Development of Parametric Trend Life Cycle Assessment for Marine SO_x Reduction Scrubber Systems

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ABSTRACT

In response to the impending international maritime regulation, MARPOL Annex VI Reg. 14, to curb sulphur oxides (SO_x) arising from shipping activities, this paper aimed to evaluate the environmental impacts of the entire life cycle of three different SO_x reduction scrubber systems: (1) *'wet open-loop'*, (2) *'wet closed-loop'*, and (3) *'wet hybrid'*. To achieve this goal, the paper developed 'the Parametric Trend Life Cycle Assessment (PT-LCA)' which was introduced to proceed the extensive analysis for a number of case ship studies and quantify various emissions, such as greenhouse gases (GHG), sulphur oxides (SO_x), nitrogen oxides

(NO_x), associated with the proposed systems from cradle to grave. A case study designed with the database consisting of 1,565 ocean-going Ro-Ro vessels based on Lloyd's Register has revealed that, in terms of Global Warming Potential (GWP) and Acidification Potential (AP), closed-loop scrubbers were proven more environmentally friendly than open-loop scrubbers, but the opposite was true for Eutrophication Potential (EP). By identifying specific trends in scrubber systems in relation to various input parameters, the assessment contributed to improving environmental sustainability, as well as the total estimated amount of numerical environmental impacts that the scrubber systems have for the international fleets. The proposed framework enabled us not only to evaluate the different emission levels of systems applied to various ships but also to obtain the general trends of emission levels over ship parameters, which were expressed as formulae. The novelty of this paper can be placed on the provision of an insight into the optimal selection of scrubber systems depending on ship characteristics. It could also offer an insight into the improvement of current environmental regulations and guidelines by means of PT-LCA.

Keywords; SOx regulation, scrubber systems, LCA, life cycle assessment, PT-LCA, Parametric Trend Life Cycle Assessment

ABBREVIATIONS and TERMS

AE	Auxiliary Engine
AP	Acidification Potential
CH4	Methane
CO	Carbon Monoxide
CO_2 Equivalence.	Expression of the GWP in terms of CO_2 for the following three components CO_2, CH_4, N_2O, based on IPCC weighting factors
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGCS	Exhaust Gas Cleaning System
EP	Eutrophication Potential
GHG	Green House Gases
GRE	Glass Reinforced Epoxy
GWP	Global Warming Potential
HCl	Hydrogen Chloride
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LNG	Liquid Natural Gas
m/m	mass by mass
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	Main Engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
NaOH	Sodium Hydroxide
NMVOC	Non-Methane Volatile Organic Compound
NOx	Nitrogen Oxides
PT-LCA	Parametric Trend LCA
PM	Particulate Matters

PO_4 Equivalence.	Expression of the EP in terms of PO_4 for the following three components NO_3, NH_3, PO_4 based on IPCC weighting factors
Ro-Ro vessel	Roll-on/roll-off vessel designed to carry wheeled cargo
SFOC	Specific Fuel Oil Consumptions
SO_2 Equivalence.	Expression of the AP in terms of SO_2 for the following three components SO_2, NH_3 based on IPCC weighting factors
SOx	Sulphur Oxides

1. Introduction

In the past decades, International Maritime Organization (IMO) has made a vigorous effort to mitigate the air pollution impacts pertinent to waterborne transportation. As one of the most remarkable outcomes, new international convention for the protection of marine air pollution was adopted and included in Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1997 (IMO, 2018). The Regulation 14 of MARPOL Annex VI introduces a progressive restriction of sulphur content levels in marine fuels to keep as low as 0.5 % m/m (mass by mass) since 1 January 2020. Such an emission is more severely limited in Emission Control Areas (ECA) where the sulphur contents in those fuels should not exceed 0.1 % m/m since 2015 (IMO, 2018).

In response, the exhaust gas cleaning system (EGCS), known as 'scrubber', which can remove SO_x and particulate matters (PM) contained in the exhaust gases of conventional engines or boilers by means of sea water, chemical or dry substances, has started to being introduced in the marine industry. Figure 1 shows that the increase in the number of scrubber systems applied to marine vessels over the last decade; prior to 2010, only 5 scrubber systems were applied to marine vessels, but as of 2018, the cumulative number of vessels to be installed or under contract has reached over 1,200 sets of scrubber systems. Considering that the IMO SO_x regulations are applied to hundreds of thousands of international vessels having 400 gross tonnage or above, this trend is highly expected to increase exponentially in the future.

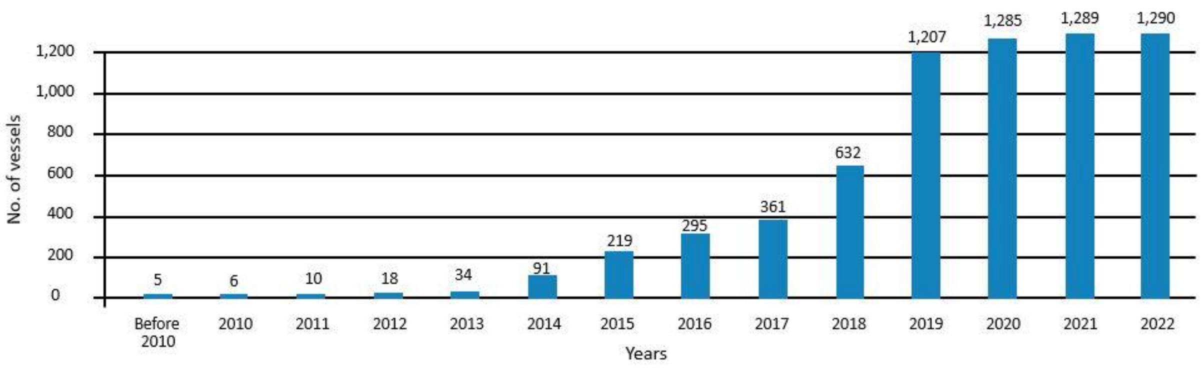

Figure 1: Scrubber systems market trend (DNV.GL, 2018).

Along with the remarkable growth in the marine scrubber system market over a decade, a number of research on investigating the performance of scrubber systems has been conducted (AIR, 2016). However, the aim and scope of those past research and technical reports are highly focused on confirming the limits of SO_x emission after treatment to certify the compliance of the SO_x regulation. While more than 30 manufacturers produce marine scrubber systems, those publications were not sufficiently able to answer on the best scrubber system that is outstanding for reducing shipping emissions other than SO_x. Particularly, there lacks research on quantifying the increment in the emission levels attributed by additional electricity consumption for operating the subject system.

Meanwhile, in recent years, there has been a strong argument among IMO member states and stakeholders that the evaluation of shipping emissions should not only fall into the operation phase alone. In other words, the maritime emissions need to be evaluated in a broader and holistic perspective in recognition with each life stage of a ship and/or a system contribute to generating emissions. For example, if electricity is used to manufacture a scrubber system, emissions produced during power generation should be considered shipping emissions. To respond to such a demand, the life cycle assessment has been introduced as an optimal solution for the marine industry.

2. Literature review

2.1. LCA in marine industry

With a growing awareness of environmental protection around the world, all industries have been a great deal of efforts to evaluate the environmental impact of certain products and services in order to identify and use the most environmentally-friendly ones among numerous candidates. Given this background, the introduction of LCA enabled us to quantify a variety of emissions pertinent to such commodities from the cradle to the grave; this is a comprehensive approach to model and examine the lifetime process of certain products from the raw material stage up to the disposal/recycling stage (Guinee et al., 2010).

The history of LCA began in 1963 when Harold Smith presented the cumulative energy consumptions across the industries at the World Energy Conference (Jensen, 1998). With this motivation, LCA was conceptualised and firstly implemented by the Coca-Cola (Guinee et al., 2010). The process of LCA has been standardised in ISO 14040 and ISO 14044 (ISO, 2006) and has been applied to extensive research on pollution control across industries such as automobile, construction, etc. (Blanco-Davis, 2015).

Over the past decade, the marine industry has begun to recognise the importance of LCA (Wang et al., 2018) so that the LCA-oriented studies are drawing more attention in this field. Fet and Michelsen (2000) are considered initiators as firstly applying a life cycle perspective methodology to the marine sector. Kameyama et al. (2007) conducted on environmental impact assessment for shipbuilding and operation whereas Utne (2009) investigated the holistic environmental impacts of fishing vessels. Those frontier research have revealed the excellence of the LCA approach for estimating the holistic environmental impacts of maritime activities.

LCA studies have been extended to marine power sources for ship propulsion (Bengtsson et al., 2011) as well as marine systems/technologies and retrofitting activities (Blanco-Davis and Zhou, 2014). Additionally, an LCA model formulation for shipping energy efficiency was developed, which was proposed to be dynamically useful in the marine industry by improving the functionalities of current IMO environmental indicators: Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI) (Blanco-Davis and Zhou, 2016).

