Enhancing energy efficiency for new generations of containerized shipping

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ABSTRACT
The present paper aims to study the best methods that can be applied to improve energy management onboard container ships of large capacity. Container ships of class A13, A15, and A19 are considered. Those ships are taken as a reference to evaluate the impact of the proposed methods from the viewpoints of environmental and economic aspects. Their calculated energy efficiency values are 3.94, 4.28, and 16.29 gCO₂ per ton. Nautical mile, respectively. Ship class A19 appeared as the best ship in terms of emissions rates that can be reduced annually with reference to the transported cargo. These rates are 3.4, 149.9, 13.8, 5677, and 1.8 kg/TEU for SO₂, NOₓ, CO, CO₂, and PM emissions, respectively. To enhance energy management for the A13, the ship will be forced to decrees its speed by 45 percent. The proposed concept will fulfill with 2023-year legislations by rate of 5860 $ per each ton CO₂ decreased. Alternatively, applying the strategy of LNG fueled engine for container ship class A19 can expand the energy measure about 9.34% at yearly operating reduction by 24.7 million dollars.

1. Introduction
For a long time, ships relied on fossil fuels as an energy source. (Merten-Paul et al., 2018; Hua et al., 2017; Seddiek, 2016) implied that this type of fuel has become one of the problems facing ships. (IMO, 2014b; Johanson et al., 2017) showed that in its recent reports; the International Maritime Organization (IMO) indicated that the shipping industry is responsible for 2.7% and 6.6% of greenhouse gases of carbon dioxide (CO₂) and nitrogen oxides (NOₓ), respectively, with perceptions of a rising trend (Seddiek and Elgohary, 2014; Seddiek, 2016; Yang et al., 2012) explained that to mitigate the negative impact resulting from vessels’ emissions; the IMO set guidelines 13 and 14 to curtail NOₓ and SO₂ emissions, respectively. Such legislations are found in the International Convention for the Prevention of Maritime Pollution MAR-POL 73/78, Annex VI. A further policy has been imposed to reduce Carbon dioxide emissions by 30 percent at the end of 2023 (Ammar, 2018; Hou et al., 2019; Same and Köpke, 2012). The measures include the Energy Efficiency Operational Indicator (EEOI) and the Energy Efficiency Design Index (EEDI) (Rehmatulla et al., 2017). Fig. 1 presents data about top categories of ships that have the greatest impact on fuel consumption and CO₂ emissions. From the Figure, it could be found that container vessels became accountable for emitting nearby two hundred million tons of CO₂ as a result of consume a huge amount of fossil fuels, this represents around 27% of whole ships’ consumed fuels (IMO, 2014b; UNCTAD, 2011).

At the worldwide level, the IMO executed a few methods that proposed for enhancing vessels energy. The estimations of the vessel’s power effectiveness including vessel’s profile, propulsion means, prime movers, and vessel’s arrangements. (Guangrong et al., 2013) showed that the influence of the vessel’s profile can be attained through enhancement of the forward section design, body painting, and resistance reduction. (Sarasquete et al., 2011) explained that propulsion means and ship’s steering devices will contribute to power management employing Kort nozzle propellers, and twin or multi-engine propeller. (Diab et al., 2016; Benvenuto et al., 2014) revealed that the prime movers development play a role in the way of power management including electronic injection upgrades, and other technologies such as wind and solar power. Shipping financial aspects presents a significant influence on the growing of the international trade. Transfer cost of a cargo onboard container vessels valued giving to size of the cargo’s unit twenty or forty feet, in addition to the location where the cargo will be shipped. Since the harbor of Shanghai is one of the major harbors in the world to receive ships carrying containers, the harbor could be used for actual statistics. Fig. 2 represents the information of transferring cargo.

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between Shanghai and other famous harbors, such as with Shanghai-West Africa, Shanghai-Mediterranean, Shanghai-Northern Europe, and Shanghai-United State West Coast (UNCTAD, 2011; Brent-Petersen and Rex, 2018; Deloitte, 2019).

