle assessment was introduced to comparison and selection of marine power and propulsion systems [12]. By using life cycle assessment, the environmental impacts of two design concepts of a Panamax bulk carrier were compared: lighter and heavier lightship weights [13]. And the result was interesting that the heavier hull bulk carrier is friendlier to the environment. However, life cycle assessment wasn’t introduced to ship speed optimization neither in slow steaming research nor in ship schedule and routing optimization. To a certain extent, the optimized ship speed is the result of local optimization without life cycle assessment, because only the operational phase of the ship life is involved. In fact, energy consumed in other parts of ship life, i.e. building, maintenance and scrapping, has to be compensated in operational part of life. Therefore, the optimized speed during operational phase of ship life may not be the “real” optimized speed. This paper tries to find the impact on ship speed and EEOI after introducing the energy consumed during other parts of ship life. The efficiency of main engine is varying with different engine revolution or ship speed. Moreover, the ship resistance is also varying with different ship speed and draft. Hence, the modeling and simulation method is applied here in order to get more accuracy results. Ship propulsion model can calculate fuel consumption and exhaust emissions under various navigation conditions [14], and had been used to investigate propulsion performance of a large container ship running at slow steaming conditions [15]. The bulk carrier YUMING, which is also the training ship of Shanghai Maritime University, is taken as the case ship. Life cycle assessment was applied to the ship. Ship propulsion model with a low-speed two-stroke diesel engine model was built. Energy consumption in other parts of ship life was converted into a part of real time EEOI. Simulation results were presented. And the impact on ship speed and EEOI were discussed.

2. Real Time EEOI with LCA

2.1. Real Time EEOI

In the guide issued by IMO in 2009 [16], single trip and average EEOI were defined. For the purpose of optimization of EEOI, the real time EEOI for a single trip was defined as Equation 1.

$$EEOI = \frac{\sum_{j=0}^{n} \int_{t}^{t+T} C_{f} f_{C} \, dt}{M \int_{t}^{t+T} v_{s} \, dt}$$

(1)

where $C_{f}$ is the carbon dioxide conversion factor of the $j$th class of fuel, $M$ is the cargo capacity (t), $T$ is the cycle time (s), $f_{C}$ is the $j$th class of instant fuel consumption rate (g/h), and $v_{s}$ is the instant ship speed (knots).

2.2. Real Time EEOI with LCA

A ship’s life is passing whatever she is berthing or running after the ship was put into operation. Energy consumptions and CO$_2$ emissions in other parts of her life have to be compensated in the operational phase. Therefore, it’s reasonable to take life cycle assessment results into account when calculating EEOI. The average CO$_2$ emissions rate from life cycle assessment can be obtained by divided the design ship life, as shown in Equation 2.

$$f_{C,LCA} = \frac{F_{C,LCA}}{L_D}$$

(2)
where $f_{c,LCA}$ is the CO2 emission rate from LCA results (g/h), $F_{c,LCA}$ is the total CO2 emission from LCA results (g), $L_{D}$ is the design life of ship (h).

By adding the CO2 emission rate from LCA, the real time EEOI can be defined as Equation 3.

$$EEOI = \frac{\sum_{j=0}^{n} C_{f,j} \int_{t}^{T} f_{c,j} dt + \int_{t}^{i+T} f_{c,LCA} dt}{M \int_{t}^{i+T} v_{s} dt}$$  (3)

The cargo capacity $M$ is zero when there is no cargo on board. Hence, Eq.1 and Eq.3 cannot work when the ship has no cargo. Furthermore, there is energy consumed even if the ship is empty. Therefore, the cargo capacity can be substituted by the displacement of the ship. The advantage of doing that is the real time EEOI can be obtained whatever the ship is full load or ballast condition.

### 2.3. Life Cycle Assessment

There are four main phases in the whole life of a ship, namely building, operation, maintenance and scrapping, as shown in Figure 1, because the CO2 emission during design phase is negligible. In the building phase, manufacture of hull and machinery will consume a large quantity of steel and other materials, electricity and other forms of energy. In the scrapping phase, energy will consumed, but a part of materials would be recycled. In the operation phase, the main energy consume is fuel consumption. The total CO2 emissions within building, maintenance and scrapping phases have to be compensated in the operation phase, because the ship can produce benefits only in this phase. Therefore, the purpose of this section is to establish a basic framework to calculate the total CO2 emissions without that in operation phase. And then, it will be converted to the average CO2 emission rate during the operational phase of the ship.

