Transportation Research Part D 118 (2023) 103662

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

On the inconsistency and revision of Carbon Intensity Indicator for cruise ships

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A R T I C L E I N F O

Keywords:
Cruise market
Cruise ships
Carbon Intensity Indicator
GHG emissions
Correction of CII

A B S T R A C T

The Carbon Intensity Indicator (CII) is one of the major instruments to assess the CO_2 emissions coming from ship operations. Thus, it has a strong impact on the decisions taken by cruise companies regarding fleet allocation and itineraries planning. Although the CII works well with cargo vessels, it leads to misleading results when applied to cruise ships since the hotel load of a cruise ship is comparable to propulsion power. This leads to an inconsistency between emissions and CII values, which foster the adoption of itineraries having a higher environmental footprint. Here, a data-driven correction of the CII for cruise ships is proposed to remove the dependence of CII from the time at port/at sea. The correction is determined using a database relating to operative and forecasted emissions of a large fleet of cruise ships. The application to a medium-size cruise ship proves the potential of the proposed methodology.

1. Introduction

Global shipping activity emits significant amounts of greenhouse gases (GHGs) and contributes substantially to climate change. GHGs emissions from international maritime transport in 2018 are estimated to be around 2.9 % of the overall emissions (IMO, 2020). Besides, they are the object of specific studies in terms of environmental and cost impact (Mondello et al., 2021). In particular, passenger ships are under the spotlight of a much wider public that does not include only embarked passengers, but involves also citizens living nearby harbours where cruise ships dock. As a result, they are seen as non-necessary heavy pollution producers by a huge number of persons; however, in the global reality of the shipping industry, passenger ships are less responsible for CO_2 emissions in comparison with other types of merchant ships (European Commission, 2022). Furthermore, in the last years, cruise tourism has increased considerably, becoming one of the most appealing sectors within the touristic economy (Sun et al., 2011), as witnessed by the data relating to the years prior to the SARS-COV2 pandemic (CLIA, 2021). In 2023, estimates assert that passenger volume is expected to recover and surpass 2019 levels (CLIA, 2022). In response to this growing demand from passengers, the most important cruise companies have placed several orders for ships that will enter into service in the near future.

A natural consequence of the increase in cruise ships' number is an increment of atmospheric pollutant emissions; this affects the environment both during navigation and in port (Huang et al., 2017; Kizielewicz, 2022; Perdiguero and Sanz, 2020). Among the pollutant emissions produced by cruise ships, the most concerning for environmental health, with repercussions on humans' lives due

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https://doi.org/10.1016/j.trd.2023.103662
Received 13 December 2022; Received in revised form 27 January 2023; Accepted 14 February 2023

to the substantial contribution to the global warming phenomenon, are GHGs and carbon dioxide (CO_2) in particular (Huyen et al., 2022; Nunes et al., 2017). In response to the problem, technological advancements such as innovative power systems (Gianni et al., 2022) and energy management strategies (Balcombe et al., 2019; Eide et al., 2013) have been implemented so far, along with studies aimed at assessing the economic and environmental impacts of such solutions (Zis et al., 2022). Furthermore, various policies at different levels have been issued (Larkin et al., 2017; Zhu et al., 2022).

In this context, the International Maritime Organization (IMO) is responsible for maritime emissions regulation. In particular, as regards the environmental impact of maritime activities in terms of air pollution, IMO's Annex VI of the MARPOL Convention (IMO, 2005) is the reference text: this sets global emission limits for atmospheric pollutants and introduces special areas called Emission Control Areas (ECAs) where the policies regarding other types of atmospheric pollutants such as sulphur oxides (SO_X), nitrogen oxides (NO_X), and particulate matters (PM_X) are more stringent. Specifically, IMO's environmental limits are often determined based on statistics that consider the current global fleet and then progressively applied. This process can be classified as a data-driven approach.

IMO issued in July 2011 the resolution MEPC.203(62) that established the "Energy Efficiency Design Index" (*EEDI*) as a design index mandatory for new ships and the "Ship Energy Efficiency Management Plan" *(SEEMP)* as an operative index mandatory for all ships (IMO, 2011). The *EEDI*, valid since 1st January 2013, addresses to most of the world's merchant fleet, which is responsible for around 85 % of the CO_2 global shipping emissions. The SEEMP, on the other hand, helps shipping companies to enhance energy efficiency in a financially sustainable way by considering normal commercial operations and monitoring the efficiency performance of fleets over time. The above-mentioned measures were issued by IMO for reducing CO_2 emissions within the "*Initial Strategy on GHG reduction from ships*" (IMO, 2018a). This strategy aimed at achieving by 2050 a reduction of total GHGs emissions from international maritime transport at least equal to 50 % and of CO_2 emissions per transport work at least equal to 70 %, in comparison with the 2008 values. Within the "Fourth IMO GHG Study 2020" (IMO, 2020), which provided carbon intensity and emissions inventory and projections towards 2050, the emissions increase in the future years was estimated according to several forecasts concerning long-term economy and energy trends (not considering the SARS-COV2 pandemic impact). The impressive results underlined how, without the application of additional measures, emissions from shipping would increase from 90 % compared to 2008 in 2018 to around 90–130 % compared to 2008 in 2050. It emerged that, even if the carbon intensity of maritime transport could be improved, reaching the 2050 GHGs emission reduction target by only implementing energy-saving technologies and reducing ship speeds would be extremely difficult.

In this context, the IMO introduced a new index called attained annual operational "Carbon Intensity Indicator" (*CII*), which has entered into force in January 2023 and is mandatory for each ship of 5000 GT and above (IMO, 2021a). This index measures the efficiency of a ship during transportation of either goods or passengers and is given as mass of CO_2 emitted in relation with the capacity/size and the travelled distance. From 2024, at the latest by 31 March, the *CII* must be calculated and reported along with the aggregated data for the previous year, including any correction factors and voyage adjustments. IMO, 2020 "suggests that a successful implementation of this energy efficiency framework by 2050 could reduce CO_2 emissions from shipping by up to 1.3 Gt per year".

Given the absolute novelty of the *CII* index, the IMO is still working on the appropriate calculation to apply. Indeed, on the occasion of the *CII* issuance, the Marine Environment Protection Committee (MEPC) agreed to evaluate proposals regarding potential corrections applicable to specific ship types, operational profiles and/or voyages. The outcome of such efforts resulted in the issue of the resolution MEPC.355(78) (IMO, 2022a), in which several correction factors are proposed for the attained annual operational *CII* formula. As an example, a voyage adjustment is foreseen for the distance travelled that can be excluded from the *CII* calculation due to particular conditions such as emergency situations, heavy weather, sailing in ice conditions, etc. However, almost all the proposed correction factors are valid for cargo ships (i.e., tankers, ships carrying refrigerating containers, gas and LNG carriers), so cruise ships cannot benefit from them.