The objective of this research is to illustrate the economic and environmental profits from spread over the EED strategy for maritime vehicles. Container ships of A19, A15, and A13 are considered. Moreover, different methods for enhancing energy effectiveness are demonstrated, specifically ship’s speed reduction, LNG engines, and ship’s optimum dismissions.

2. Environmental and economic modeling of the energy efficiency indexes

Environmentally, CO₂ emissions from ships are evaluated using energy efficiency design indexes. For ships, two standards of EEDI could be estimated, the reference (EEDIₐref) and the calculated or the attained (EEDIₐatt) values (Ammar, 2018; IRCLASS, 2013). The estimated value for a given class of vessel should not surpass the IMO reference value (IMO, 2014a). EEDIₐref could be calculated as expressed in Eq. (1).

\[
EEDI\text{ₐ}_{\text{ref}} = \left( \frac{d}{C} \right) \left( 1 - \frac{R}{100} \right)
\]

(1)

where, (z) and (d) are the constants depends on ship characteristics and equal 0.201 and 174.22, respectively for container vessels. (C) is the container ship deadweight. It depends on the ship type. Re is the percentage of reduction in the EEDI rated value, as determined by the vessel-built year. These reduction percentage are set to be 10 percent in 2015 and 20 percent in 2020 to 30 percent in 2025 by IMO (Tran, 2017; Ancić and Sestan, 2015).

The attained value (EEDIₐatt) are expressed in terms of (gCO₂/ton-NM) using Eq. (2) (IMO, 2014a; Zhu et al., 2017; Beckmann and Steen, 2016).

\[
EEDI\text{ₐ}_{\text{att}} = \frac{\prod_{j=1}^{M} f_j \sum_{i=1}^{n} P_{ME(i)} \cdot SFC_{ME(i)} \cdot C_{FME(i)}}{\sum_{i=1}^{n} P_{PTI(i)} \cdot f_{eff(i)} \cdot P_{AEeff(i)} + \sum_{i=1}^{n} P_{AE(i)} \cdot SFC_{AE} \cdot C_{FAE} + 250}
\]

(2)

where, \(P_{ME(i)}\) is the power output of ship prime mover, \(P_{AE}\) is the power output of the diesel generator(s); 
\(SFC_{AE}\) is the diesel generator’s quantity of the consumed fuel per gram hour; 
\(C_{FME(i)}\) and \(C_{FAE}\) are the fuel conversion factors of the prime mover and the diesel generator to CO₂. 
\(P_{PTI(i)}\) is the power take in for the shaft motor/generator; 
\(P_{AEeff(i)}\) are the power saved duo to using innovative technology methods with availability factors of \(f_{eff(i)}\).

The output power of the auxiliary engines (\(P_{AE}\)) is estimated according to the prime mover maximum continuous rating (MCR) as shown in the following two equations.

\[ P_{AE(MCR(ME)>10MW)} = 0.025 \left( \sum_{i=1}^{n} MCR_{ME(i)} + \sum_{i=1}^{n} P_{PTI(i)} \cdot 0.75 \right) + 250 \]

(3)
\[ P_{AE(MCR(ME)<10.00kW)} = 0.05 \left( \frac{MCR_{Rh} + \sum_{ph}^{\text{PTI}} P_{\text{PTI}}}{0.75} \right) \]  

(4)

The transported work could be evaluated as follows.

\[ \text{Transport work} = v_{ref} \cdot C_{f1} \cdot f_{c} \cdot f_{e} \cdot f_{w} \]  

(5)

where, \( v_{ref} \) is the reference vessel speed in knots; \( f_{c}, f_{1}, f_{w}, f_{e} \) are parameters depending on the ship characteristics. The values for these parameters equal 1.0 if they are applicable onboard the ship (IRCLASS, 2013). For container ships, the correction factor for the decrease in speed due to both weather and environmental conditions \( f_{w} \) can be calculated using Eq. (6).

\[ f_{w} = 0.0208 \times \ln(\text{Capacity}) + 0.633 \]  

(6)

Moreover, the operational energy efficiency design index (EEOI) could be calculated in terms of tone CO\(_2\)/transport work as expressed in Eq. (7) (IMO, 2009).

