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The Port Environmental Index: A Quantitative IoT-Based Tool for Assessing the Environmental Performance of Ports

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Abstract: The increasing exchange of goods by sea is contributing significantly to pollution in port areas. Although several methods have been developed to assess the environmental performance of ports, most of them have shortcomings including a qualitative-only approach and self-assessment of environmental performance. Therefore, there is a pressing need to develop a different approach based on quantitative measurements obtained through measurements at ports. In this paper we present the Port Environmental Index (PEI), a quantitative composite index of port environmental performance driven by IoT. The index allows for environmental measurements to be collected in real time or close to real time through sensors providing an assessment of a port's environmental performance in real time. In addition, since the methodology for creating the index is standardised, the index makes it possible to compare different ports and rank them in terms of their environmental performance. As a proof of concept (PoC) this paper also describes the application of the index to the port of Thessaloniki (Greece).

Keywords: port environmental performance; key environmental performance indicators (eKPIs); ports; pollution; environmental aspects; Port Environmental Index

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1. Introduction

The rapid expansion in global trade has led to an increase in the movement of goods by the sea, making shipping and ports crucial components of international commerce. Shipping accounts for approximately 90% of world trade and generates environmental impacts which are often difficult to measure, control and regulate, especially in coastal areas where ports are located [1]. For example, the combustion of fossil fuels in diesel engines used by marine vessels and cargo handling equipment in ports contributes to climate change and air pollution, which adversely affects human health [2–4]. As a result, policy makers are advocating for the maritime industry and ports to reduce their emissions and mitigate the impact on human health and the environment.

According to the report by the European Sea Ports Organisation (ESPO), air quality is the top environmental priority of port operations due to the emission of diesel exhaust, particulate matter, and nitrogen oxides which heavily impact air quality in port areas [5]. In general, high concentrations of pollutants in the atmosphere lead to an increase in both morbidity and mortality [6–8]. Noise pollution is also of concern, especially for urban ports [9,10]. In addition, waste generated on ships and wastewater emissions are adversely affecting terrestrial and marine ecosystems in the proximity of port areas [11–13].

The above effects are generated by a range of port-related activities, including shipping, cargo handling and bunkering. Thus, it is essential for ports to measure their environmental impact and implement effective mitigation strategies. Developing standardised, robust, quantitative, and transparent metrics for quantifying pollutant emissions from ports is an essential part of this strategy.

Although the exchange of environmental data already occurs in ports via the Port Authority System (PCS), often the data used are not standardised and are mostly qualitative, making robust assessment of environmental impacts and environmental comparisons between ports impossible [14]. While many medium or small ports face limitations when integrating their operational data, there is a constant increase in the availability of such data and the accessibility of data related technologies [15–17]. Despite this, the sharing of operational data is still limited.

The study presented in this paper addresses the above problems along two axes: (1) it presents a novel information and communication technology (ICT) infrastructure which allows the integration of data from IoT devices, sensors, and systems into a fully operational data centre and (2) it introduces and describes a novel methodology for aggregating all environmental impacts of port activities into a single metric. The metric, called the Port Environmental Index (PEI) provides close to real-time information of the environmental impact of a port area. This can help operators monitor their environmental performance and take timely mitigation actions in case of environmental emergencies. In addition, it enables rapid inter-port comparisons and environmental ranking of port areas.

2. Material and Methods

2.1. Defining Significant Aspects of Port Operations

According to the ISO 14001 standard, the term "significant environmental aspect" (SEA) is defined as "elements of activities, products or services of a port authority that can interact with the environment". Thus, SEAs are those aspects that have a significant, mostly negative, impact on their environment.

Significant environmental aspects have been defined using different criteria. Before the criteria were applied, a list of possible environmental aspects was created according to Darbra et al. [18].

The first and the simplest criterion was the legal regulation of an aspect. If the aspect has been regulated, it is by default considered to be significant. In addition to this, a group of experts, consisting of employees of the four pilot ports, were asked to fill a questionnaire to determine the relation between different port activities and the impact that they have on the listed environmental aspects. Based on their response, a significance assessment of the aspects was performed.

The "significance" has been defined as a function of "magnitude" ("severity" of negative impact on the environment) and "probability" of that negative impact happening or

$$Significance = Probability * \ Magnitude \tag{1}$$

Both probability and severity were ranked on the scale from 0, meaning non-existent, to 5, meaning extremely probable/severe. Based on those scores, a list of environmental aspects and their significance was created and used to choose the relevant ones.

Both "probability" and "magnitude/severity" were rated based on the subjective assessment of environmental experts. To minimise the bias, three steps were used: (1) including as many experts as possible in the questionnaire; (2) double checking the answers against the available scientific and technical literature; (3) comparing the significance assessment between different pilot ports since experts in different ports are less likely to have the same bias.

Based on these criteria, six environmental aspects were chosen as the most significant ones: emissions to the atmosphere, wastewater generation, generation of solid waste, noise and light pollution, as well as odour pollution, which is a significant environmental aspect only for ports such as fishing ports and those used for cattle transport. The first four of the listed aspects are also the ones with the biggest increase in the percentage of ports that are monitoring them [19,20].

2.2. Identification of Key Environmental Performance Indicators (eKPIs)

Once the SEAs of port operations were identified, the next step was to choose the indicators that would assess the ports' performance in those aspects representatively and will be used for the final calculation of the composite index—the Port Environmental Index. To choose the best possible set of indicators, the following criteria were applied:

- Significance;
- Representativeness;
- Measurability—must be measured in real time;
- Must be quantitative.

An in-depth analysis and examination of pilot ports were required to determine data availability. An inventory of the available data from different ports made it possible to obtain the needed numerical values for each of the eKPIs and are described below.

2.2.1. Waste and Wastewater from Ships

The EU Directive on port reception facilities for ship waste is a top concern for ports. It is crucial to differentiate between waste generated within the port or terminal and waste produced by ships since their priorities and regulations differ.

In acquiring data related to waste produced by ships, the MARPOL regulations have proven very valuable. Annex V of the MARPOL Convention outlines the guidelines for minimizing ship-generated waste, with the central objective of reducing and preventing garbage discharge into the sea.

Vessels with a gross tonnage exceeding 100 are obligated to establish a waste management plan, encompassing documented procedures for waste minimisation, processing, storage, collection, and disposal. For ships with a gross tonnage of 400 or more, the provision of a garbage record book is mandatory.

The calculation of each eKPI can be achieved by aggregating all data registered under MARPOL categories for all vessels entering the port.

Table 1 displays the eKPIs associated with ship-generated waste.

Table 1. Estimation of eKPIs for the generation of waste by ships [21] [1].

eKPI Name	eKPI Description	Subindex	Units
Plastics	Plastics wasted by ships	waste	mass
Food waste	Food wasted by ship crew and passengers	waste	mass
Domestic waste	Domestic waste created by ship crew and passengers	waste	mass
Cooking oil	Cooking oil used by the ship crew and passengers	waste	mass
Incinerator ashes	Incinerator ashes created	waste	mass
Operational waste	Waste created during maintenance or ship operations	waste	mass
Animal carcass(es)	Self-explanatory	waste	mass
Fishing gear	Self-explanatory	waste	mass
E-waste	Electronic waste (from electronic devices)	waste	mass
Cargo residues (harmful)	Self-explanatory	waste	mass
Cargo residues (non-harmful)	Unique Self-explanatory	waste	mass
Passively fished waste	Waste caught in the next during fishing	waste	mass
Other substances	All waste not covered with other categories	waste	mass

Wastewater can lead to considerable damage to marine life. Ballast waters, which are filled in one locality and discharged into another, contain microorganisms that threaten local species of marine life. Wastewater from ships can be classified as black or grey water. Black water, also known as sewage, consists mainly of wastewater from ship toilets (sanitary wastewater). Black water contains bacteria, viruses, and nutrients at high concentrations since less water is used for flushing. Gray water encompasses drainage originating from onboard laundry facilities, kitchens, and showers [21].

Similar to ship-generated waste, MARPOL outlines regulations in Annex IV concerning ship-produced wastewater. This annex defines the various types of discharges that ships can generate and release while in ports. Annex IV of the International Convention for the Prevention of Pollution from Ships establishes guidelines regarding sewage discharge from vessels, including requirements pertaining to ship equipment and wastewater control systems, the establishment of wastewater reception facilities within ports, and a range of related regulations.