Moreover, for cruises, the current formulation for the annual calculation of the *CII* might be quite challenging and detrimental for ships that spend a lot of time in port. Indeed, during the berthing time, a cruise ship shall still provide a certain hotel load that may be inferior to the navigation value due to the decreased number of passengers onboard and the lower services required, but still significant. Thus, the quantity of CO_2 emitted would contribute to increase the total emissions while the nautical miles would stay the same, with the result of an unreasonable magnification of the *CII* value. Consequently, ships spending more time at berth during their itinerary would be more penalised in terms of *CII*. Since *CII* will be the major indicator of the environmental impact of a ship, cruise companies will be encouraged to plan and operate itineraries which minimise the *CII*. This behaviour will be fostered also by the introduction of carbon taxes which might be linked with *CII* or similar indexes.

The present work aims to propose a solution for the inconsistencies that might arise for cruise vessels between *CII* and actual emissions per unit of time. The objective is to open a discussion for the introduction of the correction for cruise ships at an international level. In detail, to consider the peculiar operational profile of cruise ships, the authors propose a *CII* correction factor based on the percentage of time at sea/at port. Following the IMO common practice, here a data-driven approach is proposed: the correction is based on the analysis of a database of *CII* computed for a quite large number of cruise vessels including both operative and forecasted data. The remaining paper has the following structure: first, the framework of the work is given, including *CII* definition and peculiarities of the cruise ship compared to cargo ones; then, the correction strategy is presented and applied to the database; finally, the correction is tested on a cruise vessel considering multiple itineraries. The results are then discussed and conclusions are drawn.

2. Pollutant emissions from cruise ships: Current situation

Due to the nature of the power generation systems installed on-board and the composition of the fuels commonly used (Gray et al., 2021), cruise ships potentially produce several types of pollutant emissions; the most common are GHGs, SO_X, NO_X, PM_X, and Volatile

Organic Compounds (VOCs). However, as a positive aspect, it is worth considering that the 2020 data regarding the average age of the current cruise ships fleet report a value of 14.1 years (CLIA, 2020). Hence, it can be assumed that, in general terms, such a fleet is equipped with modern technologies aimed at reducing atmospheric pollution and so is compliant with the related requirements. Specifically, the use of Selective Catalytic Reduction (SCR) systems allows the reduction of NO_X (Kim et al., 2020; Zhang et al., 2021), with removal percentages up to 90 % (Napolitano et al., 2022). As regards SO_X, the use of scrubbers ensures a reduction of emissions up to 98 % (Wilailak et al., 2021; Jang et al., 2020) and the adoption of ultra- and very-low sulphur heavy fuel oils (Vedachalam et al., 2022) merged with a fuel switch to Marine Diesel Oil (MDO) in port areas may reduce even more the emission of such pollutants. Furthermore, the modern technologies employed for marine diesel engines allow an important reduction of VOCs and PM_X. However, almost all the in-service ships' prime movers involve the combustion of fossil fuels, with the unavoidable consequence of GHGs production. For this reason, IMO's international policies are strenuously aimed at limiting such emissions. Unfortunately, results have been not completely satisfactory so far and national governments are feeling the need for local and more stringent requirements, as it happened in the Norwegian waters (Babri et al., 2022; Simonsen et al., 2019). In this context, the presence of different international, national and even regional regulations creates a variegated rule framework that is pointing in the same direction but not always fully aligned (Dong et al., 2022). Nevertheless, these policies have fostered the deployment of technical solutions and strategies towards compliance with the IMO's CO_2 thresholds (Bouman et al., 2018; Wan et al., 2018; Bertagna et al., 2023), which can be a challenging task for cruise ships due to the structure of the Regulations themselves as shown in detail in the next sections.

3. Framework

In the present section, the current definition of the *CII* is given, focusing on both attained and required value as well as on ship categorisation. Moreover, the peculiarities of cruise vessels' operative profile leading to *CII* inconsistencies are introduced.

3.1. The CII formulation

The *CII* is an annual indicator based on the efficiency of ships during services. Such efficiency "is calculated as the ratio of the total mass of CO_2 (M) emitted to the total transport work (W) undertaken in a given calendar year, as follows" (IMO, 2022b):

$$Attained\ CII = \frac{M}{W} \tag{1}$$

In which.

- $M = FC_j \cdot C_{Fj}$, being j the type of fuel oil, FC_j is the yearly consumption (mass) of the j-type fuel oil; C_{Fj} is the emission factor for the j-type fuel oil, as specified in (IMO, 2018b);
- $W = C \cdot D_t$, where C represents, for cruise ships, the gross tonnage GT, and D_t stands for the total nautical miles travelled during the calendar year.

Equation (1) providing the *CII* formulation can be summarised and simplified as follows:

$$CII = \frac{CO_2Emissions\ (Fuel\ Consumption)}{GT \cdot Distance} \propto \frac{Engine\ Load \cdot Time}{GT \cdot Distance} \tag{2}$$

In Equation (2), GT is the only constant value, as the others vary and depend on the operation of the ship.

As for all the IMO's indexes, the annual attained *CII* must be compared to a reference value that sets the assessment and the fulfilment of the requirements. This is calculated through the following equation (IMO, 2021b):

$$Required\ Annual\ Operational\ \ CII = (1 - Z/100) \cdot CII_R \tag{3}$$

In which.

- CII_R is the 2019 reference value (IMO, 2021c) and formulated as follows: $CII_R = a \cdot Capacity^{-c}$, where Capacity is equal to GT for cruise passenger ships, "a and c are parameters estimated through median regression fits, taking the attained *CII* and the Capacity of individual ships collected through IMO DCS in the year 2019 as the sample" (IMO, 2021c). For cruise passenger ships, their values are equal to 930 and 0.383, respectively: thus, the reference value is calculated as $CII_R = 930 \cdot GT^{-0.383}$
- Z "is a general reference to the reduction factors for the required annual operational CII of ship types from the year 2023 to 2030" (IMO, 2021b), as shown in Table 1. Z factors for years 2027–2030 are not yet defined, but, for later calculations, a gradual increase of 2 % may be assumed.

Table 1
"Reduction factor (Z%) for the *CII* relative to the 2019 reference line" (IMO, 2021b).

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Reduction factor relative to 2019	5 %	7 %	9 %	11 %	–	–	–	–

Ships are then rated by receiving a classification label among five grades (IMO, 2021d): the possible grades range from A to E, in ascending order per emissions. Considering the overall database used for the definition of the *CII* regulation, four boundaries are defined parallel to the median applicable to the type of ship (Fig. 1).