\[ \text{EEOI}_{\text{average}} = \frac{\sum_{ph} \sum_{i} \sum_{j} \sum_{m} M_{\text{cargo}} \times D_{i}}{\sum_{ph} \sum_{i} \sum_{j} \sum_{m} \sum_{c} F_{E} \times L_{c} \times EF_{c} \times m_{\text{fuel}} \times P_{c}} \]  

(7)

where, \( i, j \) and \( m \) are the number of ship voyage and the type of the used fuel onboard, respectively; \( M_{\text{cargo}} \) is the mass of the consumed fuel; \( C_{f} \) is the fuel conversion factor to CO\(_2\). \( M_{\text{cargo}} \) is the mass of the transported cargo; \( D_{i} \) is the trip or voyage distance travelled by the ship.

Generally, the total ship emissions during one trip \( (E_{\text{trip}}) \) will equal the summation of the total ship emissions for hoteling, maneuvering, cruise operations as shown in Eq. (8).

\[ E_{\text{trip}} = E_{\text{hotel}} + E_{\text{man}} + E_{\text{cruise}} \]  

(8)

When the engine power is known in each navigational phase, the ship emission per trip \( (E_{\text{trip}}) \) expressed in tons can be calculated using Eq. (9).

\[ E_{\text{trip,i,j,m}} = \sum_{ph} \sum_{c} T_{ph} \sum_{c} (P_{c} \times L_{c} \times EF_{c} \times m_{\text{fuel}} \times P_{c}) \]  

(9)

where, \( ph \) is the different phases of trip, \( e \) is the main or auxiliary engines category, \( P \) and \( L \) are the main engine output power (kW) and load, respectively; \( T \) is the trip time in hours; \( i \) is the type of pollutant emissions, \( j \) is the engine type, \( m \) is the fuel type, and \( EF \) is the emission factors expressed in g/kWh for SO\(_2\), CO\(_2\), PM, HC and CO, respectively for slow speed diesel engine running with fuel contains 0.1% S (ICF, 2009; Ammar, 2019). According to the air pollutant emission inventory guidelines (Trozzi and De Launetris, 2016) the average NO\(_x\) emission factors expressed in g/kWh for slow speed diesel engine with regards to the vessel phase (cruising, hoteling, maneuvering) and the installation years are as follows: In case of ship’s cruise mode, NO\(_x\) emission factor is 17, 16.4, and 15.8 g/kWh for engines marked at year 2000, 2005, and 2010, and beyond respectively. But, in case of maneuvering and hoteling mode, this factor will be 13.6, 13.1, and 12.7 g/kWh for engines marked 2000, 2005, and 2010 and beyond, respectively. These values are estimated for the engines without installation of De-NOx emission system.

Economically, the annual ship profit (ASP) can be calculated using Eq. (10).

\[ \text{ASP} = \left[ F_{c} - (C_{f} + C_{p} + C_{\text{fuel}} \times m_{\text{fuel}}) \right] \times N_{l} \]  

(10)

where, \( F_{c} \) is the freight cost for each trip; \( C_{f} \) is the fixed costs for each trip; \( C_{p} \) is the passed navigational canal fees during cruise; \( m_{\text{fuel}} \) is the mass of the consumed fuel, \( C_{\text{fuel}} \) is the consumed fuel cost, and \( N_{l} \) is the number of trips per year.