![Figure 1. Main phases within the whole life of a ship.](image)

A calculating framework without operation phase is shown in Table 1. A ship is divided into two parts, namely hull and machinery. The hull is further divided into materials and protection. And the machinery is further divided into main engine, auxiliary engine and other machinery. Each part consumes different materials and energy in different life phase.
Table 1. Calculating framework for life cycle assessment without operation phase.

| Phase     | Hull | Machinery |
|-----------|------|-----------|
|           |      | Main Engine | Auxiliary Engine | Other machinery |
| Building  | Steel production | Coating | Construction | Construction | Construction |
|           | Steel handling | Transportation | Shop Test | Shop Test | Sea Trails |
|           | Transportation |               |               |           |           |
| Maintenance | Steel production | Coating | Main Spares | Main Spares | N/A |
|           | Steel handling | Transportation |               |           |           |
|           | Transportation |               |               |           |           |
| Scrapping | Energy | N/A | Steel Recycled | Steel Recycled | Steel Recycled |
|           | Steel Recycled |               |               |           |           |

In the manufacture of hull, not only a large quantity of steel and other materials but also a large quantity of transportation and processing work are required. The steel weight of a ship can be estimated by dead weight. The production of steel involves many materials, including iron ore, hard coke, coal, fuel etc, and technological process, including mining, transportation, sinter, iron making, steel rolling, etc. Therefore, CO2 emission during the process of steel production is different from country to country. In this paper, the data from mainland of China are adopted.

During the transportation of hull materials, CO2 emissions include emissions from fuel consumed and emissions from the production of the fuel. The CO2 emissions are also related to the transportation distance. This is different from shipyard to shipyard.

Rectification, cutting, blasting and welding are major process of steel handling. Steel plate rectification will consume energy. CO2 emissions in cutting are related to the cutting area, which can be estimated by the ship weight. Welding stick, energy and CO2 will be consumed. The CO2 emissions are related to the total welding length which can be estimated by the ship weight too. CO2 emissions during blasting are related to the surface area of hull and the blasting material. Paint quantity consumed is decided by the surface area of hull and the thickness of painting.

It’s difficult to exactly calculated CO2 emissions during maintenance phase. According to relative literatures, materials consumed in maintenance phase are about one tenth of materials consumed in building phase. So are the CO2 emissions.

The recycled steel during ship scrapping phase will compensate a considerable part (about 80%) of steel consumed in building phase. Calcium carbide, oxygen, water and electric power will be consumed during dismantling ship hull. That will add CO2 emissions. However, steel recycling is equal to decrease CO2 emission. Therefore, CO2 emissions will decrease in ship scrapping phase.

Almost all steel used for machinery will be recycled. CO2 emission during construction phase will be compensated in scrapping phase. Therefore, CO2 emissions from steel can be neglected. But, energy consumed during shop test and sea trail cannot be compensated. CO2 emissions during shop test and sea trail have to be calculated into the total value. When calculating CO2 emissions from main engine test, fuel consumed by main engine should be involved. In addition, electricity energy consumed by auxiliary machinery should be involved too.

The total CO2 emissions during ship life without operation phase can be calculated by Equation 4.

\[
F_{C,\text{LCA}} = F_{H,E} - F_{H,R} + F_M, \tag{4}
\]

where is CO2 emissions from hull building, maintenance and scrapping; is CO2 emissions from hull steel recycled, \(F_M\) is CO2 emissions from test of machinery.

3. Dynamic Modeling of the Ship Propulsion System

The main engine of most merchant ship is a low-speed two stroke direct reversion marine diesel engine. The engine directly drives a fixed-pitch propeller to overcome the resistance of the ship from water and
The relations among ship, main engine and propeller are very complicated especially in varying navigation conditions. CO₂ emissions of main diesel engine are various with time in real navigation conditions. To observe the energy efficiency and CO₂ emissions of the main engine, a dynamic model of ship propulsion system, including ship, propeller and main engine, is required which should have the ability to continuously run in all navigation conditions.