The distance between boundaries is defined to assign a predefined percentage of ships from database to each grade. The expected results coming from the appropriate rating are the following: speaking of individual ships, the average 30 % will be assigned to grade C; the upper and lower 20 % is assigned to grades D and B, respectively; the remaining ships (further upper and lower 15 %) are assigned to grades E and A, respectively.

The reduction factors for the operational carbon intensity will be incremented over time, thus the performance boundaries will be subsequently synchronised while maintaining the unaltered relative distance between each boundary. The details are provided in (IMO, 2021d).

3.2. *Inconsistency of CII for cruise ships*

At a first approximation, the resistance of a ship increases as a squared function of its speed and thus the propulsion power increases as a cubic function of the ship's speed. Considering a cargo ship, such as a bulk carrier, a tanker or a container ship, propulsion power mostly contributes to the total fuel consumption. The remaining fuel is used to drive the electric generators for auxiliary systems and crew hotelling (Molland et al., 2011). Usually, the installed power of 4-stroke electric generators is about 20–25 % of the "Maximum Continous Rating" (MCR) of the 2-stroke main engine which directly drives the propeller(s) (Goldsworthy and Goldsworthy, 2019). However, considering cargo fleet, the weighted average power required by auxiliaries and boilers during navigation is about 7.5 % of MCR (IMO, 2020).

On a cruise vessel, the situation is completely different. The hotel load (mainly driven by the air conditioning system) has the same order of magnitude as the electric power required by propulsion (Micoli et al., 2021; Wei et al., 2020). This is why in the last decades, almost all cruise vessels utilise a diesel-electric energy system, where propellers are driven by Propulsion Electric Motors (PEMs). Therefore, propulsion became just one user of the electric generation system that usually is composed of 4-stroke diesel generators (Molland et al., 2011; Paul, 2020).

Fig. 2 shows the comparison of the Fuel Oil Consumption (*FOC*) per travelled nautical mile of a cargo vessel with the cruise ship one. The propulsion power of both vessels is almost a cubic function of the speed. Even though having comparable sizes, a cargo vessel has usually lower fuel consumption than a passenger one. Namely, cargo ships benefit from the higher efficiency of 2-stroke engines and the direct connection of the engine to the shaft line (in diesel-electric systems also the efficiency of electric generators, main switchboards, frequency converters and PEMs shall be taken into account). But the main difference occurs when hotel load is considered. In such a case, the shape of the FOC/D_t curve changes for passenger ships, showing a minimum. In fact, at a very slow speed, although the propulsion power is much lower, the hotel load shall be sustained nonetheless and shall be sustained for a longer period while moving over the same distance.

Hence, considering that CO_2 emissions are proportional to *FOC*, for each cruise ship operating with a fixed hotel load, an optimal speed V_{opt} exists, which minimises the emissions per nautical mile. Therefore, considering the definition of *CII* given in Equation (1), this speed drives to the minimum possible *CII* value during navigation.

As clearly shown by Fig. 2, as speed tends toward the null, the amount of consumed fuel per nautical mile of the cruise ship one tends towards infinity. Therefore, as the ship is calling a port, it shall still sustain the hotel load, usually reduced due to the lower number of passengers and lower power required by auxiliaries, but still having the same order of magnitude. Thus the emissions of the ship are still intensely rising whereas the ship is not increasing the travelled distance. Hence, considering the current *CII* formulation,

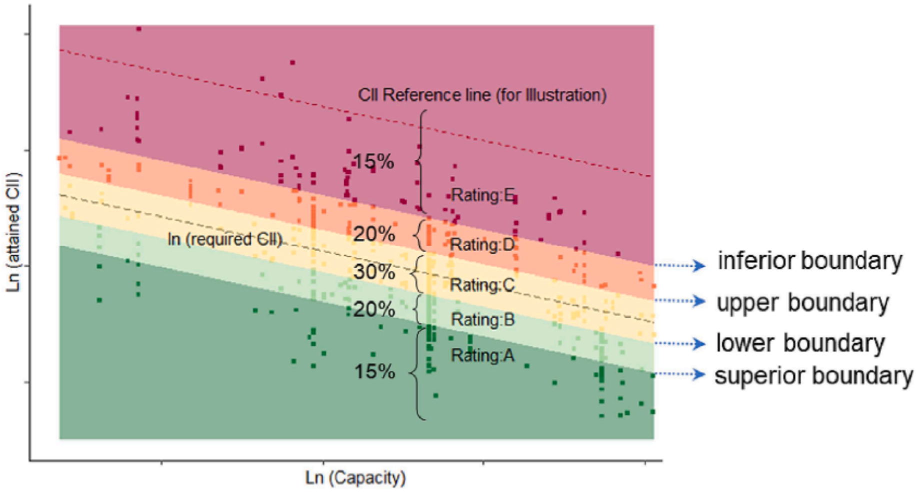

Fig. 1. "Operational energy efficiency performance rating scale" (IMO 2021d).

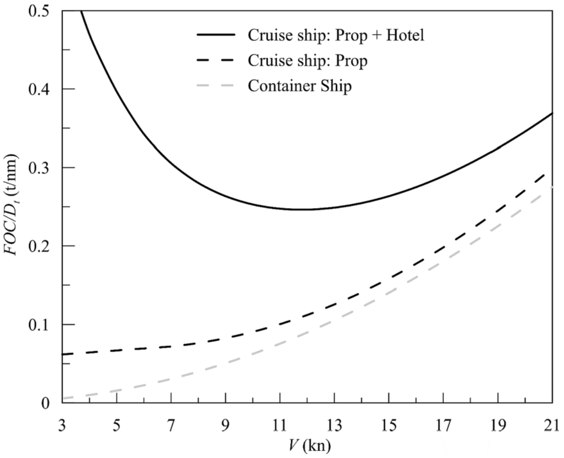

Fig. 2. Comparison of the fuel consumption per nautical mile for a 110,000 GT cruise ship and an 8700 TEU container ship having comparable size (Data from Carnival Corporation and from personal elaboration).

as the ship is calling a port, the numerator increases while the denominator does not, leading to an unreasonable magnification of the *CII* value. Therefore, the more a ship is staying at berth during an itinerary, the more it is penalised in terms of *CII*.

Consequently, the *CII* for cruise ships is a decreasing function of the percentage of time at sea, whereas for freight ships (having negligible auxiliary load) no correlation among these factors can be found. This issue can limit the capability of the *CII* to truly normalise the emission of cruise vessels for applying the proper classification: classification becomes strictly dependent on the time at sea associated with a chosen itinerary and there are no guarantees that *CII* fosters the choice of itineraries having the lowest environmental footprint.