### Table 1

<table>
<thead>
<tr>
<th>Specifications</th>
<th>A19</th>
<th>A15</th>
<th>A13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship’s Name</td>
<td>MV. AL DAHNA</td>
<td>UMM QABN</td>
<td>AL RIFFA</td>
</tr>
<tr>
<td>IMO No.</td>
<td>9708825</td>
<td>9732333</td>
<td>9525912</td>
</tr>
<tr>
<td>Built</td>
<td>2016</td>
<td>2016</td>
<td>2012</td>
</tr>
<tr>
<td>L.P.P. m</td>
<td>383.00</td>
<td>352.00</td>
<td>350.0</td>
</tr>
<tr>
<td>Moulded breadth, m</td>
<td>58.60</td>
<td>51.00</td>
<td>48.20</td>
</tr>
<tr>
<td>Displacement, ton</td>
<td>257947</td>
<td>194967</td>
<td>187974.2</td>
</tr>
<tr>
<td>Dead weight (MT)</td>
<td>199744</td>
<td>149360</td>
<td>145227.9 MT</td>
</tr>
<tr>
<td>Ship speed, Kt</td>
<td>22/21</td>
<td>22/23</td>
<td>24.1/25.23</td>
</tr>
<tr>
<td>Operation/Design</td>
<td>HAUN-DAIN</td>
<td>Hyundai - MAN</td>
<td>MAN &amp; W</td>
</tr>
<tr>
<td>Main engine type</td>
<td>B&amp;W 105900E</td>
<td>B&amp;W 98900 ME-C</td>
<td>12898ME</td>
</tr>
<tr>
<td>Power (85% MCR) (kW)</td>
<td>41800</td>
<td>37620</td>
<td>64570</td>
</tr>
<tr>
<td>Auxiliary Generators</td>
<td>3 X 4320 KW</td>
<td>4 X 4320 kW</td>
<td>3 X 4250 kW</td>
</tr>
<tr>
<td>Waste Heat Recovery (kW)</td>
<td>2650 T/G</td>
<td>2650 T/G</td>
<td>1818 T/G</td>
</tr>
<tr>
<td>Shaft Generator (PTI/ PTO) (kVA/kW)</td>
<td>5620/4500</td>
<td>5620/4500</td>
<td>3222/2578</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Diesel fuel consumption (m³)</th>
<th>A19</th>
<th>A15</th>
<th>A13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per year</td>
<td>43,672</td>
<td>39,305</td>
<td>103,682</td>
</tr>
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<td>43,672</td>
<td>39,305</td>
<td>103,682</td>
</tr>
</tbody>
</table>

3. New generation of container ships: case study

Three vessels are considered for evaluating effect of increasing the capacity of container ships regarding the environmental issue, especially EEDI estimations. The selected vessels owned by one of the famous container ship companies, named Hapag-Lloyd that participated by valuable percentage in maritime transport sector. According to the container ships classification, the ships called A19, A15, and A13. A13 follows Malta maritime authority, home-port Valletta, with 13500 containers; A15 follows Marshall Islands maritime authority, home-port Majuro, with 14993 containers; and A19 follows Malta maritime authority, home-port Valletta, with 19870 containers. The other important data are described in Table 1.

The three ships depend on slow speed diesel engine to generate the energy necessary to move the ship with the use of fuel containing 0.1 percent sulfur. The engine is also equipped with a system to recover lost heat. Ships are used to transport cargo between several ports in the United States of America, the Mediterranean and the Middle East region.

4. Results and discussion

The benefits and the eco-friendly impact caused by the application of various methods to be enhancing energy management on the three vessels are studied during this section. A comparison between the achieved energy measure and the setting value by the international legislation is held. The ships’ environmental and economic situation is also identified for ship of class A13, in case of implement speed reduction strategy. Lastly, the applicability of using LNG as a fuel onboard vessel of class A19, where the infrastructures are already initially installed on-board; is studied. It is assumed that the three vessels sailing between Shanghai and United States west coast harbors, where a huge amount of cargo transported between these harbors (UNCTAD, 2011; Deloitte, 2019). According to the collected data, the ships rout is 20600 N.M. Each ship spends a certain period from the beginning of journey to the end of its rout, according to its characteristics. For simplicity of estimations, the present research considering six journeys annually.
mode \((P_{AE} \text{ neglect})\). So, ships will depend on the shaft generators as a source of electricity. Moreover, \((V_{ref})\) will be used for ships, calculations (Perera and Mo, 2016).

4.1. Environmental results

For the selected case studies, the prime mover is the main source of pollutant emissions, in the open sea. This is because the source of the electric power is provided by the shaft generator connected to the prime mover reduction gear system. Calculating the consumed fuel for the case study could be taken as a clear indicator of the vessel’s rate of pollutant emissions. Table 2 illustrates the fuel consumption of the selected ships A19, A15 and A13. The highest fuel consumption is for A13 class container ship, despite of its low capacity. This is due to the high output power of the ship prime mover (64,570 kW), which sails with a speed of 24.1 knots, compared to the other two ships.