The eKPIs related to wastewater from ships are shown in Table 2.

Table 2. Estimation of eKPIs for the generation of wastewater by ships [21].

eKPI Name	eKPI Description	Subindex	Units
Oily bilge water	Water accumulated in the bilge	wastewater	volume
Oily residues (sludge)	Mixture of oily residues created by ships	wastewater	volume
Oily tank washings	Washing out the residue using crude oil	wastewater	volume
Dirty ballast water	Seawater pumped in fuel tanks for ship stability	wastewater	volume
Scale and sludge from tank cleaning	Self-explanatory	wastewater	volume
Other—oil	Oil substances not covered above	wastewater	volume
Noxious liquid substances (NLS)—type X	Present major hazard to marine resources or human health, prohibited from discharging	wastewater	volume
NLS—type Y	Present hazard to marine resources or human health, limited discharging allowed	wastewater	volume
NLS—type Z	Minor hazard to marine resources or human health, more discharging allowed	wastewater	volume
NLS—other	No harm to marine resources or human health	wastewater	volume
Sewage	Domestic wastewater created by crew and passengers	wastewater	volume

2.2.2. Waste and Wastewater from Terminals and Port Authorities

Various activities influence waste production in ports such as management and planning operations, shipping industry activities, cargo handling, shipbuilding and repair, cruise ships, etc. [18]. Port operations generate sewage, a variety of solid wastes, oil discharges and leakages of harmful materials both from shore and ships [22]. The waste handling generally takes place in two phases—collection and treatment. The eKPIs used are based on port activities and are representative, as confirmed by several studies [22–27]. Unfortunately, sensor technologies for measuring these eKPIs in real time are currently not available.

Waste from terminals has been divided in two categories:

- hazardous waste—waste with properties that make it dangerous or likely to be harmful to human health or the environment;
- non-hazardous waste.

This information is not obtainable through sensors or automated means; instead, ports maintain manual records of this data. Each value for the two eKPIs pertaining to terminal waste generation is specified within a particular interface, and these eKPIs are calculated by summing the total quantity of terminal waste generated at the port over a given period.

eKPIs used are shown in Table 3.

Table 3. Estimation of eKPIs for the generation of waste by port terminals.

eKPI Name	eKPI Description	Subindex	Units
Non-hazardous waste	Waste that is not decomposable, but also not chemically or biologically active	waste	mass
Hazardous waste	Waste hazardous for public health or environment	waste	mass

As mentioned earlier, water pollution has been identified as one of the top 10 environmental priorities for the port sector [19]. This is linked to port activities such as handling of waste, activities from ship to ports, cargo terminal activities such as external and internal storage and distribution, urban activities including construction and demolition processes, maritime activities such as antifouling activities, ballast water, ship waste, invasive species in ship hulls, etc. [28].

The eKPIs related to terminal wastewater encompass metrics associated with port operational activities, including sanitary and technological wastewater, along with a parameter for rainfall. To obtain individual values for wastewater produced by the terminals, distinct categories were used which were provided by port operators. Each eKPI value can be computed by summing the cumulative volume of wastewater discharged from the port terminals over a specific timeframe. The relevant eKPIs are listed in Table 4.

Table 4. Estimation of eKPIs for the generation of wastewater by port terminals.

eKPI Name	eKPI Description	Subindex	Units
Sanitary wastewater	Wastewater created by usual domestic activities	wastewater	volume
Technological wastewater	Wastewater created by industry and ship maintenance	wastewater	volume
Storm water	Water resulting from rain, snow, etc.	wastewater	volume

Considering waste generation, the only category of waste relevant to port authorities is municipal solid waste [29] since port authorities do not perform industrial activities.

The amounts of waste generated by the port authorities were collected using a similar approach as for terminals. These data were not automatically acquired but were supplied by the port authorities. The values for the various eKPIs were derived by aggregating the overall quantities of waste within specific categories over a designated timeframe.

The relevant eKPIs are shown in Table 5.

Table 5. eKPI related to waste generation by port authorities.

eKPI Name	eKPI Description	Subindex	Units
Non-hazardous waste	Waste that is not decomposable, but also not chemically or biologically active	waste	mass

The only eKPI related to port authorities was sanitary wastewater. All the guidance provided for measuring and treating this type of wastewater at terminals is equally applicable to port authorities.

The quantities of wastewater produced by the port authorities were obtained using the same methodology that was used for terminals.

The values for the various eKPIs were computed by aggregating the total volumes of wastewater discharged within specific categories and over a designated time period.

The relevant eKPIs are shown in Table 6.

Table 6. eKPI assessment of wastewater generation by port authorities [22].

eKPI Name	eKPI Description	Subindex	Units
Sanitary wastewater	Wastewater created by usual domestic activities	wastewater	m^3

2.2.3. Noise, Light, and Odour

Noise pollution, together with light pollution and, to an extent, odour pollution, diverges from the three previously described environmental aspects in that there is no physical substance involved. Despite that, in several sources including the ESPO report [19], noise pollution was defined among the most important "environmental priorities".

The reason for the significance of environmental noise from ports lies in the fact that ports are usually located near large urban areas. Such areas host a large number of both business and residential buildings, increasing the amount of people exposed to it [30].

Unlike some of the previous environmental aspects, noise pollution contains only two such indicators—(L_{DEN} and L_{night}), which are described in Table 7.

Table 7. Estimation of eKPIs for noise pollution.

eKPI Name	eKPI Description	Subindex	Units	Calculation from Data Sources
Noise pollution (L_{DEN})	Noise levels calculated from day, evening and night levels	noise	dB	Raw data provided by sensors, and calculation of L_{DEN} indicator
Noise pollution (L_{night})	Noise levels during the night	noise	dB	

The values of the two eKPIs have to be measured (and calculated) over a defined time period. For that reason, the use of adequate noise sensors is highly recommended, enabling automatic collection of data. Regardless of that, additional "quality control" is desirable, as sensors can be subjected to various conditions, lowering their accuracy and precision.

The L_{DEN} indicator can itself be described as a simple composite indicator, as it is calculated from three separate sub-indicators [31], using the following expression [32]:

$$L_{DEN} = 10 \cdot \log\left[\frac{12}{24} \cdot 10^{\frac{L_{day}}{10}} + \frac{4}{24} \cdot 10^{\frac{L_{evening}+5}{10}} + \frac{8}{24} \cdot 10^{\frac{L_{night}+10}{10}}\right] \quad (2)$$

where:
L_{day}—A-weighted noise level during the day (7:00–19:00) (dB (A))
$L_{evening}$—A-weighted noise level during the evening (19:00–23:00) (dB (A))
L_{night}—A-weighted noise level during the night (23:00–7:00) (dB (A))

In the context of the PEI, odour pollution has the distinction that it is not applicable every port, but only in those ports that deal with activities which can cause significant odour pollution [33,34].

In the case of odour pollution, there is only one corresponding eKPI, simply called "odour pollution". It is measured in "European odour units per cubic metre" (OU_E/m^3), where 1 OU_E/m^3 corresponds to the odour level that can be detected ("detection point") by 50% of the population. This type of pollution can also be measured using appropriate sensors ("electronic noses"). Measurement methodology was specified by the European Standard for olfactometry [35]. In this exercise, metal oxide gas sensors have been proposed instead, which should provide concentrations of volatile organic compounds (ppm/m^3) which can then be converted to odour intensity. The final eKPI values are equal to the average value obtained during a chosen period.

The relevant eKPI is shown in Table 8.

Table 8. Estimation of eKPIs for odour monitoring.

eKPI Name	eKPI Description	Subindex	Units	Calculation from Data Sources
Odour	VOCs detection	odour	ppb	Raw data collected by sensors and averaged over a time period

According to Elsahragty and Kim [36], light pollution is defined as "the brightening of the night sky caused by streetlights and other man-made sources that hinder the observation of stars and planets" or "any adverse effect of artificial light". Light pollution, among various sources, results from light towers, traffic (both maritime and terrestrial), crane illumination, gate technologies, and lighting in public spaces. Considering the nature of these sources and the lack of a clear way to distinguish between their level of influence on final pollution levels, this environmental aspect was grouped with noise and odour pollution under aspects that are always considered on the level of the whole port.