Such inconsistencies in the current formulation of the *CII* are even more magnified considering that, usually, cruise ships have a higher percentage of time in port compared to cargo ones (IMO, 2020). In fact, they need to provide passengers with sufficient time to visit the touched ports or their neighbourhood. This is one of the essential drivers making cruise itineraries attractive to potential customers (Asta et al., 2018; Mancini and Stecca, 2018).

4. Proposed revision of the CII for cruise ships

In order to solve the inconsistencies of current *CII* for cruise ships, a data-driven approach is here proposed. Due to its mathematical formulation, the *CII* tends towards positive infinity as the time-at-sea tends to zero, since this leads travelled nautical miles to tend to zero too. This behaviour can be observed on a database of cruise vessels operating in a one-year time frame. For each cruise vessel in the database, the time-at-sea and corresponding *CII* can be defined. These data can be used to define the correction as:

$$dCII = CII_c - CII \tag{4}$$

where CII_c and *CII* are the corrected and original values of the carbon intensity indicator respectively. Therefore, the correction is expected to be lower or equal to zero. The correction shall be kept as simple as possible to be easily applicable while avoiding overcorrection, which is one of the main causes of correction proposals' rebuttal. These two pillars have driven the definition of the correction proposed hereinafter.

4.1. Database data fitting

The first task is to define the trend of the *CII* as a function of time at sea. To capture the asymptotic behaviour of the *CII* with a simple function, here an inverse proportion has been utilized. Thus, the *CII* trend to fit available data is defined as:

$$CII^* = f(t_s) = a + \frac{b}{t_s} \tag{5}$$

where t_s is the fraction of time-at-sea obtained by dividing the yearly hours-at-sea by the total hours in a year (8,760) whereas a and b are two coefficients that control the curve and should be tuned to fit the *CII* database. Here, the coefficients are defined through an optimisation process minimising the sum of squared error, defined as:

$$SSE = \sum_{i=1}^{N} \left(CII_i - CII_i^*\right)^2 \tag{6}$$

where N is the number of ships in the database, CII_i and CII_i* are the index values for the *i*-th ship from the database and estimates according to Equation (5), respectively. Here a Nelder-Mead simplex algorithm as defined in (Lagarias et al., 1998) is used to search for the values of a and b which minimise *SSE*.

4.2. Definition of correction baseline

Equation (5) represents the behaviour of *CII* for the database population. Thus, it is possible to observe how *CII* increases as t_s decreases. Such an increase shall be removed, in order to make the *CII* independent from the time-at-sea. Thus, a first correction can be defined as:

$$dCII_1(t_s) = c - CII^*(t_s) \tag{7}$$

where CII_1 is the corrected value of *CII* and *c* is a baseline value of *CII* used to evaluate the correction. The obvious mathematical assumption is to put $c = a$, namely assuming the horizontal asymptote of the *CII* trend as a baseline. However, this choice can lead to overcorrection: the *CII* trend might reach the horizontal asymptote at values larger than 1 (that represents a ship navigating 365 days per year). In such a case, all the ships, including the ones with high time-at-sea, could benefit from a strong correction of the *CII*. Hence, the asymptote ordinate represented by coefficient *a* has not been considered a suitable baseline value for the computation of the correction.

It shall be noted that this baseline value can be arbitrarily defined. However, in the present work, a reasoned proposal is given, although its value can be further discussed and agreed upon by rule/policy-makers from the international/regulatory bodies. Here, the reference value is assessed considering the average fraction of time-at-sea t_{s_c} of cargo vessels (excluding passenger ones, which are the objective of the correction). The fraction has been computed using the 2018 statistics from (IMO, 2020), obtaining $t_{s_c} = 0.69$. Then the baseline value *c* has been defined as the *CII* value computed with Equation (5) at $t_s = t_{s_c}$:

$$c = CII^*(t_{s_c}) = a + d \tag{8a}$$

$$d = b/t_{s_c} \tag{8b}$$

For all cruise ships having $t_s \geq t_{s_c}$ this choice will result in an increment of the corrected *CII* instead of a reduction. To avoid a penalty for ships that have a long time-at-sea, in these cases the *CII* shall remain uncorrected. Thus, applying a null upper threshold the correction shall be rewritten as:

$$dCII_2(t_s) = \min[0, c - CII^*(t_{s_c})] \tag{9}$$

4.3. Lower threshold and final correction formulation

The proposed correction tends towards positive infinity as the t_s tends towards null. In order to avoid overcorrections for ships having very short time at sea, it is here proposed to apply a lower threshold on the correction. This can prevent ships to plan extremely long stays in port only to benefit from *CII* correction. The level *e* of the lower threshold of the correction can be arbitrarily defined and again shall be further discussed by rule/policy-makers. However, here it is proposed to limit *CII* correction in order to make it applicable only to cases representative of business-as-usual. It means that, *e* is defined considering the minimum value of the fraction of time-at-sea $t_{s_{min}}$ comprised within the database. The threshold is then defined by flooring the correction value $dCII_2(t_{s_{min}})$. This approach will prevent cruise lines to establish future itineraries with time at port higher than current ones, with a consequent increase in local pollution in such critical spots. Thus, incorporating *e*, the resulting final formulation of the *CII* correction reads:

$$dCII = \max\left\{\left[e, \min\left[0, d - \frac{b}{t_s}\right]\right]\right\} \tag{10}$$

In Fig. 3 the graphical representation of the proposed correction is qualitatively given.

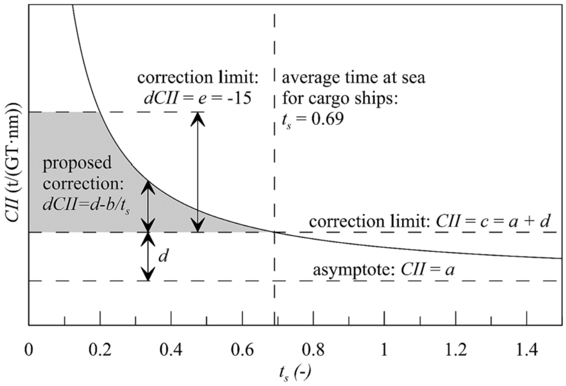

Fig. 3. The proposed strategy for the correction of the *CII*.

The proposed correction can be also intended as an increase in travelled distance. In such a case a port equivalent distance D_e can be defined as the equivalent distance that the ship should cover to obtain with the current definition of the *CII* the corrected value CII_c. Hence, combining Equations (1), 4 and 10 the following formulation can be derived:

$$CII_c = \frac{CO_2}{GT(D_t + D_e)} \tag{11a}$$

$$D_e = \min\left\{ D_{e_{\max}}, \max\left[0, \frac{D(b - dt_s)}{(CII + d)t_s - b}\right] \right\} \tag{11b}$$

$$D_{e_{\max}} = -\frac{CO_2}{(e - CII)GT} - D_t \tag{11c}$$

The distance D_e is then capable of properly normalising also the emissions that are produced in port while being easily incorporable in the current formulation of the *CII*.