The different emission rates can be calculated for the three container ships by means of the predetermined fuel consumption values as illustrated in Table 3. A13 container ship produces the highest NO\(_x\), SO\(_x\), CO, CO\(_2\), and PM emission rates per trip. This is due to the high amount of the consumed fuel for its prime mover engine when be comparable to A19 and A15 class container vessels. In contrast, A15 container ship results in the lowest emissions per trip. In addition, the annual exhaust gas pollutants are estimated per one unit of the container vessel’s capacity. A19 class container vessel has the lowest emission values per transported container for the different pollutant gases.

The new generations of container vessels are built with the installed selective catalytic reduction system for reducing NO\(_x\) emissions in order to comply with IMO 2016 emission legislations. In addition, SO\(_x\) emissions are to be complied with IMO 2020 regulations. Fig. 3 shows NO\(_x\) and SO\(_x\) emissions rates for the three classes of container vessels compared with the latest IMO emission regulations. It is noticed that, the case studies achieve the required SO\(_x\) emission rates due to the use of ultra-low sulfur fuel. For NO\(_x\) emissions, SCR system installed on the exhaust gas piping system reduces these emissions by 80% which achieves the required IMO restrictions. The values of NO\(_x\) and SO\(_x\) emissions in kg/min during maneuvering are lower than cruise mode. This is due to the reduced engine efficiency and the increased specific fuel consumption at low engine loads (ICF, 2009; Ammar and Seddiek, 2017, Eea, 2000).

It is necessary to take the load dependency of SCR performance into consideration when evaluate the SCR system regarding the ship’s NO\(_x\) emission reduction. Experiments carried out by (Briggs and Mccarney, 2013, Fujibayashi et al., 2013, Zheng et al., 2014) implied that the most important factors to ensure steady and optimal SCR operation are to ensure good mixing of urea, controlling the temperature into the SCR reactor and soot blowers performance. The SCR efficiency shows a slightly increment with the increase of engine load at part load zone, however it will be fixed at the normal condition loads if the correct operation is followed as shown in Fig. 4. This include control the warmup period of the SCR reactor, which takes from 30 min to 50 min to ensure that the catalyst surface is not covered with soot, ash or sulfates. Hence, although that the SCR system can achieve a NO\(_x\) reduction percent of 90%, during the calculation; 80 percent will be taken as an average value during ship’s cruise mode in anticipation of an occurrence malfunction of soot blower (Christensen, 2018). For the case study ships, the NO\(_x\) emission rates are reduced by 80% using SCR. Therefore, NO\(_x\) and SO\(_x\) emission rates comply with the IMO limits during maneuvering and cruise modes.

IMO regulations for reducing CO\(_2\) emissions depends mainly on improving the design and the operation of ships through EEDI and EEOI.

![Fig. 3. IMO limits for NO\(_x\) and SO\(_x\) emissions.](image-url)

![Fig. 4. Load dependency of SCR performance.](image-url)
The calculated EEDI and EEOI for the three container ships.

<table>
<thead>
<tr>
<th>Capacity (TEU)</th>
<th>EEDIcal. [gCO\textsubscript{2}/ton-NM]</th>
<th>EEOI [g CO\textsubscript{2}/TEU.NM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A19</td>
<td>3.94</td>
<td>60.17</td>
</tr>
<tr>
<td>A15</td>
<td>4.28</td>
<td>68.7</td>
</tr>
<tr>
<td>A13</td>
<td>16.3</td>
<td>183.5</td>
</tr>
</tbody>
</table>

Table 4

Table 5

The actual EEDI is compared with the IMO reference values presented in three phases. The initial values for the EEDI recommended by IMO for A19, A15, and A13 container vessels are 14.99 gCO\textsubscript{2}/ton-NM, 15.89 gCO\textsubscript{2}/ton-NM, and 15.98 gCO\textsubscript{2}/ton-NM, at deadweights of 199744, 149360, and 145327.9 metric ton, respectively. In 2025, these reference standards would be decreased to 10.49 gCO\textsubscript{2}/ton-NM, 11.12 gCO\textsubscript{2}/ton-NM, and 11.18 gCO\textsubscript{2}/ton-NM, respectively. Further reductions by 10%, 20%, and 30% is applied for the first, the second, and the third phase, respectively. Table 4 illustrates the calculated EEDI and the EEOI values for the three container vessels. A19 class container vessel has the lowest CO\textsubscript{2} emissions compared with the other two vessels from the design and operational points of view.