As for the odour pollution, only one eKPI was used ("light pollution"), which is measured in luxes (lx). The measurement can also be taken using relevant sensors, usually referred to as "light meters" or "lux meters". It is important to have quality control, since those sensors, as well as noise sensors and electric noses, can be subjected to influences outside of the port. The final value is obtained by taking the average value over a defined period.

The relevant eKPI is shown in Table 9.

Table 9. Summary of the calculation of eKPIs for odour monitoring.

	eKPI Name	eKPI Description	Subindex	Units	Calculation from Data Sources
ALL	Light pollution	Self-explanatory	light pollution	lx	Raw data collected by sensors and averaged over a period

2.2.4. Ship Emissions

Ship emissions are one of the most significant pollution sources in the maritime industry [19]. Therefore, they play a very important role in PEI calculations. Assessing them requires an extensive amount of data that are often difficult to obtain. To make this approach as successful as possible, several solutions for the estimation of emissions to the atmosphere by ships have been proposed. Missing data were obtained using various calculations and approximations.

To compile an emissions inventory for the PEI, the primary focus lies on data collected automatically and the estimation of pollutant emissions on a regular basis, such as daily, weekly, or monthly, depending on the frequency of dataset updates. For this methodology to be effective, it is preferable that the data originates from an integrated IT system that consolidates various data sources, including ship arrivals, GIS systems, and an engine characteristics database. Data regarding vessel type and engine type have been assessed using either the Maritime Mobile Service Identity (MMSI) or the International Maritime Organisation (IMO) number.

The activity-based approach utilised for PEI calculations relies on detailed data pertaining to the ship's engine specifications and its movement within the port area, which are acquired through the Automatic Identification System (AIS). Combining this information with emission factors related to the engine and fuel types enables the quantification of emissions. The essential data required for estimating air emissions are as follows:

- berthing and manoeuvring time;
- installed power of main and auxiliary engines;
- vessel, engine, and fuel types;
- emission factors

Having obtained all the data, it is possible to calculate the emissions using the following equation [37,38]:

$$E_M = T_M \cdot \left[\left(ME \cdot n_{ME} \cdot LF_{ME,\,M} \cdot EF_{ME} \right) + \left(AE \cdot n_{AE} \cdot LF_{AE,\,M} \cdot EF_{AE} \right) \right] \cdot 10^{-6} \quad (3)$$

and:

$$E_B = \left[T_B \cdot TO_B \cdot \left(ME \cdot n_{ME} \cdot LF_{ME,\,B} \cdot EF_{ME} \right) + T_B \cdot \left(AE \cdot n_{AE} \cdot LF_{AE,\,B} \cdot EF_{AE} \right) \right] \cdot 10^{-6} \quad (4)$$

where:

E_M and E_B—ship emission during manoeuvring or at berth respectively [Mg]
T_M and T_B—time spent manoeuvring and at berth [h]
ME and AE—main engine MCR power and auxiliary engine MCR power [kW]
n_{ME} and n_{AE}—number of main and auxiliary engines, respectively
$LF_{ME,M,}$ and $LF_{ME,B}$—Load factor of the main engine in manoeuvring or at berth, respectively
$LF_{AE,M,}$ *and* $LF_{AE,B}$—Load factor of the auxiliary engine in manoeuvring or at berth, respectively
TO_B—percent of the time all ME operating
EF_{ME} and EF_{AE}—Emission factor of the main and auxiliary engine and for each of the emitted species [g (kWh)$^{-1}$]

The sum of these equations gives the estimated pollutant values for a single ship in a port area:

$$E_T = \sum E_i = E_M + E_B$$

Obtaining vessel characteristics presents a significant challenge in the process of collecting data for PEI calculations. This type of information is accessible through private providers such as Lloyds Register, Vesseltracker, or Fleetmon. These subscription-based services offer data on primary vessel engine specifications, cargo type, vessel classification, and the type of fuel utilised. However, it is important to note that in many instances, data regarding auxiliary engines is not readily available and must be estimated.

Knowledge of a vessel's engine and fuel type is essential for estimating both the main engine (ME) and auxiliary engine (AE) power. Typically, acquiring data for the main engine is more straightforward compared to auxiliary engines. It can often be sourced from ship call records or tracked through the vessel's IMO number. Alternatively, if this information is unavailable, approximations based on vessel type can be employed to fill in the gaps [37,39,40].

Emission factors play a pivotal role in the emission calculation process, as they are necessary to convert the power usage into emissions. In the context of PEI, the primary pollutants, also referred to as eKPIs, required for constructing a ship emission inventory include NO_X, SO_X, CO_2, NMOVC, and PM (ENTEC/DEFRA, 2010).

To calculate air emissions from ships, it is essential to gather information regarding the time spent on manoeuvring and berthing, often referred to as 'hotelling'. This data can be obtained through several methods. Ports equipped with GIS systems can utilise them for this purpose. Alternatively, one can record the vessel's entry into the port area and subtract it from the time it docks. The same approach can be applied when the vessel departs from the port. Like many other types of data, approximations are also available for manoeuvring and berthing times [37,39,40]. Figure 1 illustrates the process of calculating emissions from ships within the port and their release into the atmosphere.

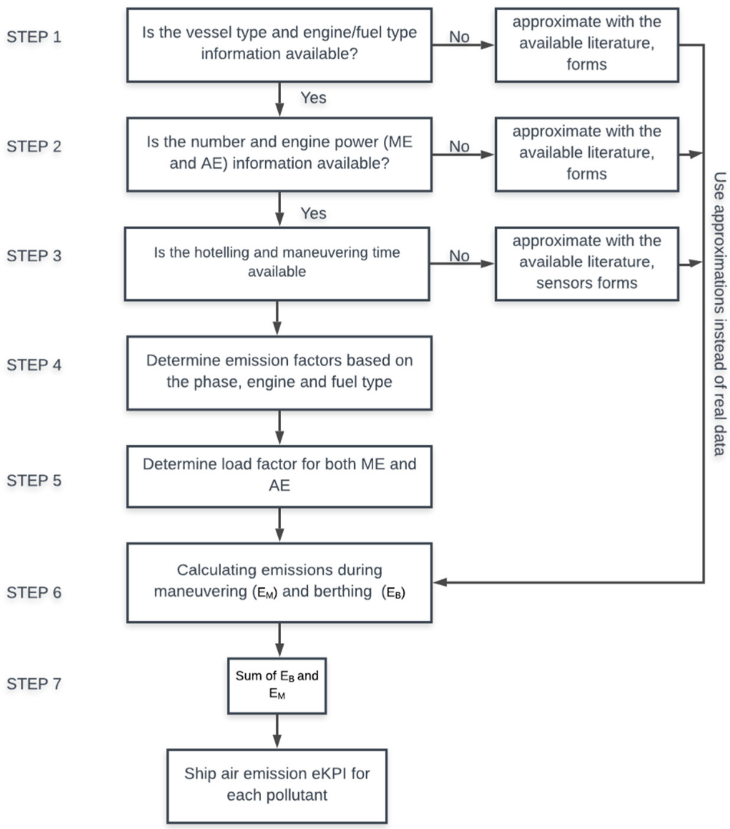

Figure 1. Flow diagram for calculating ship emissions.

2.3. Terminal Emissions and Energy Consumption—The Port Activity Scenario

The Port Activities Scenario (PAS), developed within the PIXEL project, has been designed to facilitate the modelling of port supply chains [41]. PAS is an automated tool that streamlines traditional data collection procedures by modelling terminal activities. By applying supply chain modelling to various cargo types, it aids in accurately identifying energy sources, equipment types, pollution sources, and the frequency of cargo arrivals and departures at the port.

This model primarily focuses on activities such as cargo loading and unloading to and from ships, cargo transfer within the port (including docks, storage areas, and gates), and support operations (e.g., warehouse and dock lighting, reefer area energy supply, etc.). A "PAS scenario" consists of a dataset describing all the activities and equipment involved within a specified timeframe and for a particular quantity of specified cargo. The PAS model comprehensively describes all cargo transition-related operations occurring within a port. Its objective is to provide an operational overview of port activities related to cargo handling.