5. Application

In the present section, the methodology described previously is applied to a database comprising historical and forecasted *CII* for a large set of existing cruise vessels. First, the database structure is introduced. Then, based on these data, the correction is defined.

5.1. Database of cruise itineraries

In order to define the data-driven correction a database of *CII* of cruise vessels is required. In this work, a database comprising 125 records has been used related to existing cruise vessels operated by Carnival Corporation composed of both operative data (28 records) and estimates (97 records). For each ship, the *CII* has been computed on a one-year time frame. The core of the database is composed of the 28 cruise vessels operated by Carnival Maritime (including Costa Crociere and Aida brands). For these vessels, the *CII* has been computed according to the 2019-yearly fuel consumption. These data have been chosen because they are representative of a pre-pandemic condition. Hence, routes and speeds are not affected by limitations due to COVID-19.

The cruise market was heavily affected by the pandemic, with a strong reduction in passenger flows and revenues (Lin et al., 2022). During 2020 most of the ships were not operated and a complete recovery of the cruise market is expected only in 2023 (Chikodzi et al., 2022). For this reason, in this work, the core database has been extended using forecasted *CII* for the year 2023 considering the entire fleet of Carnival Corporation (97 ships). The forecasts are based on publicly-available planned itineraries and the fuel consumption estimates carried out by the corporation for budget purposes (Carnival, 2021; Carnival Maritime, 2021). In Fig. 4 the resulting database is visualised focusing on the relation between *CII* and time-at-sea measured in hours at sea per year.

It can be immediately noted a descending trend of *CII* as the time-at-sea increases for both historical and forecasted data. Besides, the effect of the *CII* introduction is already notable: the estimates for 2023 already show a shift towards routes having larger time at sea. The average is moving from 5,724 h/y in 2019 to 6,106 h/y in 2023. In fact, the increase of time-at-sea is currently the only measure to mitigate the distortion for cruise ships of the CII formulation.

In Appendix A additional statistics are provided to better describe the database composition and how it is already representative of the current medium-large cruise vessels' fleet.

5.2. Results

According to the *CII* data from the database and applying the proposed methodology, the results provided in Table 2 have been obtained. The application of Equation (10) leads to the trend shown in Fig. 5. In order to ease the reproduction of the results a brief

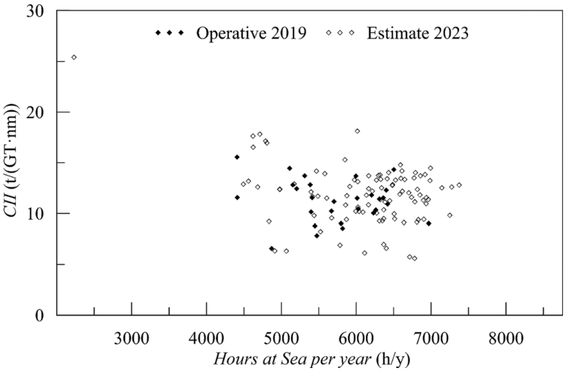

Fig. 4. *CII* as a function of time-at-sea for ships comprised in the database.

summary of the applied procedure is provided in Appendix B.

The minimum fraction of time-at-sea $t_{s_{min}}$ in the database is equal to 0.25. Thus, the lower limit of the correction is applied at time-at-sea of about 0.2, which drives to a round value of the maximum correction $e = -15$. Namely, ships staying in port for more than 80 % of the time in a year cannot benefit from a *CII* reduction larger than 15 to discourage cruise companies from further reducing the time in port compared with current business-as-usual. As time-at-sea increases, the correction decreases up to $t_s = 0.69$ with an exponential trend governed by factor $b = 4.21$. Then, for ships with large time-at-sea null correction is applied.

6. Test case

In the present section, the proposed correction is tested on a medium-size cruise ship. First, the test ship is presented along with a set of test itineraries, and then the current and corrected *CII*s will be compared focusing on the CO_2 emissions per unit of time.

6.1. The test ship

The selected ship for showing the effect of and testing the proposed *CII* correction is a medium size passenger vessel. Table 3 shows the main particulars of the ship, which are typical of cruise ships that are approaching mid-life. Hence, they are very challenging for cruise companies, since it shall be decided whether or not to undertake a strong retrofit to reduce the ship's environmental footprint. The ship has a conventional diesel-electric propulsion system with 2 shaft propellers driven by 2 three-phase synchronous electric motors having a nominal power of 21,000 kW each. The electric generation plant is composed of 6 Wärtsilä 12V46C diesel engines, having a total mechanical and electric power of 75,600 kW and 73,800 kW, respectively. In the summer condition, the hotel load is about 6,300 kW and 7,850 kW at berth and in navigation respectively. Combining the hotel and propulsion loads the optimal speed V_{opt} in terms of emissions per nautical mile is 13.5 kn.

6.2. Itineraries

Five different itineraries have been considered to test the corrected formulation of the *CII*. The itineraries are defined as follows:

- **Itinerary I**: Navigation at optimal speed and standard time in port;
- **Itinerary II**: Navigation at optimal speed and short time in port;
- **Itinerary III**: Navigation at optimal speed and long time in port;
- **Itinerary IV**: Navigation at low speed and standard time in port;
- **Itinerary V**: Navigation at high speed and standard time in port.

Details about the assumed speed, duration of navigation, and distance travelled for the five itineraries are provided in Table 4, where times in port/at sea are provided in terms of hours per week (h/w).

Itineraries characteristics have been chosen to investigate the effect on *CII* of the variation of main variables governing its assessment. In particular, Itinerary I will be a benchmark to compare the parameters of all the other ones, since it has a reasonable time at port (about 55 %) and it is supposed that the ship is navigating between ports at the optimal speed ($V_{opt} = 13.5$ kn).

6.3. Results

Fig. 6 and Table 5 show the results of the emissions and both current and corrected *CII*s. The current formulation of the *CII* leads to a macroscopic distortion between ship classification and actual CO_2 emissions per unit of time.

In detail, Itinerary I (benchmark one) with the current formulation of *CII* drives to classify the ship as C and lead to the emission of about 1461 t of CO_2 per week. With this formulation, the only way to reduce the *CII* is to change the itinerary to increase the time at sea (as for Itinerary II), with the consequent increase in weekly emissions which rise of about 12.5 % while still navigating at V_{opt}. However, Itinerary II leads to an improvement of the test ship class, which moves from C to B. The inconsistency is even worse if the time at sea is reduced (as for Itinerary III): the longer time at berth, where only hotel load is required, leads to a decrease of total fuel consumption and, thus, of the CO_2 emissions of about 12 %. Nonetheless, at the same time, the *CII* class moves from C to E.