Recent LCA works have been conducted with a short-routed hybrid ferry and an offshore tug vessel to evaluate optimal propulsion systems, integrating environmental and economic analyses together (Wang et al., 2018; Wang et al., 2019).

There have been a few attempts to evaluate the environmental impacts of open-loop scrubber systems in comparison to other possible options (Ma et al., 2012). On the other hand, those studies were largely focused on the comparative analysis among all SOx regulation-compliant options: scrubber system, LNG and MGO. The scope of analysis was limited to case specific studies, thereby it was difficult to offer practical recommendations as to what type of scrubber would be ultimately best suited for a wide range of marine vessels. This question may be possibly answered if we are considering the correlations of the basic information of the vessel - such as age, power, gross tonnage, etc. - with emission levels of subject systems.

2.2. Limitations of current LCA approach

Figure 2 shows the basic process of LCA specified in the ISO Standards (ISO, 2006): the establishment of the goal and scope (Step 1), Life Cycle Inventory (LCI) (Step 2), Life Cycle Impact Assessment (LCIA) (Step 3) and Interpretation (Step 4).

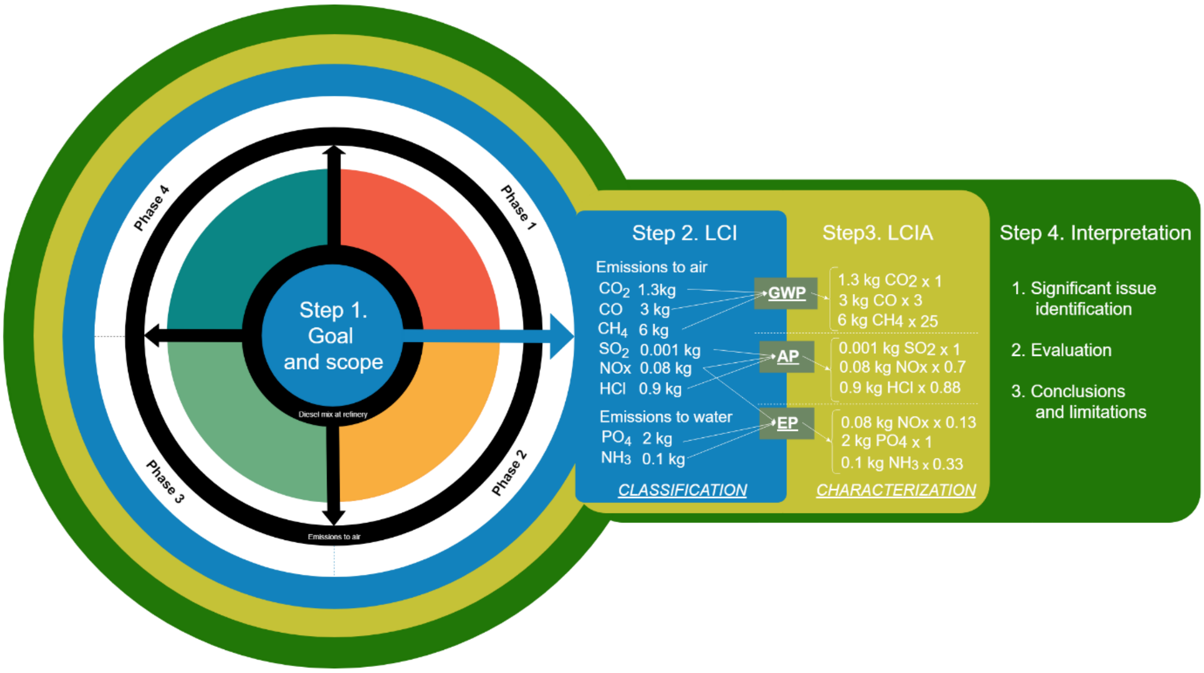

Figure 2: The four phases of LCA with sample of emission classification and characterization under different impact categories (PE-International, 2013).

The first ISO guidance is a generic approach but unable to provide details or pathway for consistency in case studies. As a result, the discrepancy in modelling, processing and data collection have arisen across LCA studies (Guinee et al., 2010). These challenges led to several methodological developments, such as dynamic LCA (Su et al., 2017), spatially differentiated LCA (Nitschelm et al., 2016), risk-based LCA (Ayoub et al., 2015) and hybrid LCA (Teh et al., 2017).

Despite these improvements, congenital limitations still remain if the LCA is intent to be applied with the purpose of decision making or regulatory frameworks. It is because that current LCAs were largely designed to indicate the environmental impact of case-specific studies with the user-defined scope, boundaries, data and assumption. Hence, LCA results obtained from those studies can hardly represent general trends or observations for all marine vessels (Guinée, 2002). For an instance of scrubber systems, the current LCAs may be expedient to investigate the holistic environmental benefits or costs for a 5,000-ton case ship. However, those results from the case study cannot predict the environmental benefits for other hundreds and thousands of ships.

In order to minimize this gap, some researchers limitedly conducted the sensitivity analysis by comparing some credible scenarios to observe the deviations according to scenario changes (Smol et al., 2019). Nevertheless, their attempts could not address the fundamental limitations of LCA on a case-by-case basis.

In view of this background, this research was motivated to introduce an enhanced framework for LCA, which can guide us to obtain general trends/insight of environmental impacts for all vessels. Therefore, those general results can be directly utilised for proper decision-making on scrubber system selection as well as future rule-making associated with marine environmental protection.

3. Method applied

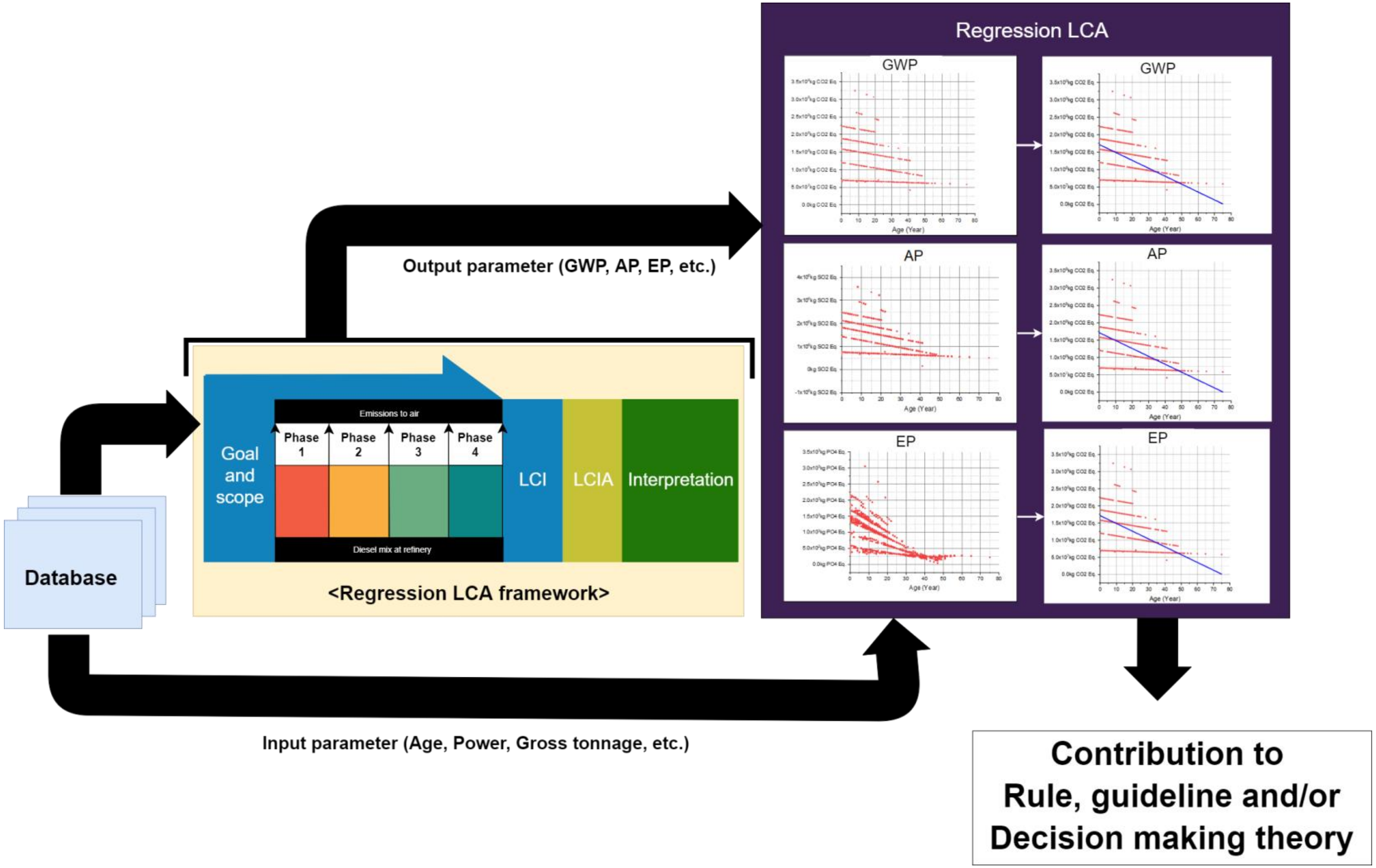

Figure 3: Schematic representation of a generic parametric trend life cycle assessment (PT-LCA).