The resulting PAS is a detailed data model that lists all the considered activities and their corresponding time series. Leveraging the supply chain description, which includes machine types, energy sources, throughput, and vessel call lists, PAS yields insights into energy consumption (with time series data on instantaneous or cumulative consumption). The PAS output enables a simulation-based assessment of the total energy consumption by the machinery required to service a vessel. This information, combined with the type of fuel or power used, can be utilised by the PEI to estimate air emissions associated with terminal activities over a given period. This functionality is seamlessly integrated as a module within the PAS [41]. Figure 2 illustrates the utilisation of PAS for PEI calculations.

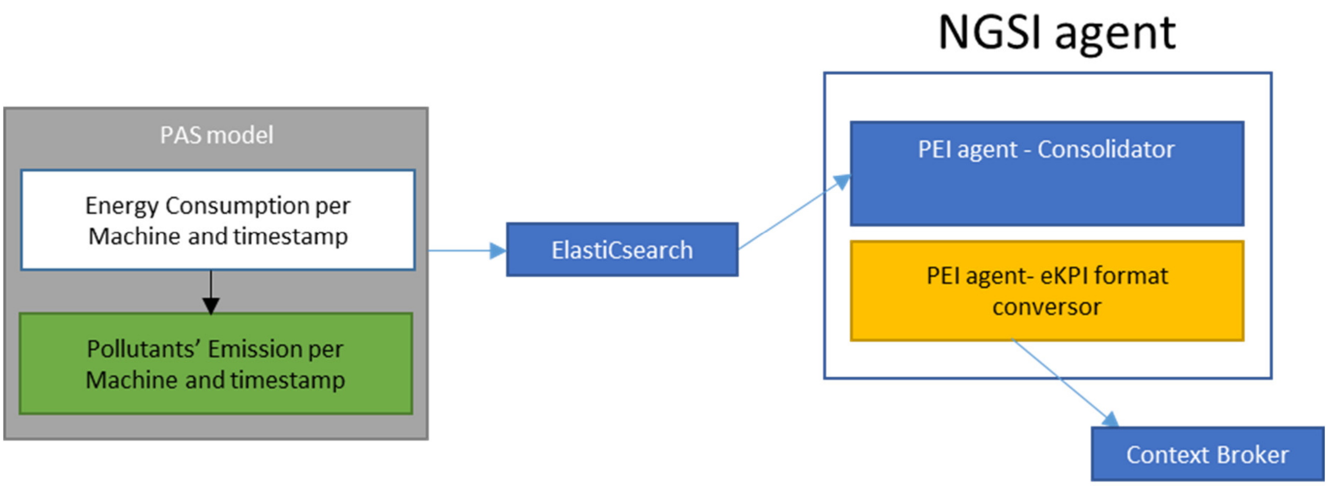

Figure 2. PAS usage for PEI calculation: technological schema.

2.4. Statistical Methods for PEI Calculations

As already stated, the PEI is categorised into four indices, each of which assigns environmental impacts to a particular entity: the port authority, terminals, ships, or a global category (all), which encompasses all of the port area and is not particularly related to an entity.

The developed software allows for the user to choose between different normalisation, weighting, and aggregation methods. The following normalisation methods have been tested: Z-scores, re-scaling, and distance to a reference.

Normalization by Z-scores, also known as standardization, is a statistical technique that converts the values of a data set into a common scale by calculating the deviation of each data point from the mean in terms of standard deviations. In this procedure, the mean of the data set is subtracted from each data point and the result is divided by the standard deviation of the data set. The result, called the Z-score, indicates by how many standard deviations a data point deviates from the mean. This method ensures that the transformed data have a mean of 0 and a standard deviation of 1, making it easier to compare and analyse variables with different units or scales. It is particularly valuable for data analysis because it removes the effects of scale differences, allowing for more meaningful comparisons, outlier detection, and statistical analysis.

The formula used for normalisation by Z-scores is the following:

$$Normalized\ value\ (t) = \frac{[Observed\ value(t) - Average\ value(t)]}{Standrad\ devioiation(t)}$$

The distance to a reference normalisation method standardises and normalises datasets by measuring the distance between data points and a selected reference point or distribution. Initially, a reference point is chosen, typically representing a baseline or a point of comparison. Distances between each data point and this reference are then calculated using various distance metrics. These distances are subsequently used to normalise the data. This method eradicates biases stemming from variations linked to the reference, rendering data more comparable and facilitating effective cross-condition or cross-dataset comparisons, ultimately enhancing analytical accuracy and insight extraction.

The formula used for normalisation by distance to a reference is the following:

$$Normalized\ value\ (t) = \frac{[Reference\ value\ (t) - Average\ value(t)]}{Standrad\ devioiation(t)}$$

Re-scaling normalisation is a technique used to standardise data by mapping it to a specific range or interval. This method proves particularly useful when the goal is to bring data to a uniform scale to eliminate variations in the magnitude of values between different variables or data sets. This involves selecting a desired range, determining the minimum and maximum values within the original data set, and applying a rescaling formula to transform each data point to the specified range. In this way, the rescaled data ensures that all values fall within the selected interval, allowing for easy comparisons and making it suitable for various analysis, modelling, or visualisation tasks.

The formula used for normalisation by rescaling is the following:

$$Normalized\ value\ (t) = \frac{[Observed\ value\ (t) - \min value(t)]}{[\max value - \min value]}$$

Here, the 'min' and 'max' values represent the minimum and maximum values observed in all ports at a given time. Applying the above formulae in the context of PIXEL results in PEI values where the worst-case scenario is assigned a value of 1 and the best-case scenario is assigned a value of 0. To reverse this scale so that the best-case scenario equals 1 and the worst-case scenario equals 0, the following formula should be applied:

$$Normalized\ value\ (t) = \frac{[\max value(t) - Observed\ value\ (t)]}{[\max value - \min value]} \tag{5}$$

Among the tested normalisation methods, Z-scores proved to be the most biased method for data normalisation since it generates both negative and positive values. Analyzing it may pose challenges for external users, and the data normalised in such a way may not be straightforward to convey, which is why it is advisable to refrain from utilizing this normalisation method for calculating the PEI. Still, the software built for calculating the PEI allows the user to chooses among the three normalisation methods. The normalisation method used is recorded and reported for transparency and comparisons with other ports.

Regarding weighting, two approaches have been proposed: equal weighting and the budget allocation method. In the equal weighting method, it is commonly assumed that all indicators hold equal significance, especially in the absence of any statistical or empirical evidence supporting an alternative approach. This approach is also acknowledged for its simplicity and ease of reproducibility. However, the metrics chosen do not have the same weights, so the developed software allows for the user to opt for the budget allocation method, which does not provide equal weights to the indicators selected. The budget allocation method provides a simple approach to soliciting expert opinions and assigning weights to various indicators. The process involves assembling a diverse group of experts, including stakeholders and end users, who collectively have a broad range of perspectives. Each member of the group is given a hypothetical budget of 100 "coins" to allocate among the various indicators related to the concept or problem under consideration. This method harnesses the power of collective wisdom, as participants allocate their budgets based on their individual assessment of the importance of each indicator. In this way, the more important indicators receive a larger share of the budget, while the less important ones receive fewer coins, and participants can easily express their assessments and preferences, making the method inclusive and understandable. Once all participants have allocated their budgets, the results can be analysed by calculating the average weight of each indicator. In addition, this aggregated weight distribution can be used for further analysis, including uncertainty assessments. The budget allocation method was performed and weights were allocated to the different sub-indexes by soliciting expert opinions from different port stakeholders. As with the normalisation methods, both weighting methods have been included in the software and the user has the option of choosing which weighting methods will be used for PEI calculation. The weighting methods are recorded and reported for transparency and comparisons with other ports.

Regarding aggregation, methods two methods have been used: the additive and geometric aggregation. In additive aggregation procedures, the normalised indicator values are combined using a specific function, the most commonly used function being the weighted arithmetic mean, in which each normalised indicator value is summed according to the weight assigned to it.

The formulae used for additive aggregation methods for each of the entities are as follows:

$$PEI(ships) = (\alpha * Emissions\ to\ air(ships) + \beta * Waste(ships) + \gamma * Wastewater(ships))/(\alpha + \beta + \gamma)$$

$$PEI(terminals) = \frac{\alpha * Emissions\ to\ air(terminals) + \beta * Waste(terminals) + \gamma * Wastewater(terminals)}{\alpha + \beta + \gamma}$$

$$PEI(port\ authority) = \frac{\alpha * Emissions\ to\ air(port\ authority) + \beta * Waste(port\ authority) + \gamma * Wastewater(port\ authority)}{\alpha + \beta + \gamma}$$

$$PEI\ (all) = \frac{\alpha' * Odour(all) + \beta' * Noise\ (all) + \gamma' * Light\ Pollution\ (all)}{\alpha' + \beta' + \gamma\prime}$$

Here, α, β, and γ represent the weights assigned to emissions of the air, waste and wastewater, while α', β', and γ' correspond to the weights assigned to odour, noise, and light pollution. When employing the additive arithmetic mean for aggregation, it results in eKPIs, sub-indexes, and PEI values having a consistent range of variation.