The application of the proposed correction leads to reducing the *CII* for the reference itinerary. In such a case, the ship is classified as class A. In itinerary II the long time at sea prevents to benefit from the correction (t_s greater than 0.69), hence the CII_c is equal to *CII* leaving the ship in class B. In Itinerary III, the short time at sea ($t_s = 0.40$) implies a strong correction of the *CII* of about 4.3 points, therefore the ship moves from class E to A. In terms of CII_c, Itinerary III becomes the preferred option, compared to I and II.

Finally, Itineraries IV and V examine the effect of different cruise speeds on *CII*. For both current and corrected *CII* formulation,

Table 2
Data-driven coefficients of the *CII* correction according to the database.

Coefficient	*a*	*b*	*c*	*d*
Value	5.490	4.210	11.591	6.101

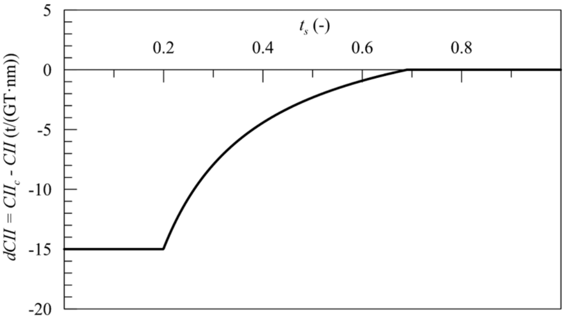

Fig. 5. Trend of the proposed correction of the *CII*.

Table 3
Main particulars of the test ship.

Quantity	Symbol	Value	Quantity	Symbol	Value
Gross Tonnage	GT	113,216 GT	Length overall	L_{OA}	290.2 m
Length between perp.	L_{BP}	290.2 m	Beam	B	35.5 m
Design draught	T	8.3 m	Height	H	62.0 m
Maximum speed	V_{max}	21.7 kn	Avg. service speed	V_S	15.06 kn

Table 4
Characteristics of the tested itineraries.

Quantity	Symbol	Unit	Itin. I	Itin. II	Itin. III	Itin. IV	Itin. V
Time in port	T_p	h/w	75	50	100	75	75
Time at sea	T_s	h/w	93	118	68	93	93
Non-dim. time at sea	t_s	–	0.55	0.70	0.40	0.55	0.55
Navigation speed	V	kn	13.5	13.5	13.5	8.0	20.0
Distance travelled	R	nm	1256	1593	918	651	1860

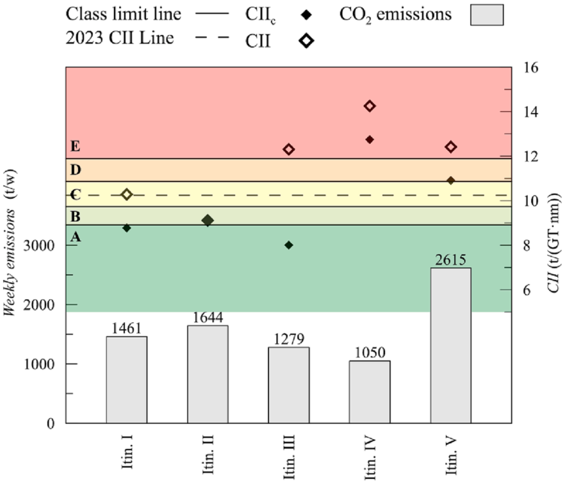

Fig. 6. CO_2 emissions per week and effect of the correction of the *CII* on the tested itineraries considering the 2023 reference line and classes.

moving from optimal speed leads to an increase in *CII*. However, this effect does not reflect the overall weekly emissions. In fact, the proposed correction does not consider the cruise speed of the ship. Hence, since Itineraries I, IV and V have the same t_s the same correction applies to all of them. This correction does not cause a substantial improvement in ship class: only in Itinerary V, the ship moves from class E to D.

Table 5
Weekly results for the tested itineraries related.

Quantity	Symbol	Unit	Itin. I	Itin. II	Itin. III	Itin. IV	Itin. V
Hotel load port	P_{hp}	kW	6298	6298	6298	6298	6298
Hotel load nav.	P_{hn}	kW	7858	7858	7858	7858	7858
Prop. power nav.	P_{PEMn}	kW	8300	8300	8300	2823	25,066
Fuel oil consumption	*FOC*	t/w	456	513	399	328	816
CO_2 emissions	CO_2	t/w	1461	1644	1279	1050	2615
CII	*CII*	t/(GT·nm)	10.28	9.11	12.30	14.25	12.42
Corrected *CII*	CII_c	t/(GT·nm)	8.78	9.11	8.00	12.75	10.91

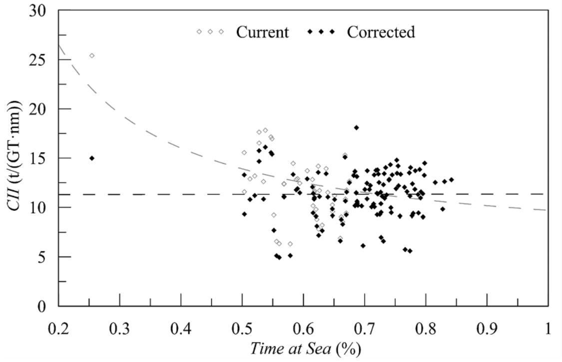

Fig. 7. Comparison of the current and corrected *CII* as a function of t_s for ships comprised in the database.

7. Discussion

The simple test cases considered for the test ship show once again that the current *CII* formulation is not consistent with the CO_2 emissions: it fosters the choice of itineraries with a heavier environmental footprint, namely the ones with long time at sea when both hotel load and propulsion power shall be provided by the diesel generators. Besides, the current *CII* formulation discourages long stays in port, when the electric power demand is lower and thus the ship has lower emissions per unit of time. The application of the proposed correction leads to better aligning *CII* with the weekly emissions for the itineraries where cruise speed is kept constant and only time at sea changes.

The alignment is again lost considering a change in cruise speed. It is well known that propulsion power demand rises dramatically as ship speed increases. It is not surprising that both weekly emissions and *CII* rise for high-speed Itinerary V. The peculiarity of cruise vessels is that, reducing the speed below V_{opt}, the *CII* rises although the weekly emissions decrease. The main reason is the higher fuel demand per nautical mile (as shown in Fig. 1). The proposed correction intentionally does not remove such inconsistency and the main reasons for this choice are discussed hereinafter.