Figure 3 shows the general process of the proposed LCA approach (defined as *Parametric Trend LCA* or *PT-LCA*), which consists of five steps. The first four steps are in the same line with the ISO guidelines but tailored accordingly for the purpose of this research. The final step of the parametric trend analysis adds a new functionality to the LCA framework. Through this step, LCA results are formatted as general indicators applicable for all ships.

The benefit of this step lies in the fact that it can reduce tremendous time and effort to be made for LCA analysis while eliminating discrepancies in each individual case study. In the end, decision-makers and rule-makers would be provided with the much broader holistic view in a consistent way, which is one of the most important elements of regulatory frameworks.

Step 1. Goal and scope

Unlike conventional methods, the PT-LCA deals with a number of case studies simultaneously by coupling with considerably larger and broader data. Given that the goal and scope of existing LCA approaches is focused on the process of estimating the environmental performance of a couple of scrubber system types fitted to an example vessel, PT-LCA repeats such a process thousand times for various cases. The general indication, therefore, can be obtained from understanding on trends of all results. In this research, a data library of the entire Ro-Ro vessels engaged in international voyages was applied for the analysis of SO_x scrubber systems.

Step 2, 3. Modelling (LCI and LCIA)

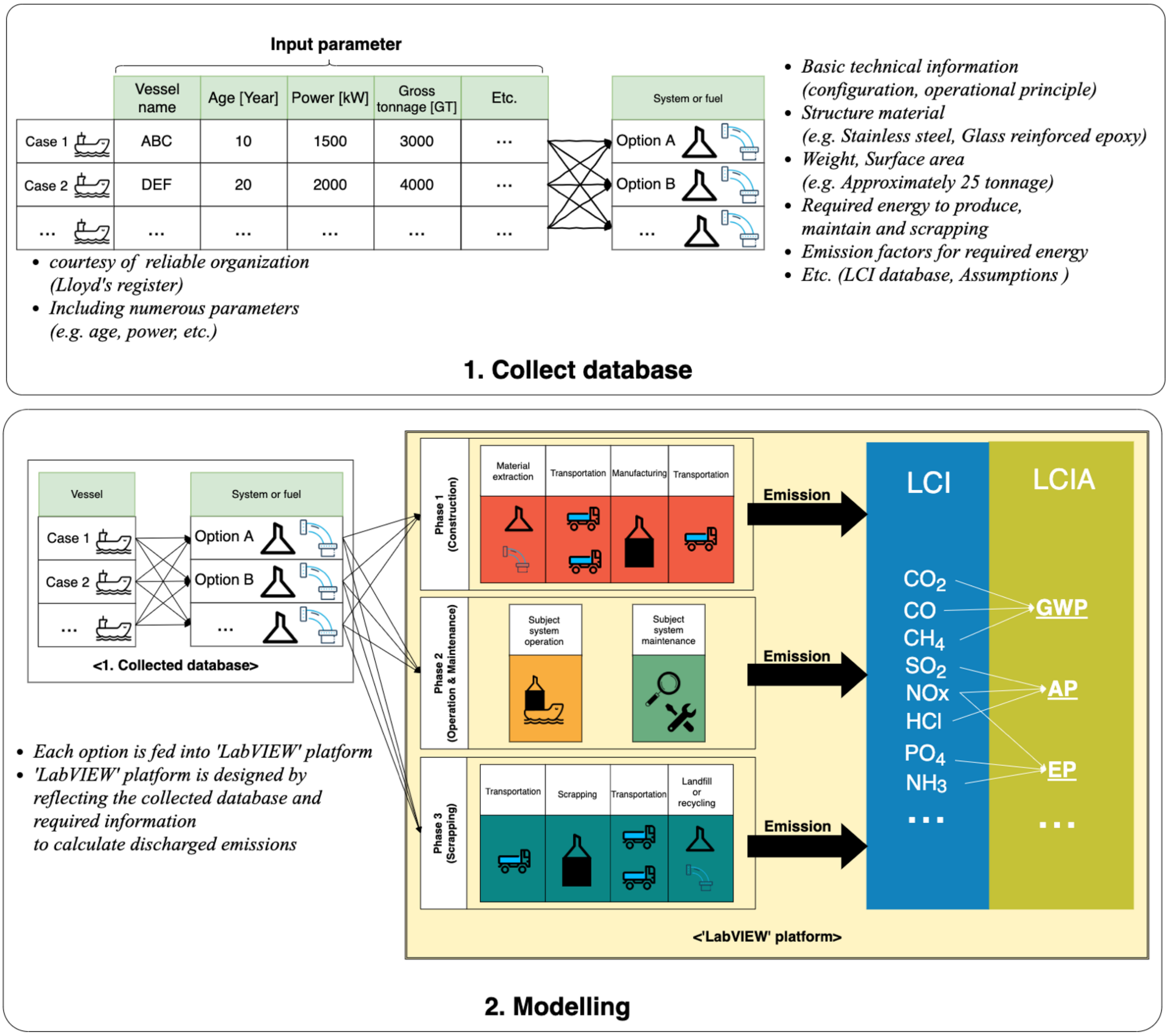

Figure 4: An example of a parametric trend LCA Modelling process.

The process of the PT-LCA is designed corresponding to each life stage of the subject systems. This research adopted a common practice of assigning four life stages: construction, operation, maintenance and scrapping (Jeong et al., 2018).

Once key activities in each life stage are modelled, the types and quantities of emissions pertinent to each activity are estimated by tracking all inflows and outflows of product systems, including raw materials, energies and emissions from certain substances. This kind of analysis is regarded complex as possibly including dozens of individual unit processes in the supply chain (e.g. material production, transportation, installation, etc.).

To facilitate the analysis, the LCA was implemented in the 'LabVIEW' platform in connection with the data library as shown in Figure 4. Ship information stored in the data library as input parameters for the analysis is fed into the analysis platform which encapsulates the LCI models and algorithms for quantifying energy consumption and emission levels.

Meanwhile, marine vessels are primarily operated on fossil fuels which mainly produce CO_2, CO, CH_4, HCl, NO_x, SO_x and NMVOC (IMO, 2015). Those emissions directly contribute to Global warming potential (GWP), Acidification potential (AP) and Eutrophication potential (EP) as presented earlier in Figure 2. Therefore, these three impact categories were selected in consideration of their local and global relevance to the subject systems. This reflects on the current maritime regulations to limit those emissions (IMO, 2015, 2018).

Step 4. Interpretation

This step of interpretation has a continual interaction with the other steps, thereby it identifies potential issues on goal and scope set-up, inventory analysis and assessment results and take corrective actions accordingly. With the combination of all results obtained from the other steps, this step guides on how to interpret the study findings.

Step 5. Parametric trend analysis

The parametric trend analysis can be regarded as generalisation process. It is because the individual results generated from repeatable LCA processes (Steps 1 to 4) are consolidated to represent a general trend which can offer an insight into the relationship between the subject systems and mother ships in terms of environmental benefits. These correlations are formulated into equations as LCA indicators for estimating the overall environmental impacts of marine systems straightforwardly. It can be greatly supportive of regulatory framework and decision-making on system selection. Indeed, it enables stakeholders who are not familiar with LCA can obtain LCA results.

4. Case Study

Figure 5 shows the outline of the case study where the proposed method in the previous section is applied to investigate the environmental benefits of marine SO_x scrubber systems.