The calculated EEDI values for the three vessels incorporate the improvement due to the installed shaft generator and turbo alternator as a waste heat recovery system (WHR) as illustrated in Fig. 5. The output electric power from the shaft generator is the main source of electric power onboard the ship at MCR. This will enhance the EEDI value for the case study. On the other hand, the output power of the three turbo generators installed onboard A19, A15, and A13 container vessels are 2650 kW, 2650 kW, and 1818 kW, respectively. It can be noticed that, the higher output powers both the shaft and the turbo generators will lead to high enhancement in the EEDI value for the case study.

Fig. 6 shows the different values for the calculated EEDI for the three case studies compared with the corresponding phases II and III reference values. The calculated EEDI for A19, A15, and A13 container vessels are based on vessel’s speeds of 21.21, 22, and 24.1 knots, respectively. Both A19 and A15 container vessels comply with the required EEDI values for the second and the third phases. In contrast, the calculated EEDI for A13 case study do not comply with IMO phases. The calculated EEDI value (16.3 gCO\textsubscript{2}/ton. NM) should be reduced to 12.78 and 11.18 16.3 gCO\textsubscript{2}/ton. NM to comply with the second and the third phase, respectively.

EOI is the second IMO index used for reducing the amount of CO\textsubscript{2} emitted from ships during their normal operations. Fig. 7 shows the average EEOI results for the three case studies. The EEOI is calculated for A19, A15, and A13 container vessels based on the number of transported containers 19870, 14993, and 13500 TEUs, respectively for 20600 nautical miles. During ship maneuvering and standby modes, the amount of the consumed fuel is calculated based on 20% and 5% engine loads, respectively. The EEOI is enhanced in case of the vessel speed is increased due to the transferred cargo and fuel consumption. Finally, the lower value of the EEOI, the more improved energy efficiency of the ship.

4.2. Economic results

The financial aspects of container ship class A13 and the new generations A15 and A19 are studied. The improvements in the new generations, build in 2016, not only includes the effectiveness with IMO emission regulations but also increased ship capacity with modification in the main dimensions especially length-to-beam ratio. To evaluate the economic benefits for the three container ships, the annual income measure is estimated for the three different ships. The measure involves the analysis of the yearly freight, ships’ operating investments for the three ships. Table 5 shows the cost of fuel used by the prime mover in $/year. The figures are according to the collected prices of marine fuel of 772.6 $/m\textsuperscript{3} (Bunkerworld, 2019) and the cost of supply the fuel to ship of 8.0 $/m\textsuperscript{3} (Ammar and Seddiek, 2017; Ammar, 2019). The maximum yearly cost of consumed fuel is 80.94 million US$ for A13 class container vessel. This is due to A13 consumes a higher quantity of oils for each trip more than ships class A19 and A15.

Also, the cost of transferred cargo could be determined using the freight rate of the vessel’s route and the number of containers transported by the different vessels. The cost of transporting one unit from Shanghai to the United State west coast is 1225 $/TEU. Therefore, the

Fig. 6. Calculated phases II and III EEDI values for the three case studies.

Fig. 7. Calculated EEOI for the case studies at the design and the operational speeds.
Fig. 8. Annual profit for A19, A15, and A13 container ships.

The total annual costs of cargo transporting are 292.1, 220.4, and 198.5 million US$/year for A19, A15, and A13 container vessels, respectively. Besides, the total annual fuel costs are 45.22, 38.08, and 90.59 million US$/year, respectively. In addition, the annual fees for passing through Suez canals are 8.78, 7.30, and 6.819 million US$/year, respectively. The average annual crew costs are assumed 0.73 million US$/year. The highest annual profit with specific cargo transporting profit of 995 million dollars with CO₂ emissions reduction in a ton. This will reduce the shipping speed, the output power of prime mover will be reduced, consequently. This will accordingly decrease the amount of CO₂ emissions.