The structure of the propulsion model is shown in Figure 2. The main parts are components of diesel engine, including governor, fuel system, cylinder, crank, intake manifold, exhaust manifold, intercooler and turbocharger. Crank transfer indication torque and starting torque to propeller. Propeller will produce force to drive the ship moving. Wind and wave force are disturbance to ship motion.

![Figure 2. Block diagram of ship propulsion model](image)

The purpose of this study is to calculating real time EEOI. Therefore, only ship longitudinal motion needs to be considered. The ship velocity can be calculated by the 2nd Newton's Law. The propeller thrust is the driven force, yet the resistance is forces acting on ship hull by water and air. The calculation of the resistance is followed the model in literature.

The widely used mean value engine model is applied here. The engine model is divided into several components (see Figure 2). These components can be grouped into three classes. The first is to produce force and power, including cylinder and crank. The second is to supply fuel, including governor and fuel system. The third is to supply compressed air, including turbocharger, intercooler, intake manifold, exhaust manifold. The turbine of the turbocharger is driven by the hot exhaust gas. The compressor is driven by the turbine to compress fresh air. The compressed air is pumped into the intake manifold after cooled down by the intercooler. Fuel and air are mixed and burned in the cylinder to produce force and heat. The efficiency of the low-speed diesel engine can be taken as a function over the fuel/air ratio, which is varying with the navigation conditions.

### 4. Case Study

An ocean-going bulk carrier YUMING was chosen as the case ship, which is also a training ship of Shanghai Maritime University. Its main parameters are shown in Table 2. The ship equipped with a low-speed diesel engine as its main engine and four medium-speed diesels as auxiliary engines.

| Parameter                                | Value   | Parameter                                | Value   |
|------------------------------------------|---------|------------------------------------------|---------|
| Length Overall [m]                       | 189.9   | Length Between Perpendiculars [m]        | 183.0   |
| Depth Moulded [m]                        | 15.7    | Breadth Moulded [m]                      | 32.3    |
| Load draft [m]                           | 11.2    | Block Coefficient                        | 0.85    |
| Design draft [m]                         | 10.3    | Design Displacement [t]                  | 58123.9 |
| Light Ship [t]                           | 12816.0 | Design speed [knot]                      | 14.2    |
| Diameter of propeller [mm]               | 5850    | Number of blades                         | 4       |

Table 2. Main parameters of the YUMING vessel.
5. Life Cycle Assessment Results

YUMING was built in Jiangdu Shipyard. So, CO₂ emissions of materials and energy consumed during ship building, maintenance and scraping were calculated following the manufacture process of materials and power structure in mainland of China.

Table 3 illustrates the CO₂ emissions of hull during building, maintenance and scrapping. Construction of vessels needs many types of materials. But only steel and paint are calculated in Table 3 because of the difficult of data acquisition. Manufacture of these two types of materials is involved both in ship building and maintenance phase. A considerable ratio of hull steel will be recycled during scrapping. So, the CO₂ emissions are minus during steel recycling. The CO₂ emitted by main engine and auxiliary engines during shop test and sea trail are demonstrated in Table 4.

| Phase   | Material | Procedure       | Material Quantity [unit] | CO₂ per unit (kg) | Individual total (kg) |
|---------|----------|-----------------|--------------------------|-------------------|----------------------|
| Building | Steel    | Manufacture     | 1.218×10⁴ [t]           | 3692.7            | 4.496×10⁷            |
|         |          | Transport       | 2.435×10⁶ [t·km]        | 0.025             | 6.189×10⁴            |
|         |          | Cutting         | 405.8 [m²]              | 1.85              | 751.9                |
|         |          | Welding         | 1.098×10⁵ [m]           | 2.30              | 2.529×10⁵            |
|         |          | Blasting        | 3.687×10⁴ [m²]          | 2.56              | 9.425×10⁴            |
|         | Paint    | Manufacture     | 1.469×10⁴ [kg]          | 3.49              | 5.131×10⁴            |
| Maintenance | Steel    | Manufacture     | 1.218×10³ [t]           | 3692.7            | 4.496×10⁶            |
|         |          | Transport       | 2.435×10⁵ [t·km]        | 0.025             | 6.189×10³            |
|         |          | Cutting         | 40.6 [m²]               | 1.85              | 75.2                 |
|         |          | Wielding        | 1.098×10⁴ [m]           | 2.30              | 2.529×10⁴            |
|         |          | Blasting        | 3.687×10³ [m²]          | 2.56              | 9.425×10⁴            |
|         | Paint    | Manufacture     | 1.469×10³ [l]           | 3.494             | 5.131×10³            |
| Scraping | Steel    | Dismantling     | 1.218×10⁴ [t]           | 10.70             | 1.302×10⁵            |
|         |          | Recycling       | 9.740×10³ [t]           | -2614.17          | -2.546×10⁷           |
|         |          | Transport       | 1.948×10⁶ [t·km]        | 0.025             | 4.951×10⁴            |
| Total   |          |                |                          |                   | 2.468×10⁷            |