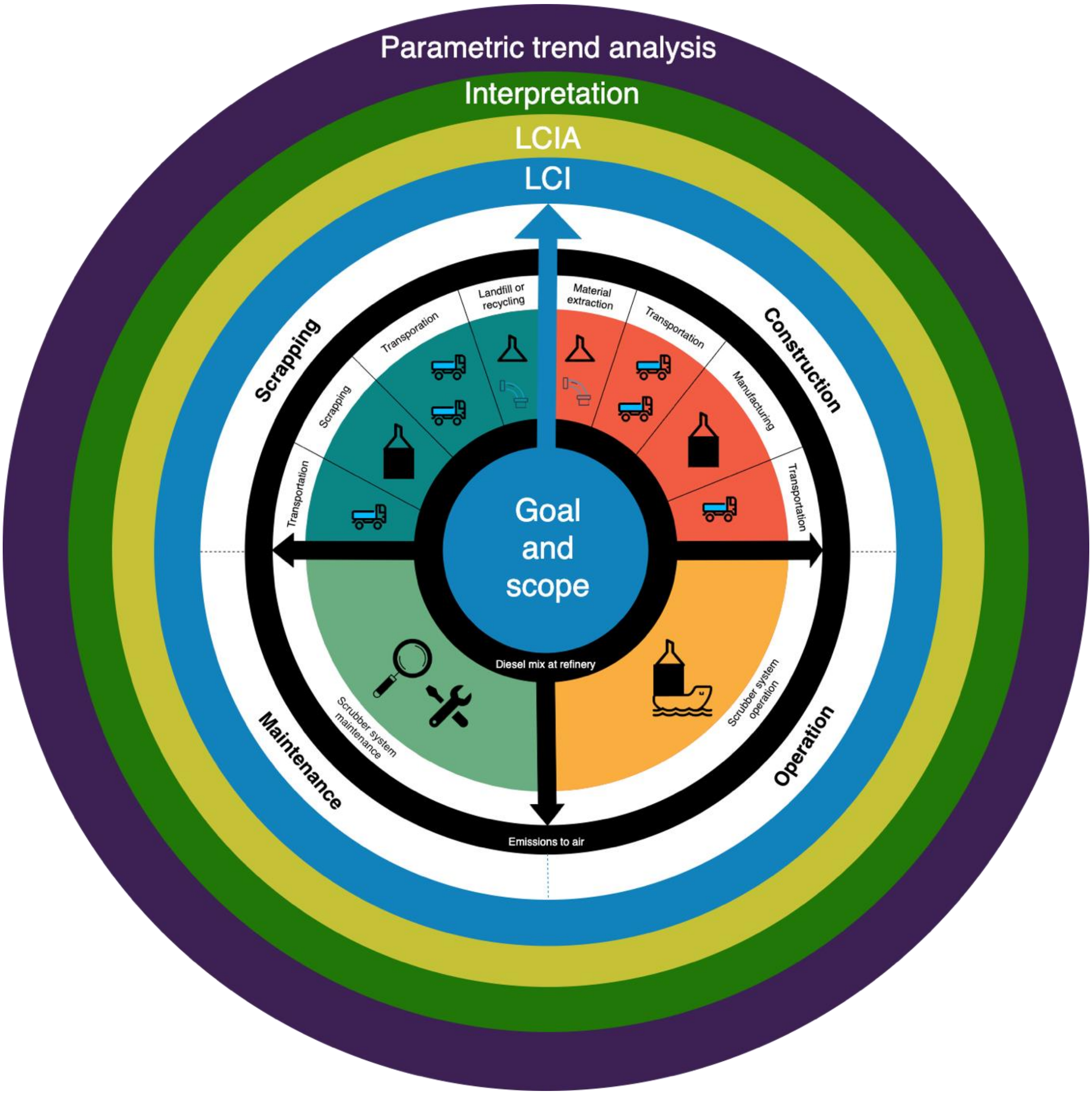

Figure 5: PT-LCA conceptual framework for case study.

4.1. Goal and scope (Step 1)

4.1.1. Goal of the study

The primary goal of this paper is to evaluate the life cycle environmental benefits of marine scrubber systems over the conventional heavy fuel oil (HFO). It is to determine the most environmentally friendly system across all scrubber candidates. Finally, potential emission levels pertinent to different scrubber systems are to be estimated in accordance with various ships.

4.1.2. General scope

The case study falls into two analyses: 1) the comparison of open-loop scrubber system with HFO, 2) the comparison among all credible scrubber systems.

4.1.2.1. Case 1: HFO with open-loop scrubber system vs HFO only

Case 1 was designed to respond to the fundamental question on whether the shipping industry can ultimately obtain environmental benefits from SO_x scrubber systems when consistently using HFO as marine fuel. Figure 6 presents the life cycle process of the scrubber systems and the HFO within the scope of this analysis. Taking into account the dominant market share, the open-loop type was adopted for this analysis (DNV.GL, 2018).

The LCA for 'Scrubber systems' represents the overall lifecycle process of the scrubber system consisting of construction, transportation, operation, maintenance and scrapping. The additional electricity consumption to operate the scrubber system, thereby extra emissions from electricity generation are considered in the analysis.

The LCA scope for 'HFO' is entirely common in both *the HFO with open-loop scrubber system* and *the HFO only*. On the other hand, in order to compare the emissions from *HFO only* to *HFO with open-loop scrubber system*, the LCA scope for 'HFO' was limited to estimate the lifecycle emissions from burning HFO in the Main Engines whereas the other life stages of HFO from production to transport onboard.

In this context, the analysis scope of *the HFO with open-loop scrubber system* covers both LCA models of 'Scrubber system' and 'HFO' presented in Figure 6, whereas *the HFO only* covers those of 'HFO'.

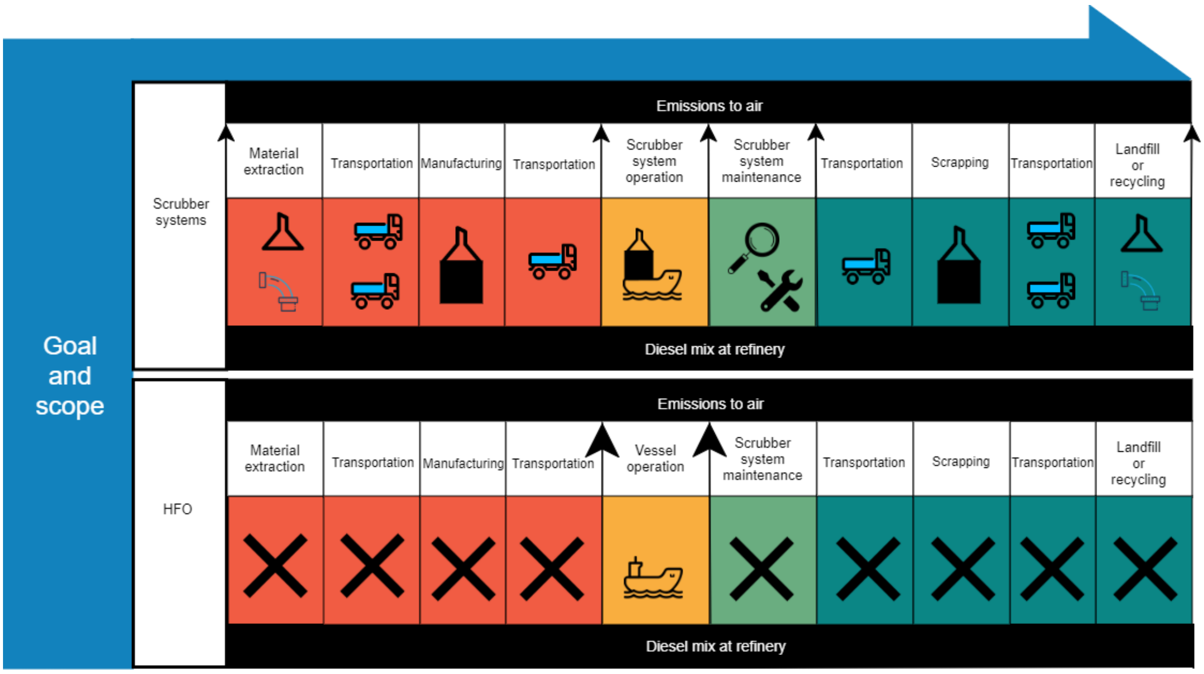

Figure 6: Outline of the LCA scope for scrubber systems in comparison with HFO only.

4.1.2.2. *Case 2: Open-loop Vs Closed-loop Vs Hybrid*

Given the purpose of Case 2 to evaluate the best solution of the three different types of scrubber systems, the scope of analysis is focused on the performance of scrubber systems. Therefore, the LCA scope of 'HFO' part given in Figure 6 is completely disregarded in this case.

The vessel data of 1,565 ocean-going Ro-Ro vessels (almost all Ro-Ro vessels subject to international regulations) was used for the analysis (*by courtesy of Lloyd's register*). Figure 7 illustrates the distribution of those vessels in accordance with ship age, engine power and gross tonnage.