However, caution must be exercised when using additive aggregation methods because of two fundamental properties. First, preferential independence assumes that indicators are independent, meaning that their contributions can be combined without interactions, synergies, or conflicts. Failure to meet this assumption can result in a biased composite indicator, making it difficult to detect the magnitude and direction of errors. Second, additive methods are not recommended when there are significant interactions between indicators because they are inherently based on compensatory logic. In these methods, the weights indicate substitution rates rather than the importance of the associated indicator.

Geometric aggregation methods on the other hand, use multiplicative functions, the most used being the weighted geometric mean.

The formulae used for geometric aggregation methods for each of the entities are as follows:

$$PEI(ships) = [\alpha * Emissions\ to\ air\ (ships) * \beta * Waste(ships) * \gamma * Wastewater(ships)]^{\frac{1}{\alpha+\beta+\gamma}}$$

$$PEI(terminals) = [\alpha * Emissions\ to\ air\ (terminals) * \beta * Waste(terminals) * \gamma * Wastewater(terminals)]^{\frac{1}{\alpha+\beta+\gamma}}$$

$$PEI(tport\ authority) = [\alpha * Emissions\ to\ air\ (port\ authority) * \beta * Waste(port\ authority) * \gamma * Wastewater(port\ authority)]^{\frac{1}{\alpha+\beta+\gamma}}$$

$$PEI(all) = [\alpha' * Odour\ (all) * \beta' * Noise(all) * \gamma' * Lightpollution(all)]^{\frac{1}{\alpha+\beta+\gamma}}$$

However, methods based on the geometric mean have limitations in terms of compensability between indicators. To effectively use geometric aggregation methods, all indicators must have the same measurement scale to eliminate scale-related effects that should be accounted for in the normalisation process. In addition, there are inherent limitations associated with these approaches. Geometric methods like additive methods, exhibit a preference for interdependence. Since using a geometric aggregation can send a misleading information and can be difficult to interpret, it is suggested not to use it for calculating PEI values. As with normalisation and weighting techniques, the method to be used is left to the end-user, which is subsequently recorded and reported for transparency and comparisons with other ports.

For the proof of concept, when the index was applied to the port of Thessaloniki, the data were normalised using the distance to a reference method, weighted using the budget allocation method and aggregated using the additive method.

2.5. ICT Infrastructure

Previous sections have described how the PEI has been conceived as a methodology and theoretical tool. Information has been provided about the science behind the index, the rationale and the mathematical mechanisms that endorse the soundness of the indicator.

However, all the previous information must be supported by actual software and hardware performing the whole process.

The PEI is a software program endorsed by the execution of a specific backend software (running under a web server) and visualised in a custom user interface. It runs in the port of Thessaloniki, relying on the deployment of the state-of-the-art IoT platform. Modules of the IoT architecture are shown in Figure 3.

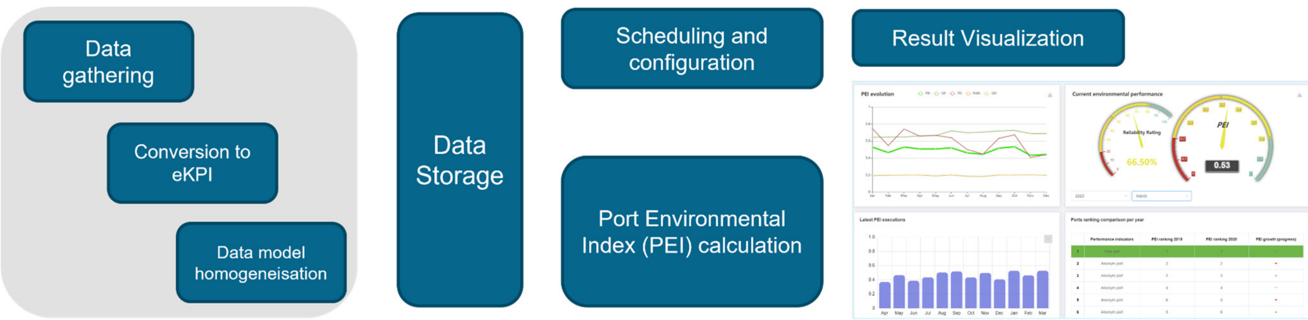

Figure 3. Modules of the IoT architecture used for deploying Port Environmental Index in the port of Thessaloniki.

Such technological baseline (PIXEL IoT platform) has been constructed (and deployed in the pilot port) based on a layered architecture building on open-source solutions.

In the paragraphs below, we aim to expose the blocks that compose the technological toolbox used for this work by the authors. In addition, some technical details of their development, customisation and application in port of Thessaloniki's deployment are provided:

Data gathering: Composed of two internal components:

Data sources which feed the calculation of the index: sensors (including Air Quality and Noise SmartSpot station by HOPU), HTTP REST APIs (information of the vessels manoeuvring at the port area, MARPOL annexes and others), connection to external systems and manual input of data.

Data Acquisition Layer (DAL), which gathers data and sends them to a Context Broker (for this work, FIWARE ORION).

Conversion to eKPI and data model homogenisation (Table 10): At this point, a clear reflection was made by the authors of the paper in the context of the overall architecture work: two actions must be secured in order to calculate the Port Environmental Index: (i) all data must be gathered with the intention of becoming an environmental KPI–eKPI and (ii) the introduction of that data in a persistence database should be completed in a structured way, defining a data model and format. The latter is crucial in Internet of Things architecture as it effectively allows the automated processing and management of the information. In this context, several NGSI agents based on the pyngsi framework were developed (which constitute one of the main blocks of the technological toolbox of the work). The agents mentioned oversee completion of both previous assignments.

Table 10. Conversion to eKPI and data model homogenisation.

Computation Block	Conversion to eKPI and Data Model Homogenisation
Software used	Python pyngsi library. Rely on PIXEL's Context Broker (based on FIWARE ORION).
Custom developments made	Python NGSI agents, description, and definition of the data model to harmonise all eKPI information obtained.

Data storage (Table 11) (in the PIXEL architecture: Information Hub—IH), which is a customised, enhanced version of an Elasticsearch database (ELK stack). This hub acts as the central element where all the data explained above is stored prior to further processing for the PEI calculation.

Table 11. Data storage.

Computation Block	Data Storage
Software used	Elasticsearch (ELK stack)
Custom developments made	Collector module to automatically transfer the information in the Context Broker to the expected input in Elasticsearch.

Port Environmental Index calculation (Table 12): This is the most relevant block of software in the work exposed by the authors in this paper. It undertakes (drawing from eKPI inputs) the calculation of PEI and its subindices given a series of considerations. For the work described, the considerations were the inclusion of all the eKPIs detailed in this document and the establishment of a monthly frequency for the tool execution. The former means that the port of Thessaloniki receives a new value of the PEI (and subindices and reliability rating info) automatically each month, representing the environmental impact of the port in the last month. This, put in the perspective of the overall architecture, is conceived as a "model" managed by the operational tools (see below). This model consists of a Java program that was containerised in order to be executed in the context of PIXEL.

For future exploitation, it is worth mentioning that the program could work perfectly outside PIXEL's scope as long as enough and proper input data is guaranteed.

Table 12. Port Environmental Index calculation.

Computation Block	Port Environmental Index Calculation
Software used	Java, data processing libraries.
Custom developments made	Full development of this component from the scratch.

Scheduling and configuration (Table 13): For scheduling and configuring the "PEI model" (see above), the authors of this work took advantage of the operational tools (OT), a Java-based component that orchestrates the proper execution of all other modules (containerised using Docker). This component analyses the input data required by the PEI software, makes enough connections and interpretations to merge model and storage, and actually "runs" the model (by building the container from model's image). The PEI model is run under a software as a service schema.

Table 13. Scheduling and configuration.