Table 4. CO₂ emissions during test of machinery.

| Engine          | Test        | CO₂ emissions from fuel [kg] | CO₂ emissions from power [kg] | Individual total [kg] |
|-----------------|-------------|-----------------------------|------------------------------|-----------------------|
| Main engine     | Shop Test   | 20451                       | 921                          | 21372                 |
|                 | Sea Trail   | 12808                       | -                            | 12808                 |
| Auxiliary engine| Shop Test   | 8125                        | -                            | 8125                  |
|                 | Sea Trail   | 4199                        | -                            | 4199                  |
| Total           |             | 45584                       | 921                          | 25133                 |

After CO₂ emissions of hull and machinery were calculated, the total value could be obtained as shown in Table 5. Table 5 also shows the average CO₂ emissions during the ship life. The results may be lower than the true value because there may be some of materials and factors that are not involved in the calculating framework.

| Parameter                  | Value     |
|----------------------------|-----------|
| CO₂ emission from hull [kg]| 2.468×10⁷|
| CO₂ emission from machinery [kg]| 2.513×10⁴|
| Total [kg]                 | 2.470×10⁷|
| Design life [year]         | 15        |
| Average CO₂ emissions [g/s]| 52.2      |
6. Real Time EEOI Results
In order to reduce the effectiveness of acceleration of ship, the initial ship speed was set to 12 m/s (about 23.67 knot). Simulation time span was set to 3600 s. A variable step size method (ode45 in Simulink) was applied here, which maximum and minimum steps were set to auto. The cycle time for the real time EEOI value calculation was set to 30 seconds. For the purpose of comparing the real time EEOI value with or without life cycle assessment when the ship is slow steaming, various revolution order were set to the main engine before a simulation was started. Figure 3 to Figure 6 show the real time EEOI value with and without LCA result (average CO₂ emissions under life cycle assessment) under different ship draft conditions.

7. Discussion
It can be seen from Figure 3 to Figure 6 that the ship speed is decreasing along the decreasing of the main engine revolution under different ship draft. However, the real time EEOI values have the lowest point both with and without LCA result. The reason is the efficiency of the main engine is getting lower when the power and revolution of the engine is lower. That illustrates the environment benefit from slow steaming has a lower bound although the fuel consumption of main engine may decrease more. The real time EEOI value at the same engine revolution is getting smaller along the increasing of ship draft. The real time EEOI without LCA result is lower than that with LCA result at each draft and each engine speed, especially at lower engine speed. This phenomenon illustrates explicitly that LCA results will enlarge real time EEOI value especially when the ship is slow steaming. The true effect may be more significant considering that the LCA result may be under estimated. The lowest real time EEOI without LCA result occurs around 60 rpm, yet the lowest real time EEOI with LCA result occurs around 65 rpm. This shows that LCA result will increase the lower limit when the speed and route optimization is conducted. The speed at which the lowest real time EEOI can be obtained is also less affected by the ship draft. There is around 7% percentage increment of the real time
EEOI value at 50% rated power. The percentage increment is large enough to be pay attention to. Hence, considering the more sailing time because of the lower speed, it may decrease the environment benefit from slow steaming if the LCA results have been involved.

8. Conclusions
Life cycle assessment result has significant effect on the real time EEOI value especially when the ship sails at lower engine speed. The engine revolution at the lowest real time EEOI value will increase explicitly, namely the lower limit speed of ship will increase during slow steaming with the consideration of life cycle assessment result. Considering the more sailing time, slow steaming may bring less environmental benefit if the life cycle assessment result is involved.

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