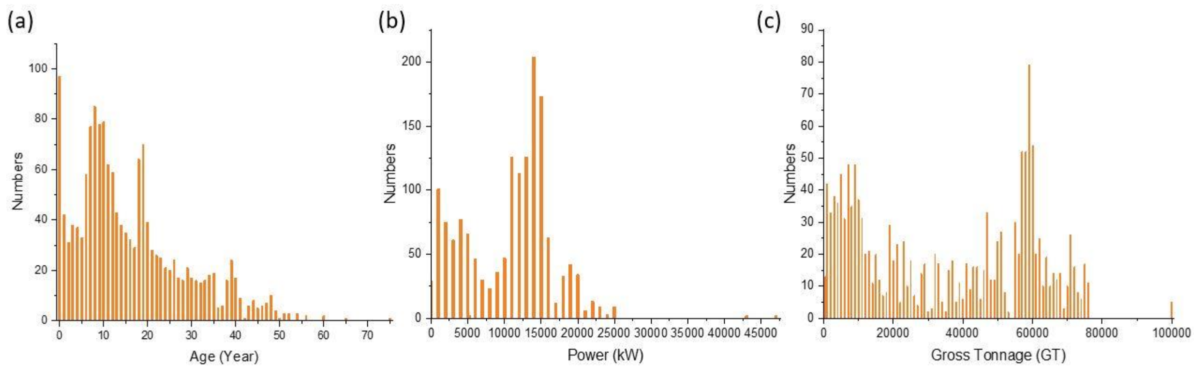

Figure 7: Distribution chart of the database source according to major input parameters: (a) vessel numbers according to age (Year), (b) vessel numbers according to power (kW) and (c) vessel numbers according to gross tonnage (GT).

Given this, three scrubber systems were applied to the whole case ships and the environmental performances of each system were investigated through PT-LCA.

4.1.3. Application of Scrubber systems

Scrubber systems are a representative end-of-pipe technology that complies with upcoming regulations. As such, the scrubber system can be technically categorised into two types: 'wet scrubber’ and ‘dry scrubber’. Furthermore, the wet scrubber can be again divided into three operating types: ‘open-loop’, ‘closed-loop’ and ‘hybrid’.

As of 2018, the open-loop scrubber systems account for about 64% in the marine scrubber market due to its simplicity and low capital costs; those scrubber systems are designed to directly spray sea water through the exhaust gas so that the natural alkalinity of sea water can neutralize acid contained in the gas (DNV.GL, 2018). On the other hand, the closed-loop scrubber systems (about 4%) are operated by chemical-controlled fresh water with Sodium Hydroxide (NaOH) as the cleaning solution. This solution is not directly discharged to the overboard. Instead, it is neutralised in the process tank with NaOH and becomes reusable. Thus, the discharge of contaminated wash water can be considerably reduced, compared to open-loop scrubber systems. The hybrid scrubber systems (about 28%) are equipped with both open-loop and the closed-loop system functions (Register, 2012). Dry scrubber systems generally use $Ca(OH)_2$ as a reducing agent supplied to the system in the form of solid particles. However, due to high space requirements and costs, few dry scrubbers have been adopted in the marine industry (Register, 2012). In this context, this research does not consider the dry scrubber systems.

For the wet scrubber systems, Figure 8 illustrates the system configurations and Table 1 presents the technical information.

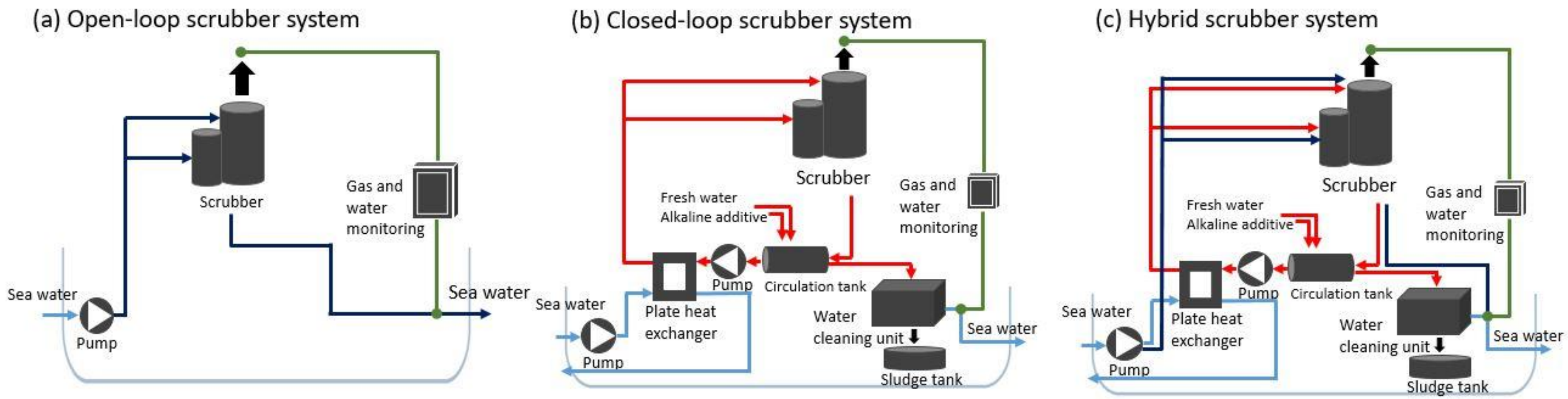

Figure 8: The configuration of proposed wet scrubber systems (ABS, 2017).

Table 1: Technical information for scrubber systems (ABS, 2017).

For engine size (MW)	5			25			50		
System	Open-loop	Closed-loop	Hybrid system	Open-loop	Closed-loop	Hybrid system	Open-loop	Closed-loop	Hybrid system
Performance	98% SOx removal								
Sources	Main engine (ME), auxiliary engine (AE) and boiler								
Size of Equipment (length × width × height)	3.9 × 2.2 × 6.4 m	3.8 × 2.1 × 6.6 m	3.9 × 2.2 × 6.4 m	8.6 × 5.0 × 11.0 m	8.2 × 4.6 × 10.8 m	8.6 × 5.0 × 11.0 m	12.1 × 7.0 × 14.3 m	11.6 × 6.5 × 14.0 m	12.1 × 7.0 × 14.3 m
Electricity consumption	59 kW	31 kW	59 kW/ 31 kW	296 kW	154 kW	296 kW/ 154 kW	593 kW	308 kW	593 kW/ 308 kW

To calculate the total emissions at the operation phase, the electricity consumption of each scrubber system is integrated with the total operating time of the case ship. The hybrid scrubber system can operate both modes (between open-loop and closed-loop) that can be switched according to voyage conditions.

Additionally, the size of sodium hydroxide tank, scrubber circulation tank and sludge tank required for closed-loop scrubber and hybrid scrubber were estimated to be 20, 15, and 20 m^3, respectively (Hansen et al., 2013).

4.2. Modelling and LCI of selected scrubber systems (Step 2)

4.2.1. Construction phase

The construction phase refers to the life stage of the scrubber systems ranging from the raw material status to the onboard installation. The identification of the main materials of scrubber systems is one of the most crucial parts in this phase in order to calculate the energy consumption, thereby emissions, pertinent to the material productions. It was found that stainless steel for scrubber part and glass reinforced epoxy (GRE) for pipeline part would be commonly used (Register, 2012). In addition, the emissions corresponding to the transportation and the installation activities for the scrubber systems are taken into account.

The amount of each material used to manufacture scrubber systems was assumed based on the surface area and weight, while the level of energy consumption for material production was estimated based on the emission data for ‘steel manufacture’. The energy consumption of manufacturing phase was estimated with the process data which guides 8.5 MJ / m^2 of electricity for the cutting process and 15.1 MJ /m for the welding process (Gilbert et al., 2017). The emission factors for unit electricity generation from diesel fuel are summarised in Table 2.

Table 2: Emission factors for 1 MJ energy production from diesel fuel (Elhami et al., 2017).

Emissions substance	CO_2	CH_4	N_2O	NO_x	CO	NMVOC	SO_2	PM
Amount (g/MJ diesel)	74.5	0.00308	0.00286	1.06	0.15	0.068	0.0241	0.107

4.2.2. Operation phase

The operation phase corresponds to the operational activities of the proposed scrubber systems over the ship lifetime. In this perspective, the underlying analysis for operation phase is to determine the energy consumption to operate those systems; the more energy consumption, the higher emission levels (Wang et al., 2018).

In principle, scrubber systems typically remove more than 97% of SO_x emissions from engine exhaust gas (ABS, 2017). With reference to this point, the annual voyage was assumed to be 360 days at sailing and the specific fuel oil consumptions (SFOCs) for main engines and generator engines were assumed to be 172 g/kWh and 183 g/kWh respectively (Kristensen, 2012; Turbo, 2014). The marine HFO emission factors, as shown in Table 3, were used to calculate the emission levels from those engines.

Table 3: Emission factors for top-down emissions from combustion of fuels (IMO, 2015).