Computation Block	Scheduling and Configuration
Software used	PIXEL Operational Tools (Java, data processing libraries, CEP rules engine).
Custom developments made	Custom development in project PIXEL, just usage and configuration in the work of this paper.

The dashboard showcased to the members of the port is a web application (developed in Vue.js) for configuring and observing the results of the PEI and the Reliability Rating indicators. Further details on this visualisation tool can be found in Section 4 below.

3. Results and Discussion

The results of the execution of the PEI model in the port of Thessaloniki have been provided to the port via the developed User Interface (UI). It is important to highlight that this dashboard has been designed to display the PEI results with a monthly periodicity due to the port features. The overall aspect of the tool showing the PEI results is shown in Figure 4.

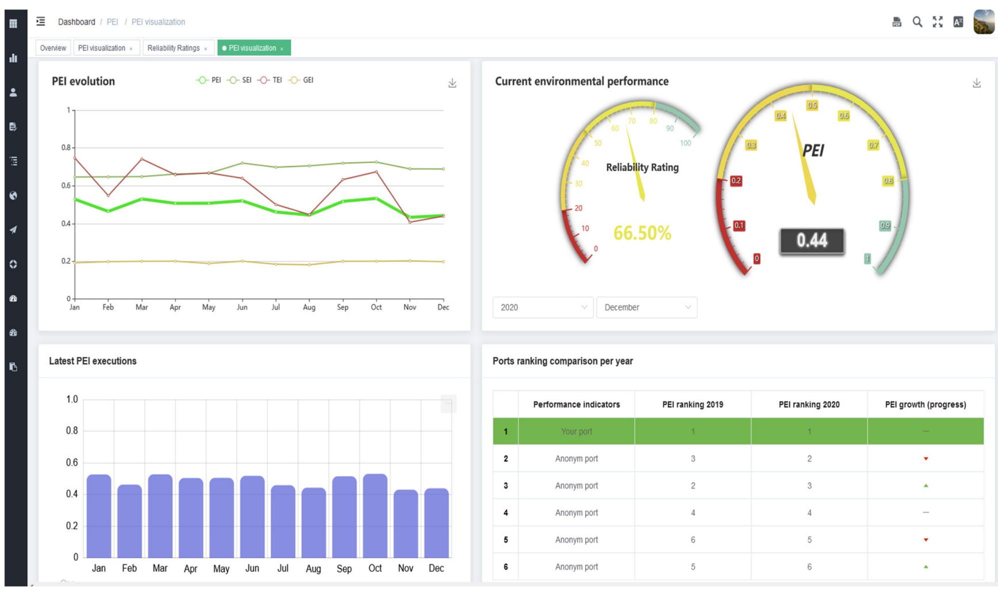

Figure 4. PEI User Interface.

Here below there are the different parts of the UI explained:

Month and year selectable: displayed under the current environmental performance charts, allows the user to select the year and month to show the results of the PEI of the selected period. This selectable alters the displayed values of all the charts.

PEI evolution chart (Figure 5): a multi-line chart that contains the PEI and the PEI indices (SEI, TEI, GEI) values (month by month) of the selected year. It only shows the values of the months in which the PEI has been calculated, starting at the month of January.

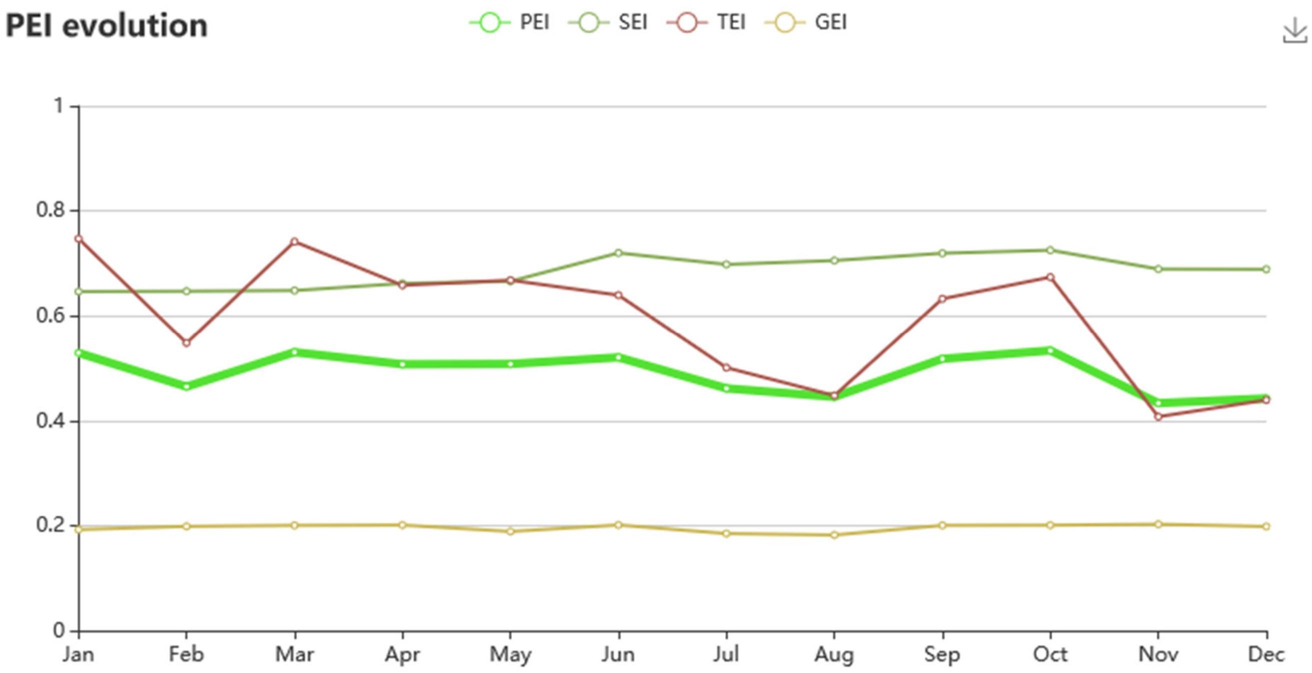

Figure 5. PEI evolution chart.

Current environmental performance (Figure 6): the PEI and reliability rating (RR) values of the selected month displayed in a gauge metre chart. The green colour indicates better results.

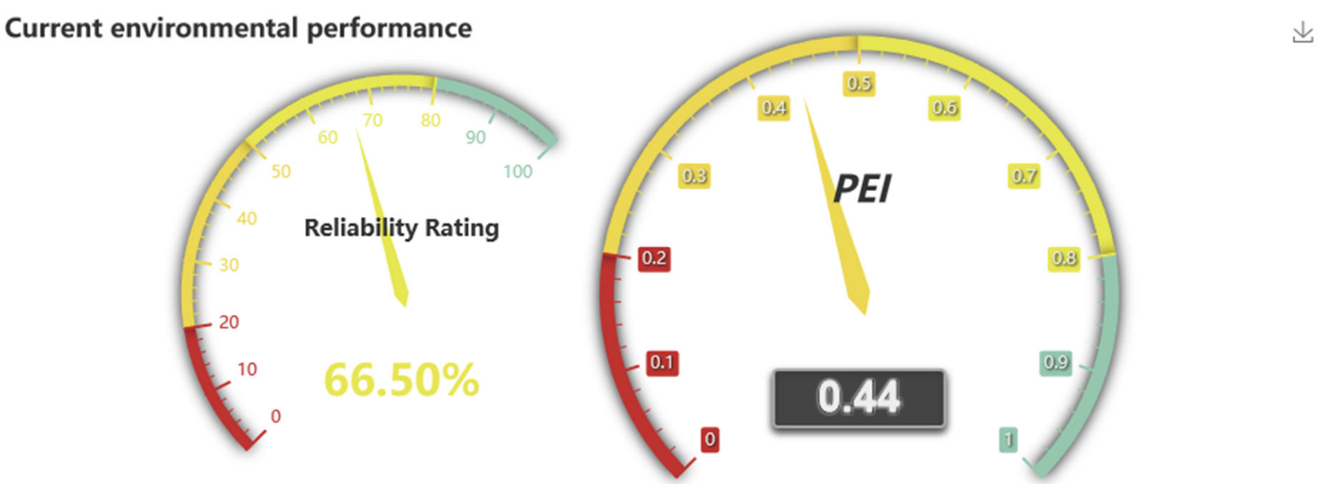

Figure 6. Current environmental performance.