Fig. 9 shows the annual profit for the three ships. Ship of class A19 has the highest annual profit with specific cargo transporting profit of 995 million US$/TEU. While the A13 container ship uses shaft generator and turbo-generator which improve the calculated EEDI value, it is still not complied with IMO requirements. To improve the energy efficiency for this ship, in the short run, the speed reduction is assumed. This will reduce both CO₂ emissions and the cost of the consumed fuel, especially in case of increased fuel prices (Tezdogan et al., 2016). Amount of the consumed fuel in case of ship slow steaming (m₀ₙ) could be estimated for the journey depending on the relation between designed speed (V₀) and the operation speed (Vₙ) (Banawan et al., 2013; Ammar, 2018) as shown in Eq. (11)

\[
m₀ₙ = \left[ m_{AE} \cdot \left( \frac{V₀}{Vₙ} \right)^3 + \frac{m_{ME}}{24 \cdot Vₙ} \right] Dₙ \]

(11)

where, \(m_{AE}\) and \(m_{ME}\) are daily amounts of diesel generator and prime mover, respectively.

On the other hand, the annual fuel saving costs (FSC) at the different scenarios of speed reduction could be estimated as follows.

\[
FSC = m₀ₙ \cdot \left[ C_{fuel} \cdot \left[ 1 + i)^n \right] \right]

(12)

where, (m₀ₙ) is the mass of fuel saving per journey; (i) is the annual fuel price change percent; (n) is the anticipated working years for the vessel.

The value of carbon Di-oxide cost-effectiveness (CERCO₂), which result due to ship’s speed reduction; could be determined as follows (Eide et al., 2009; Bishop et al., 2014).

\[
CERCO₂ = \frac{P_{loss} - C_{off}}{R_{CO₂}}
\]

where, \(P_{loss}\) presents the loss of vessel’s income due to reduce the speed, \(C_{off}\) is the financial paybacks through the vessel life as a result of fuel-saving; \(R_{CO₂}\) is the amount of CO₂ emissions reduction in a ton.

To evaluate the outcome from the viewpoint of energy measure, in case of ship speed reduction for the ship class A13; the value of specific fuel consumption of the prime mover at various loads should be estimated. Using the MAN B&W K98ME-C7.1 project guide (Man, 2014), the relation between prime mover load and the consumed fuel could be estimated using a curve fitting concept as shown in Fig. 9. As the vessel speed is reduced, the output power of the prime mover will be reduced, respectively. These estimations are based on 13,500 TEU of transported cargo for each ship journey along with the distance from Shanghai to United States west coast harbors (20,600 nautical miles). The impact of low speeds on the efficiency of the A13 vessel could be assessed using the enhancement in energy efficiency indexes. With reduce the shipping speed, the output power of prime mover (PME) will be reduced. This reduction will affect the EEDI value as illustrated using Eq. (2). The enhancement in the EEDI relative to the international restrictive values in three phases is revealed in Fig. 12. On the other side, the reference energy efficiency standards are 14.38, 12.78, and 11.18 gCO₂/ton-NM for phases I, II, and III, respectively. The estimated EEDI values are 16.09, 15.56, 14.75, and 13.55 gCO₂/ton-NM corresponding to ship slow steaming by 10%, 20%, 30%, and 40%, respectively. The relative calculated to the required IMO standards for phases I and II will be 89% and 99.7%, respectively, at ship speed reduction of 45%.