Emissions substance	CO_2	CH_4	N_2O	NO_x	CO	NMVOC

Marine HFO emissions factor (g/g fuel)	3.114	0.00006	0.00016	0.093	0.00277	0.00308

4.2.3. Maintenance phase

The maintenance of scrubber systems is largely engaged with simple inspections such as pH level and spray nozzle which do not require any significant level of energy consumption or pollutants. Therefore, this phase was neglected due to its minimal environmental impact (AIR, 2016).

4.2.4. Scrapping phase

Lastly, the scrapping phase was assumed to be conducted in Bangladesh which is one of the most representative developing countries as well as India, Turkey and Pakistan due to low labour costs and weak environmental legislation (Abdullah et al., 2013). The scrubber systems are mainly comprised of stainless steel which is more likely to be recycled rather than disposal (Rahman et al., 2016). The amount of emission generated by each electrical energy was estimated according to Table 4. The material of GRE was assumed to be disposed without extra energy consumption. Like construction phase, the electrical energy production emissions factors, as shown in Table 2, were used to quantify the emissions produced from electricity consumption.

Table 4: The summary of the energy consumed and emissions produced for recycling process (Moats, 2011).

Item			**Stainless steel (per 1kg)**
Energy	MJ	Electricity	**7.18**
		Natural gas	**2.6**

Emission	kg	SO_2	**4.28E-04**
		NO_x	**5.27E-06**
		CO_2	**4.41E-01**
		CO	**1.01E-02**
		$PM_{2.5}$	**6.71E-02**
		PM_{10}	**8.46E-04**

4.3. Results of analysis (step 3, 4 and 5)

According to the methods presented in Section 2, steps 3-5 were performed. The process of the parametric trend analysis (step 5) repeated the LCI (step 3) and LCIA (step 4) processes by inputting various parameters that might have affected the LCA results. For the sake of this case study, the key parameters to be considered would be the ship specification information such as engine power, age, dead weight, etc.; those factors contribute to determine the size and the lifespan of scrubber systems.

Finally, all the results from individual calculation are plotted into a single graph. The general trend displayed on the graph helps us to identify the correlation between each input parameter and emission levels. In this context, it can be said that the functional units for the PT-LCA are those correlations (formatted as equations or can be said ‘indicators’) that can unswervingly represent the general trends or correlations over parametric changes as well as the total environmental impacts of target systems; this format of functional units are proposed to remedy the shortcomings of the common format of functional units (largely expressed as ‘emission factors per unit energy consumption’) that circuitously describes the environmental performance of scrubber systems through energy consumption basis.

4.3.1. Results according to Age

4.3.1.1. Case 1: HFO with open-loop scrubber vs HFO only

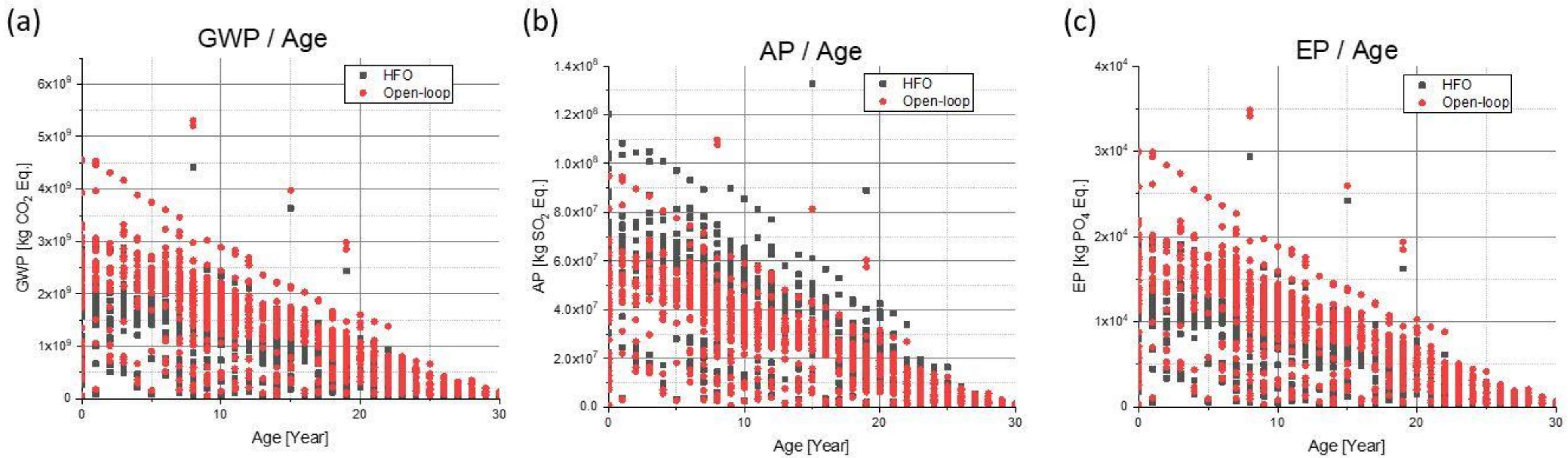

Figure 9: Results of parametric trend LCA for *HFO with open-loop scrubber systems* and *HFO only* describing environmental impacts according to age [Year]: (a) GWP according to age (Year), (b) AP according to age (Year) and (c) EP according to age (Year).

Table 5: Total environmental impacts amount of *HFO with open-loop scrubber systems* and *HFO only* when all individual ships adopt either way based on 1,341 Ro-Ro vessel samples.

	HFO with Open-loop	HFO only	Difference
GWP [kg CO_2 Eq.]	1.98E12	1.44E12	+37.5%
AP [kg SO_2 Eq.]	4.03E10	5.28E10	-23.7%
EP [kg PO_4 Eq.]	1.29E07	9.62E06	+34.1%

Figure 9 shows the analysis results of Case 1, indicating the environmental impacts of GWP, AP and EP over ship ages. The maximum life span of vessel was assumed 30 years and only 1,341 cases, younger than 30 years, were included among the total of 1,565 ships in the dataset. As illustrated in the figure, respective dots in graphs indicate the environmental impacts of individual case ships according to their ages. It clearly shows generally proportional correlation between environmental impacts and vessel age; the younger ships are more likely to produce more lifetime emissions due to longer scrubber system operation. On the other hand, it can infer that the reason why the same ship age has a wide range in GWP, AP and EP is due to different ship size, power and other parameters. Their sensitivities on the environmental performance of different scrubber systems will be further discussed with Case 2.

Results from Figure 9 (a) reveal that the option of using *HFO only* was noticeably lower in the GWP than the other option of using *HFO with the open-loop scrubber system*. Such a tendency can be observed more clearly in Table 5 where the environmental potentials for each ship was integrated into the total levels. That is 1.44E+12 kg CO_2 Eq. indicates the total GWP level with 1,341 vessels using *HFO only* whereas 1.98E+12 kg CO_2 Eq. represents the same vessels but using *HFO with the open-loop scrubber system*, indicating 37.5 % increase in GWP. The analysis results are exactly opposite to what our common sense tells us; it is entirely credible to think that a cleaning system will improve the environmental impact as a whole.

Considering AP results in Figure 9 (b), *HFO with the open-loop scrubber systems* were proven to be an excellent AP reduction system. Table 5 shows 5.28E+10 kg SO_2 Eq. for the 1,341 vessels using *HFO only* whereas 4.03E+10 kg SO_2 Eq. for the same vessels using *HFO with open-loop scrubber systems*. Hence, it was found that open-loop scrubber systems could contribute to reducing 23.7 % of AP from the whole fleet.

On the other hand, the 23.7% reduction in AP still seems to be lower than our expectation. This gap can be explained with the fact that while the AP is contributed by several emission types, in particular SO_x, NO_x and HCI, the scrubber systems are only designed to remove SO_x emissions from the engine exhaust gases. These findings are thought to motivate the expansion of current SO_x regulations to AP restrictions.

A trend similar to that of Figure 9 (a) can be observed in EP results plotted in Figure 9 (c); the *HFO only* was lower in EP than the *HFO with the open-loop scrubber systems*. The total EP for the whole fleet for the *HFO only* was estimated at 9.62E+06 kg PO_4 Eq., whereas the ships using *HFO with open-loop scrubber systems* was 1.29E+07 kg PO_4 Eq. (34.1 % increment in EP).