Latest PEI executions (Figure 7): the PEI values of the last 12 months shown in a bar graph, starting the count from the selected month. The main difference with the PEI evolution chart is that in this chart, the displayed months do not necessarily match with the months from the selected natural year, as this chart may show results of months from a different year or ad hoc, per-request executions.

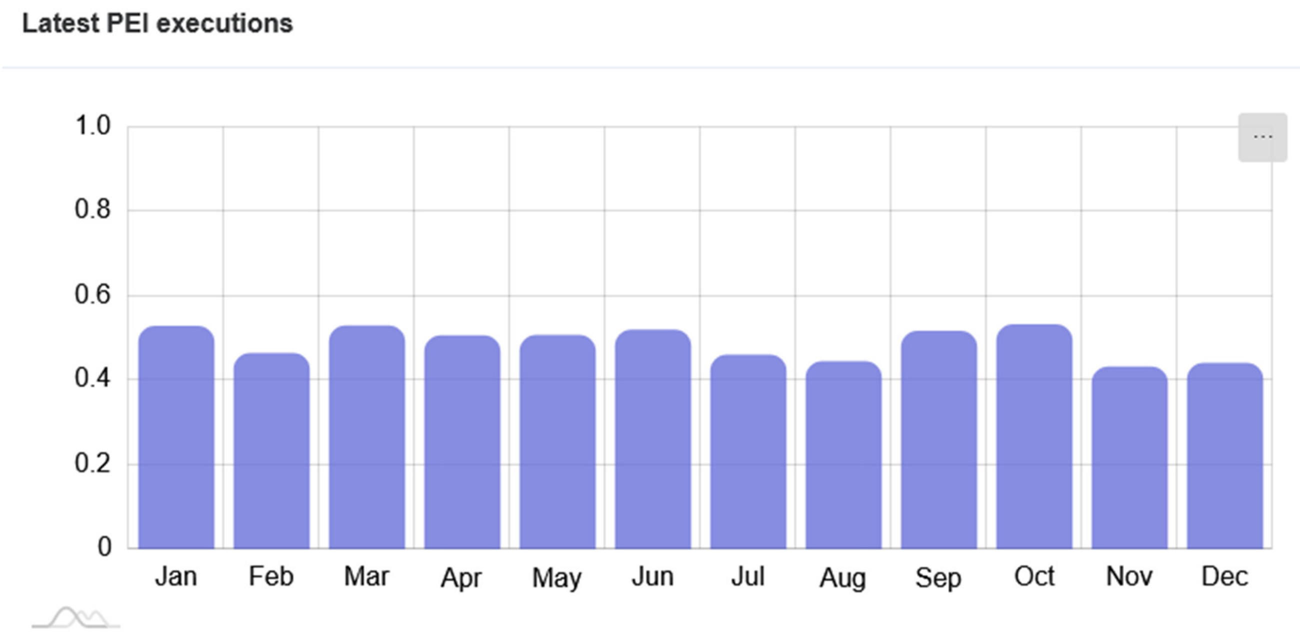

Figure 7. Latest PEI executions.

Ports ranking comparison per year (Figure 8): a table is provided containing all the ports currently utilizing the PEI, arranged in order of their mean PEI values from the past year. The table additionally displays each port's change in rank compared to the previous year's results. To maintain privacy and confidentiality, only the name of the respective port is disclosed. This ensures that no port can access the PEI values of other ports (preventing identification), while still allowing each port to ascertain its position within the ranking.

	Performance indicators	PEI ranking 2018	PEI ranking 2019	PEI growth (progress)
1	Your port	1	1	–
2	Anonym port	3	2	▼
3	Anonym port	2	3	▲
4	Anonym port	4	4	–
5	Anonym port	6	5	▼
6	Anonym port	5	6	▲

Figure 8. Ports ranking comparison per year.

eKPI values chart (Figure 9): consists of a polar chart displaying the normalised (minimum value of zero and maximum value of one) value of each eKPI of the selected PEI calculation. The eKPIs are grouped and painted with different colours depending on the PEI index (ships-SEI, terminals-TEI, global-GEI) that they belong to.

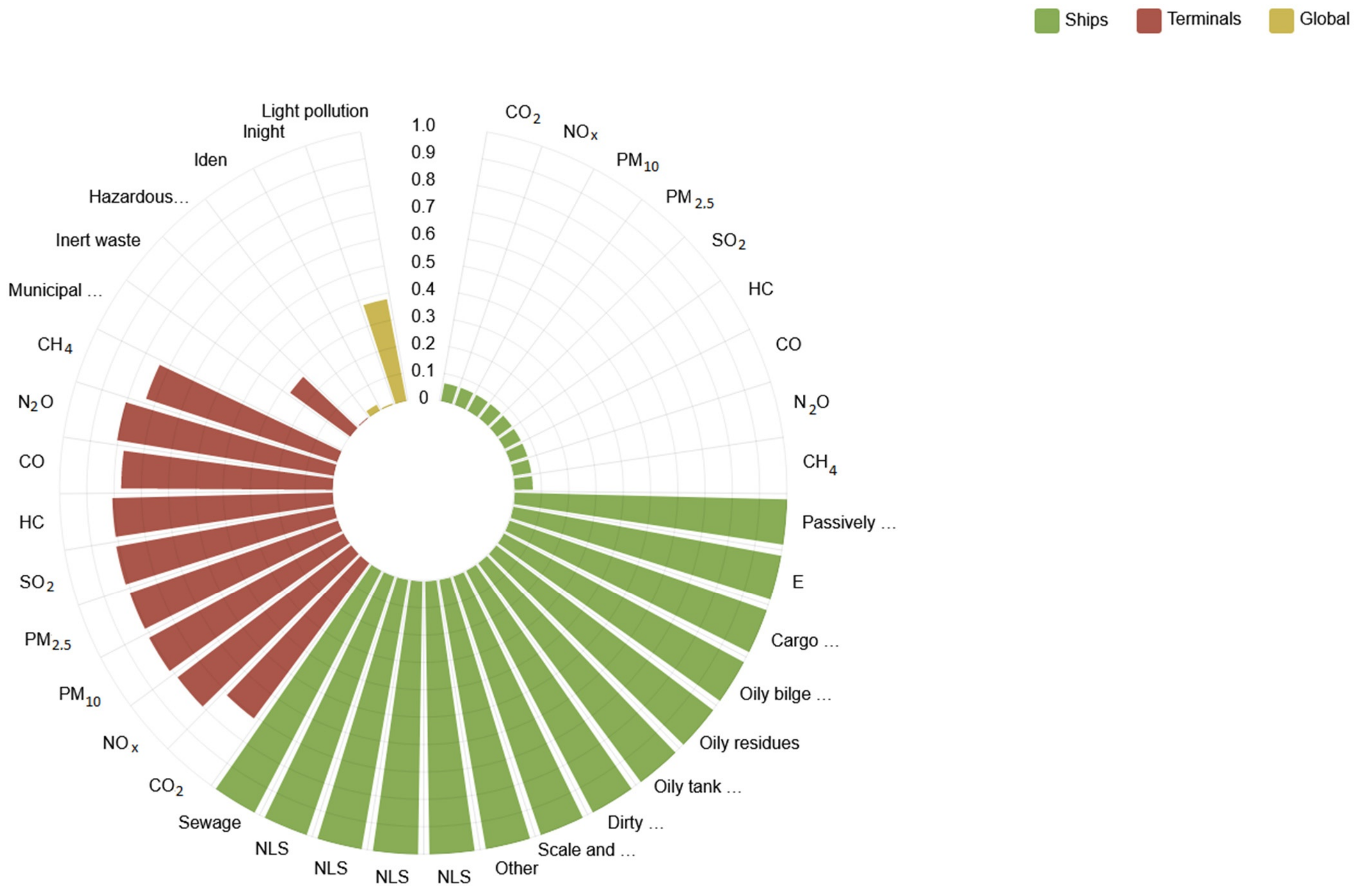

Figure 9. eKPI values chart.

Reliability Rating values (Figure 10): displayed in an independent view of the dashboard inside the PEI section, consisting of a table displaying the results of the RR obtained in the selected execution of the PEI. Each entry of the table is a different RR data piece, and the RR data pieces are grouped depending on the Data origin value (Ships, Terminal or Global, like the PEI indices) and, in second instance, depending on the Subindex value. The aggregated RR value of each Data origin and Subindex block are also shown.