Lastly, the present diesel fuel and LNG infrastructure, which installed onboard ship class A19 could be used for the analysis of the outcome of applying dual fuel on energy efficiency and fuel-saving costs. In this case, the dual-fuel emission factor (EFDFDE) should be used in place of fuel emission factor in Eq. (9). (EFDFDE) could be estimated by means of the emission factors of the diesel and LNG fueled engines (EFₜ and EFₜNG), as stated in Eq. (14), considering the dual 95% LNG and 5% diesel fuel.
The cost of a metric ton of natural gas fuels and diesel oil are 0.1075 and 772.6 $, respectively (Eia, 2019; Bunkerworld, 2019). The cost of fuel delivery to the ship for diesel fuel and LNG is 8 $/m$^3$ and 0.009, respectively (Ammar and Seddiek, 2017; Ammar, 2019). Fig. 13 shows the outcome of applying different percentages of the original fuel and LNG, and the corresponding EEDI and fuel saving for the A19 container ship on the other side. The lowest EEDI value is 3.572 gCO$_2$/ton-NM which corresponding to the highest improvement percent of 9.34% using dual fuel (5%DO, 95%NG). The annual fuel saving at these percentages is 24.7 million dollars.

4.3. Comparing the results with the new emerging technologies

According to the data provided by the maritime transportation inventories and researchers, container vessels produce the highest greenhouse gases in terms of million tons of CO$_2$ compared with other cargo ships. In addition, container vessels have a significant share in the transported cargo worldwide and this percentage is in a continuous increase every year (UNCTAD, 2011; Brent-Petersen and Rex, 2018). In order to reduce the exhaust gas emissions from container vessels, many of the navigational corporations will highly consider using mega or medium vessels. The increased capacity of containerized shipping will decrease the amount of required fuel for transported container. Consequently, the energy efficiency of big container vessels will be enhanced with the reduced fuel consumption and CO$_2$ pollutants per transported container. This will increase the ship profit and decrease the emitted greenhouse gases for the international containerized shipping. Therefore, container vessel capacities are increased in a continuous rate through the last decades. Moreover, it is noticed that, the orders for the new-built container ships for the next 5–10 years will increase the TEU capacities with 60% percent by selecting the most effective ship breadth to length ratio which may reach 6.514 (UNCTAD, 2011; Pani et al., 2015; Knowler, 2019; UNCTAD, 2019). This agrees with the current
research finding where the environmental impact and the EEDI values for the three case studies are enhanced by increasing both the ship beam and the number of transported containers per trip.

5. Conclusions

Reducing exhaust gas emissions from ships is one of the main concerns of the IMO. The energy efficiency of the three container ships classed, A19, A15, and A13, with the possible enhancement methods for the EEDI and the EEOI were discussed. In addition, other emission rates from the three ships were evaluated. The main findings from the present study are as follows:

- Environmentally, A19 container vessel generates the lowest average pollutant emissions per TEU. It releases 3.4, 149.9, 13.8, 1.8, and 5677 kg/TEU for SO\textsubscript{2}, NO\textsubscript{x}, CO, PM, and CO\textsubscript{2} emissions, respectively. The three ships comply with IMO emission regulations for NO\textsubscript{x}, SO\textsubscript{2} and CO\textsubscript{2} emissions except A13 container ship. It will be complied with the required EEDI values advised by IMO after reducing its speed by 45% from the designed value. The calculated EEDI values are 16.3, 4.28, and 3.94 gCO\textsubscript{2}-eq/ton-NM for A13, A15, and A19 container vessels, respectively. Waste heat recovery and shaft motor enhances the EEDI by 31.71%, and 9.39%, respectively, for A15 container vessel. Besides EEDI, the EEOI will be improved as the ration of the ship length to breadth is reduced.

- Economically, the cost of fuel consumption for the A13 class container vessel is the highest compared with A19 and A15. A19 container ship has the highest annual profit for transported cargo of 995 US$/TEU. In addition, reducing the speed of A13 container vessel by 45% will lead to a reduction in CO\textsubscript{2} emissions with cost effectiveness of 5863 $/ton. At this speed, the calculated EEDI value will be complied with IMO values by 89% and 99.7% for the first and the second phases, respectively. A further reduction in the EEDI value by 14% is required in 2025. Finally, using natural gas for operating A19 class container vessel will reduce fuel cost by 24.7 million dollars per year with the enhanced EEDI value by 9.34%.

CRediT authorship contribution statement

Nader R. Ammar: Conceptualization, Methodology, Software, Visualization, Investigation, Writing - review & editing. Ibrahim S. Seddiek: Data curation, Writing - original draft, Methodology, Visualization, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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