4.3.1.2. Case 2: Open-loop scrubber vs Closed-loop scrubber

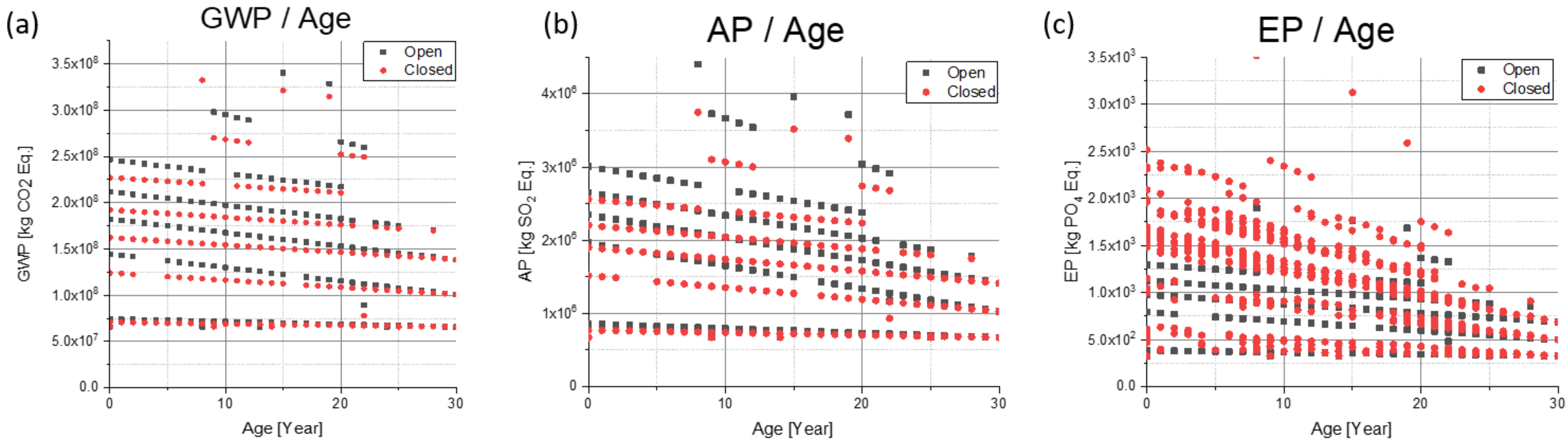

Figure 10: Results of parametric trend LCA for maritime SOx scrubber systems describing environmental impacts according to age [Year]: (a) GWP according to age (Year), (b) AP according to age (Year) and (c) EP according to age (Year).

Table 6: Total amounts environmental impacts of maritime SOx scrubber systems when all individual ships adopt either way based on 1,341 Ro-Ro vessel samples.

	Open-loop	Closed-loop	Difference
GWP [kg CO_2 Eq.]	2.13E11	2.00E11	-6.1 %
AP [kg SO_2 Eq.]	2.54E09	2.22E09	-12.6 %
EP [kg PO_4 Eq.]	1.11E06	1.61E06	+45.0 %

Although analysis results of Case 1 has raised questions on the environmental efficiency of the scrubber systems, there still needs to discuss the best options among different types of scrubbers in order to maximise the benefits through proper selection. The same number of ships under 30 years old was applied to this comparative analysis (Case 2).

In Figure 10 (a), closed-loop scrubber systems were shown more eco-friendlier in GWP than open-loop scrubber systems and a similar tendency for the AP was observed in Figure 10 (b). The results of EP described in Figure 10 (c) are in contrast to the other two potentials. Open-loop scrubber systems had smaller EP relative to closed-loop scrubber systems. The energy consumption of the open-loop scrubber system is relatively less than that of the closed-loop system, which contributes to reducing the lifetime GWP and AP. On the other hand, the sludge produced in the cleaning process of the closed-loop scrubber had a negative effect on the results of EP.

It should be also noted that the environmental assessment results were spread out and fitted into largely six layers from left to right in all Figure 10. These layers have been formed due to the varying capacities of scrubber systems related to the engine sizes. These findings confirm that the main factors for the environmental impact of the scrubber system are the system capacity and the ship age.

The hybrid scrubber systems can be expressed as a combination of the open-loop and the closed-loop systems. It means that if this hybrid system only runs in the open-loop mode over the lifetime, the environmental impacts of this hybrid system at the operation phase are surely equal to the results of the open-loop system. The same is true for the closed-loop mode.

In other words, the operating times of each mode are regarded the key parameter to determine the environmental impacts of the hybrid systems. However, it is also clear that the boundary of these impact levels is to be placed within the maximum and the minimum impacts of the two systems.

4.3.2. Results according to Power

4.3.2.1. Open-loop scrubber & Closed-loop scrubber

Using various ship powers as input parameters, a parametric trend analysis was performed to identify the general relations between the emission impacts and the ship power.

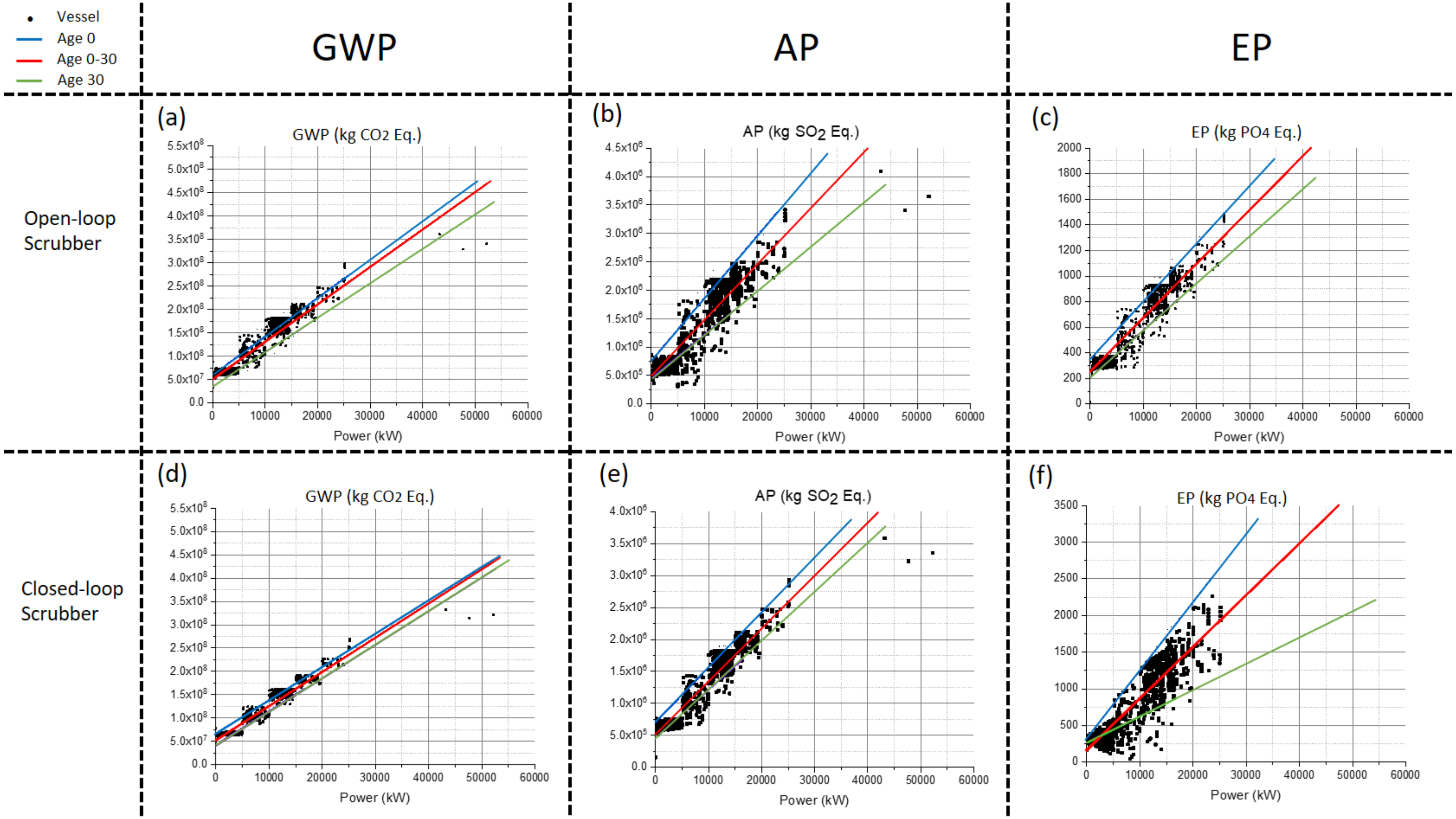

Figure 11: Results of PT-LCA for maritime SOx scrubber systems describing GWP, AP and EP according to power (kW): (a) GWP of open-loop scrubber systems according to power (kW), (b) AP of open-loop scrubber systems according to power (kW), (c) EP of open-loop scrubber systems according to power (kW), (d) GWP of closed-loop scrubber systems according to power (kW), (e) AP of closed-loop scrubber systems according to power (kW), (f) EP of closed-loop scrubber systems according to power (kW). (Blue line: regression values for vessels with age 0 group, Red line: regression values for vessels with age 0-30 group, Green line: regression values for vessels with age 30 group)

Table 7: Correlation based on the results of PT-LCA for maritime SO_x scrubber systems describing GWP, AP and EP according to power [kW].