It shall be noted that the total travelled distance is very different for all the analysed itineraries. This means that they are completely different itineraries touching a set of different ports. Since cruise companies forecast *CII* values during cruise planning and fuel budget, from a policymaker's point of view, *CII* should foster the adoption of the most environmentally friendly itineraries implying lower possible emissions per nautical mile during navigation and, then, lower possible overall emissions per unit of time.

The current formulation of *CII* already encourages navigation at speeds other than the optimal one. The second target is reached by introducing the correction, which removes the inconsistencies in overall emissions per unit of time due to time in port. Besides the test cases, these effects can be shown also on the ships' database adopted to assess the correction. In Fig. 7, the comparison of current and corrected *CII* is provided for all the ships in the database.

It can be noted that the descending trend as t_s increases has been removed. Hence, corrected *CII* is now independent of the time at sea, as shown by the horizontal trend line reported in Fig. 7.

Finally, it shall be beared in mind that the application of a data-driven technique to determine the correction is strongly dependent on the database composition. Hence, although a large database has been here employed with successful results in removing the distortion introduced by time at port, an extension of the database is advisable. In detail, considering the *CII* of all existing cruise ships in a pre-pandemic scenario might be the best option. Although it is not expected that the correction will radically change enlarging the database, the usage of data related to or preceding 2019 only will avoid incorporating the effects of current *CII* on the itineraries planned for 2023: as mentioned, an increase in time at sea can be already observed as a consequence of the existing inconsistency between *CII* and emissions.

8. Conclusions

In conclusion, this work developed a methodology to assess a data-driven correction of the *CII* to remove its dependence on the time at sea. The proposed correction applies only to ships with a time at sea from 20 % to 69 %. These thresholds are arbitrary so can be further discussed and adapted to further limit overcorrection. Between them, a correction of up to 15 points is applied. The proposed methodology has been proven to successfully remove both the dependency of the *CII* on the time at sea for the ships in the database and the inconsistency between emissions per unit of time and *CII* for the test case.

In future works, it is advisable to enlarge the ships' database, for instance, considering all the ships owned by CLIA members in 2019. Then, based on the results of the present paper, a discussion might be opened at the IMO level to propose a revision of the *CII* for cruise vessels aimed to reach a better alignment between the corrected index and the environmental footprint of the ships. It shall be beared in mind that the application of the correction would require also a redefinition of the ship classes based on corrected values of *CII*.

Finally, it is worth noticing that, in future rules, the effect of cold ironing, not considered in the present word, should be taken into account. The time when electric power is supplied by shore connection shall be considered as "time at sea" to avoid an overcorrection of the *CII*.

CRediT authorship contribution statement

Luca Braidotti: Conceptualization, Methodology, Software, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Serena Bertagna:** Conceptualization, Methodology, Validation, Data curation, Writing – original draft, Writing – review & editing. **Ruben Rappoccio:** Investigation, Data curation. **Samuele Utzeri:** Investigation, Data curation, Writing – review & editing, Visualization. **Vittorio Bucci:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Alberto Marinò:** Writing – review & editing, Supervision, Funding acquisition.

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.

Appendix A

In Figs. 8-10, additional insights are provided about the database composition and data related to the real operation in 2019 and the estimates for 2023. In the figures, the letter *N* stands for the number of records within the database.

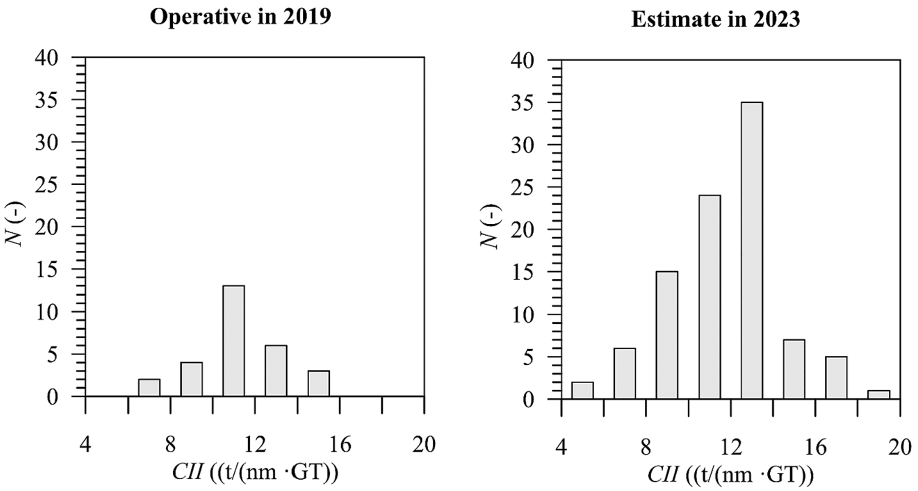

Fig. 8. Database composition: CII.