Data origin	Subindex	Piece of data	Optimal retrieval way	Current retrieval way	Reliability Rating	Aggregated RR (subindex)	Aggregated RR (origin)
Ships	Air Emission	IMO number and gross tonnage of ships	Real time API	Periodic API	80.56 %	67.96 %	83.47 %
		Main and auxiliary engine of ships	Periodic API	Average value from literature	36.84 %		
		Berth and maneuvering time of ships	Sensors	Periodic API	86.49 %		
	Waste	MARPOL annexes about waste	Pixel proxy tool	Periodic API	97.14 %	97.14 %	
	Wastewater	MARPOL annexes about wastewater	Pixel proxy tool	Periodic API	85.29 %	85.29 %	
Terminal	Air Emission	Emissions produced by terminal machinery	Sensors	Periodic API	73.47 %	73.47 %	85.42 %
	Waste	Waste produced by the terminals	Pixel proxy tool	Periodic API	97.37 %	97.37 %	
Global	Noise	Noise values Lden - Lnight - Leq	Sensors	Average value from literature	34.69 %	34.69 %	30.61 %
	Light pollution	Luminosity-lux	Sensors	Average value from literature	26.53 %	26.53 %	

2020 December

Figure 10. Reliability Rating values.

Download of a report of the execution: A PDF report is accessible for download via the 'Download PEI report' button, conveniently located within the dashboard's toolbar.

This report comprises a summary of all preceding results, including a significant section that is not visible in the user interface: a set of recommendations designed to assist the port in enhancing its PEI results, ultimately aiming to increase the PEI value. The activation of these recommendations is dynamically determined based on the resultant eKPI values generated during the PEI calculation process.

Table 14 shows the PEI and the PEI indices values (month by month) of the PEI calculation in ThPA in the years 2019 and 2020.

Table 14. PEI and the PEI indices values (month by month) of the PEI calculation in ThPA.

Month	PEI	SEI	TEI	GEI
January 2019	0.4686443	0.6706413	0.5361399	0.19915164
February 2019	0.471104	0.7267224	0.47258773	0.21400203
March 2019	0.4318376	0.7032211	0.39533144	0.19696024
April 2019	0.37181336	0.59363574	0.32290274	0.19890161
May 2019	0.46796346	0.63084066	0.58132017	0.19172952
June 2019	0.3885618	0.65891635	0.3016308	0.20513824
July 2019	0.43815872	0.6394557	0.47639284	0.19862765
August 2019	0.5048294	0.6578068	0.66471213	0.19196934
September 2019	0.5204393	0.6663849	0.70067054	0.19426261
October 2019	0.43705472	0.65242785	0.457906	0.20083034
November 2019	0.49963644	0.6622239	0.6191919	0.21749356
December 2019	0.40889728	0.6299811	0.4004556	0.19625518
January 2020	0.5286529	0.64644486	0.7472063	0.19230756
February 2020	0.46441102	0.6471027	0.54768777	0.19844256
March 2020	0.5300134	0.64835984	0.7414118	0.2002685
April 2020	0.5070136	0.6618856	0.6582935	0.2008618
May 2020	0.50759006	0.6659783	0.66803634	0.18875548
June 2020	0.5201778	0.71992385	0.63956285	0.20104663
July 2020	0.46114784	0.6980385	0.5006641	0.18474086
August 2020	0.44496927	0.70546734	0.4474495	0.18199095
September 2020	0.5173898	0.71934056	0.6325352	0.20029363
October 2020	0.53321415	0.7251355	0.67387795	0.20062901
November 2020	0.43299818	0.68927705	0.40720263	0.20251487
December 2020	0.44202188	0.688853	0.4390271	0.19818549

The RR values for all the evaluated periods were the same as no changes were performed in the way the eKPIs have been collected (Table 15).

Table 15. Reliability Rating values in ThPA.

YEAR	RR	SRR	TRR	GRR
2019 AND 2020	66.50%	83.47%	85.42%	30.61%

4. Management Insights

A Port Environmental Index (PEI) plays a multi-faceted role in managing the operations of a port, providing a holistic view of its environmental performance and sustainability. One of its primary benefits is to provide port authorities with a comprehensive understanding of the environmental impacts associated with their activities. By quantifying key metrics related to emissions, energy consumption, waste generation, and water quality, PEI enables port managers to identify problem areas and prioritise improvement actions. This data-driven approach is invaluable for making informed decisions about investing in green technologies and implementing sustainable practices.

In addition, PEI serves as an important tool for compliance with environmental regulations and standards. Ports are subject to various local, national, and international environmental laws, and PEI helps ensure that a port's operations are in compliance with these regulations. It facilitates the tracking of performance indicators over time, which is critical for demonstrating compliance to regulators and demonstrating commitment to environmental stewardship.

The index also promotes a culture of transparency and accountability within the port community. Stakeholders, including shipping companies, local communities, and environmental organisations, are increasingly demanding greater transparency and sustainability efforts from ports. PEI provides a quantifiable measure of a port's environmental performance and enables transparent reporting and accountability to these stakeholders. Ports that demonstrate a strong commitment to environmental protection through a high PEI rating can enhance their reputation and attractiveness to environmentally conscious customers and investors.

In the broader context, PEI aligns ports with global sustainability goals as set out in the United Nations Sustainable Development Goals (SDGs). Ports are recognised as key players in achieving these goals, particularly in relation to clean energy, climate action, responsible consumption and production, and life below water. A high PEI score indicates a port's contribution to these global goals and positions it as a responsible and forward-looking player in the maritime industry.

In summary, the Port Environmental Index is a versatile and indispensable tool for the sustainable management of port operations. It enables port authorities to identify areas for improvement, ensure environmental compliance, improve transparency, and contribute to global sustainability efforts. Ultimately, PEI not only benefits the environment, but also strengthens a port's competitive position and its long-term viability in the maritime sector.

5. Conclusions

The Port Environmental Index serves a dual purpose: as a foundation for tracking a port's environmental advancements and as a tool for making comparisons among different ports. Furthermore, the PEI offers valuable insights into a port's environmental challenges and helps with their management. It also acts as a means for conveying environmental performance to stakeholders, making it a potential marketing tool. In essence, the PEI aims to present comprehensive information about overall port environmental performance in an objective and quantitative manner.

The trial of the PEI at the port of Thessaloniki has demonstrated the feasibility of this IoT-based approach, yielding valuable insights for port operators. A primary objective of the PEI is to ensure ease of interpretation, and accordingly, the visualisations have been designed to facilitate decision-making processes. The PEI serves as a tool for ports and port authorities to enhance technological processes, reduce costs, optimise operations, and potentially rank similar types of port terminals and those with a similar purpose.

Considering the above, the results derived from PEI calculations are applicable within port areas for assessing the present environmental status, identifying environmental trends within a specific port system, gauging the long-term environmental sustainability of a port system, initiating environmental and green projects within ports based on PEI analysis, and evaluating the outcomes of these initiatives.

The Port Environmental Index (PEI) serves as a comprehensive tool for promoting environmental issues in ports. It uses IoT technology to assess and quantify environmental performance, making it an important resource for comparative analysis between different ports. PEI provides port operators with valuable insights that help them make informed environmental management decisions. Its user-friendly design, including visualisations, facilitates access and action by port authorities. It also helps improve technological processes, reduce costs and optimise operations at ports by identifying areas for environmental improvement. In addition, PEI can rank similar port terminals based on their environmental performance, promoting competition and progress. It supports environmental assessments, identification of trends, and evaluation of long-term sustainability in port areas. Port authorities can use PEI analysis to initiate and prioritise green projects to promote sustainability. In addition, PEI enables continuous monitoring and evaluation of environmental initiatives, promoting ongoing improvement and accountability. In essence, PEI is a versatile tool that not only measures and compares environmental performance, but also drives positive environmental change at ports, benefiting port operators and stakeholders alike.

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Note

[1] Tables 1–9 were obtained from the deliverables of the Horizon2020 project Port IoT for Environmental Leverage (PIXEL) in the framework of which the work presented in this mansucript has been performed. The deliverables are published on www.pixel-ports.eu, accessed on 23 May 2023.

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