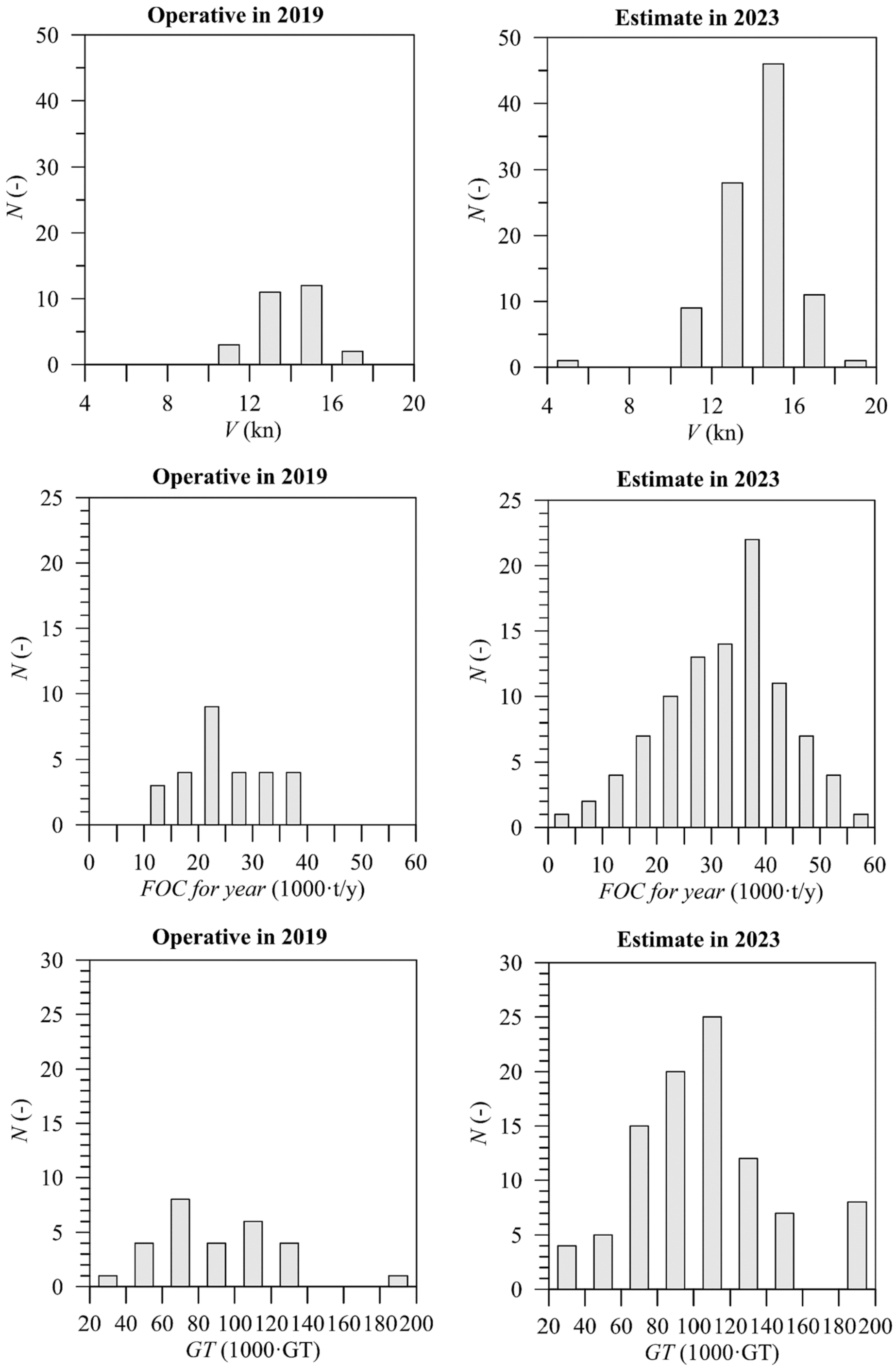

Fig. 9. Database composition: average speed in navigation, fuel oil consumption, gross tonnage and yearly hours at sea.

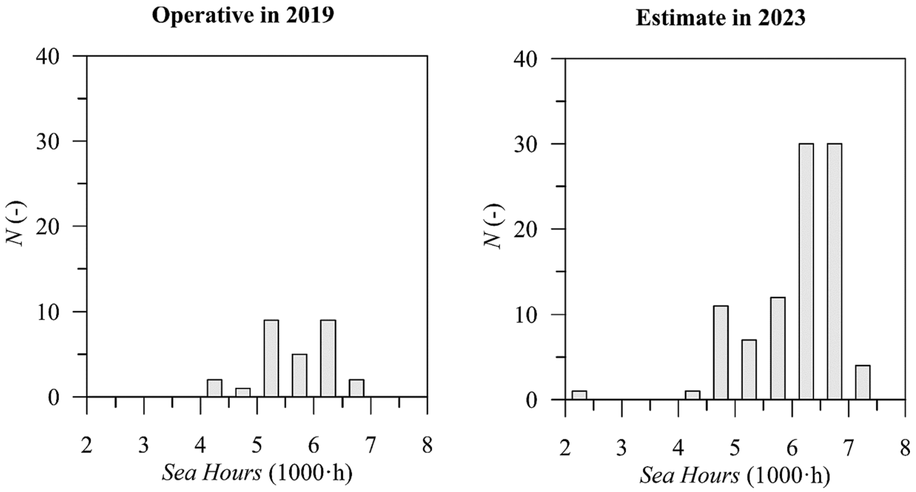

Fig. 9. (*continued*).

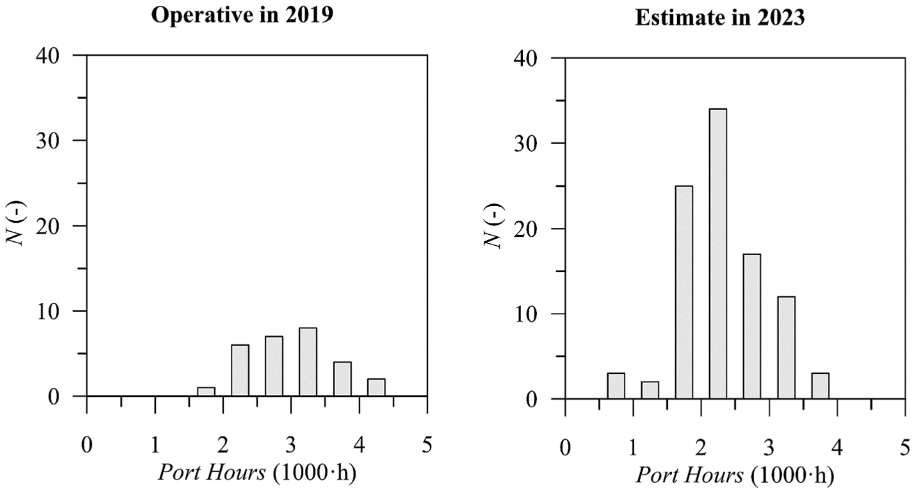

Fig. 10. Database composition: yearly hours at port.

Appendix B

In this appendix, the main steps required to reproduce the proposed methodology on a different/enlarged database are pointed out. The main purpose is to ease the update of the results of current work as additional data are made available from cruise lines or IMO. The main steps are the following:

1. *Data Collection*: to apply the current methodology a database of past/estimated fuel consumption of a sufficiently large number of ships is needed. The database shall comprise on yearly bases and for each ship:
   - (a) The *CII* value, which can be calculated according to Equation (2);
   - (b) The fraction of time-at-sea t_s, which can be computed from the Automatic Identification System (AIS) records;
2. *Database Fitting*: based on collected data, the coefficients a and b of the fitting function in Equation (5) shall be estimated in order to minimise the error between the fitting function prediction and the records in the database;
3. *Baseline Definition*: the constant c as defined in Equation (8a) shall be chosen as a function of the maximum fraction of time-at-sea t_{s_c} for which the correction will be applied. For $t_s \geq t_{s_c}$, the *CII* will not be corrected. It is suggested to choose t_{s_c} as the mean time-at-sea of cargo ships;

(4) *Lower Threshold Definition*: the minimum value of correction e shall be chosen, which is the maximum reduction applicable to the *CII*. This threshold is also the constant value of the correction applied for $t_s \leq t_{s_{min}}$. It is suggested to choose e to comprise all the database records in the variable correction region (i.e., to assure that $\forall i : t_{s_i} > t_{s_{min}}$, where i is the index of the ships within the database).

(5) *Testing*: it shall be guaranteed that the linear trend of CII_c is a horizontal line. Otherwise, it is suggested to come back to point (2) and repeat the procedure excluding from the database outliers or records having $t_s < t_{s_{min}}$ or $t_s > t_{s_c}$.

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