	Regression lines	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) $y =$ GWP $x =$ Power	Upper line (Age 0):	$y = 8236 \times x + 6.8E7$	1.8E16	0.98001	0.96041	0.96012
	Mid. Line (Age 0-30):	$y = 7989 \times x + 5.1E7$	4.2E17	0.94848	0.89962	0.89955
	Lower line (Age 30):	$y = 7326 \times x + 4.7E7$	3.9E15	0.94416	0.89143	0.88833
(b) $y =$ AP $x =$ Power	Upper line (Age 0):	$y = 110 \times x + 7.8E5$	5.4E12	0.96735	0.93577	0.9353
	Mid. Line (Age 0-30):	$y = 98 \times x + 4.9E5$	1.1E14	0.91169	0.83118	0.83107
	Lower line (Age 30):	$y = 77 \times x + 4.8E5$	4.3E11	0.94397	0.89107	0.88796
(c) $y =$ EP $x =$ Power	Upper line (Age 0):	$y = 0.04 \times x + 352.2$	6.4E5	0.97625	0.95307	0.95273
	Mid. Line (Age 0-30):	$y = 0.04 \times x + 250.4$	1.4E7	0.93739	0.87869	0.87861
	Lower line (Age 30):	$y = 0.036 \times x + 232.9$	9.7E4	0.94412	0.89136	0.88826
(d) $y =$ GWP $x =$ Power	Upper line (Age 0):	$y = 7200 \times x + 6.5E7$	1.1E16	0.98387	0.968	0.96776
	Mid. Line (Age 0-30):	$y = 7314 \times x + 5.3E7$	2.6E17	0.9606	0.92276	0.92271
	Lower line (Age 30):	$y = 7237 \times x + 4.7E7$	3.8E15	0.94421	0.89153	0.88843
(e) $y =$ AP $x =$ Power	Upper line (Age 0):	$y = 86 \times x + 7.1E5$	2.1E12	0.9792	0.95884	0.95854
	Mid. Line (Age 0-30):	$y = 83 \times x + 5.2E5$	4.8E13	0.94576	0.89446	0.89439
	Lower line (Age 30):	$y = 75 \times x + 4.8E5$	4.1E11	0.94416	0.89145	0.88835
(f) $y =$ EP $x =$ Power	Upper line (Age 0):	$y = 0.09 \times x + 328.9$	3.4E5	0.99708	0.99418	0.99413
	Mid. Line (Age 0-30):	$y = 0.07 \times x + 155.2$	7.9E7	0.88813	0.78878	0.78864
	Lower line (Age 30):	$y = 0.03 \times x + 231.4$	9.3E4	0.95288	0.90797	0.90535

Figure 11 shows the proportional relationship between the ship power and environmental impacts which are GWP, AP and EP. As discussed earlier, as results of different ship characteristics (possibly various ship ages), the environmental impacts over ship power were somewhat scattered.

In order to interpret the emission-power relationship, the regression analysis was carried out: The blue line indicates the minimum with 0 year ships; the green line represents the maximum impact with the ships of 30 years; the red line represents the average impact on all concerned vessels.

Based on these graphs, general trends formulate each of the linear functions in Table 7. Those regressions were combined into a single equation which enables us to estimate the environmental impacts of scrubber systems as a function of ship age and power.

- $EI_{i,j} = (UL_{i,j} – LL_{i,j}) \times (30\text{-}A) / 30 + LL_{i,j}$

Where,

$EI_{i,j}$: Environmental impact of i for j

$UL_{i,j}$: upper line of i for j (Blue line on the graph)

$LL_{i,j}$: Lower line of i for j: (Green line on the graph)

A: ship age

Subscript

i: environmental impact categories e.g. GWP, AP and EP.

j: scrubber system types e.g. open-loop and close-loop

4.3.2.2. Hybrid scrubber

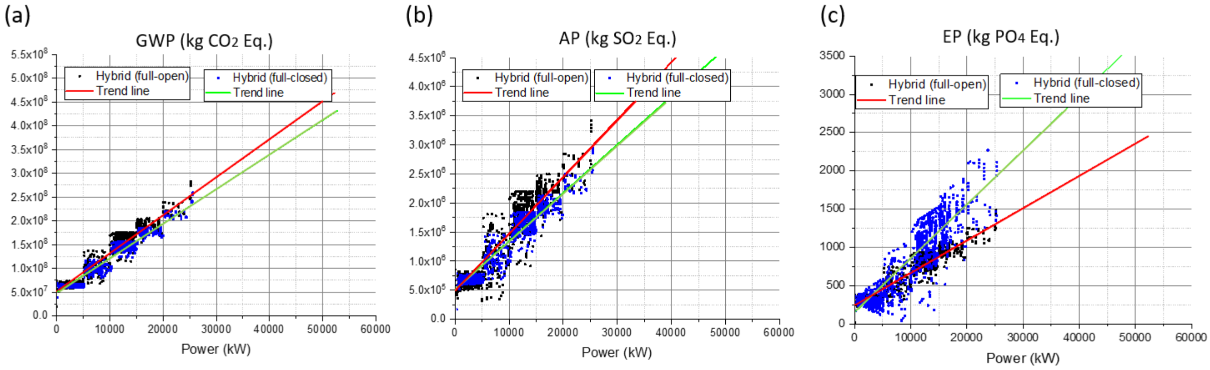

Figure 12: Results of PT-LCA for hybrid SOx scrubber systems describing environmental impacts according to power [kW]: (a) GWP according to power (kW), (b) AP according to power (kW) and (c) EP according to power (kW). (Red line: when hybrid scrubber has been fully operated by open-loop system, Green line: when hybrid scrubber has been fully operated by closed-loop system)

As mentioned earlier, since the hybrid scrubber systems consist of the open-loop and the closed-loop systems, the operating times of each mode could significantly influence to determine the environmental impacts of the hybrid systems. Based on this fact, presented the environmental impacts of the both cases when it was fully operated by open-loop system and closed-loop system with red line and green line respectively. These two lines represent the maximum and the minimum value of each environmental impacts of hybrid scrubber system. Therefore, it could be figured out that since the hybrid system will have an environmental impact value between the red and green lines, the more closed-loop systems are used in GWP and AP, the more hybrid scrubber system is environmentally friendly. On the contrast, in the aspect of EP, the more open-loop systems are used, the eco-friendlier it is. Because of this opposite result regarding each environmental impact, as mentioned earlier, the impact between each environmental impact is likely to be addressed in future studies.

4.3.3. Results according to Gross tonnage

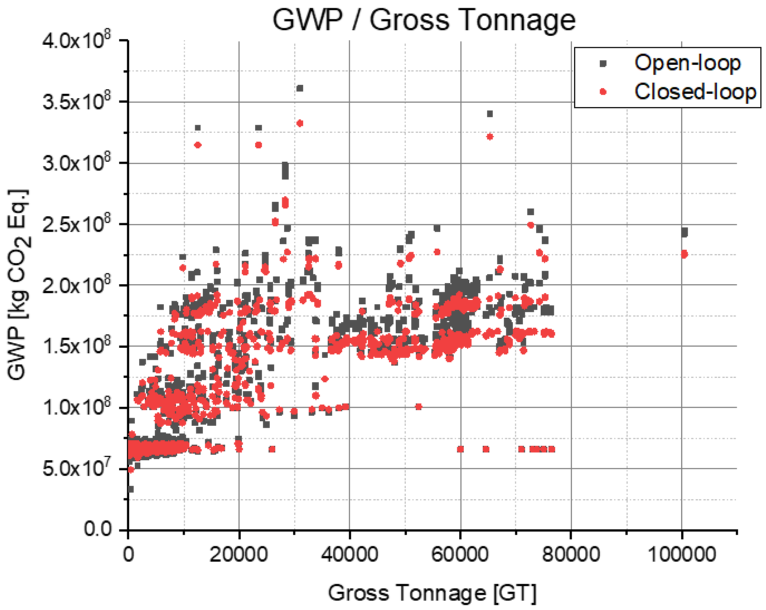

Figure 13: Results of parametric trend LCA for maritime SOx scrubber systems describing GWP according to Gross Tonnage [GT]

An additional parametric trend analysis was performed to investigate the relationship between emissions and other ship characteristics such as gross tonnage, dead weight tonnage, etc.

Figure 13 shows the GWP over various ship gross tonnages, but no clear correlation would be found. An increasing trend was observed across the tonnage, but it still seems irregular. The similar results were found in the other parameters of dead weight tonnage, ship length, etc; due to the lack of meaningful information, those results were persuaded not to be presented in this paper.

Throughout a series of trial and error, it could be concluded that the two main parameters - ship power and age - are closely associated with the emission levels.

4.3.4. Comparative analysis with container vessels

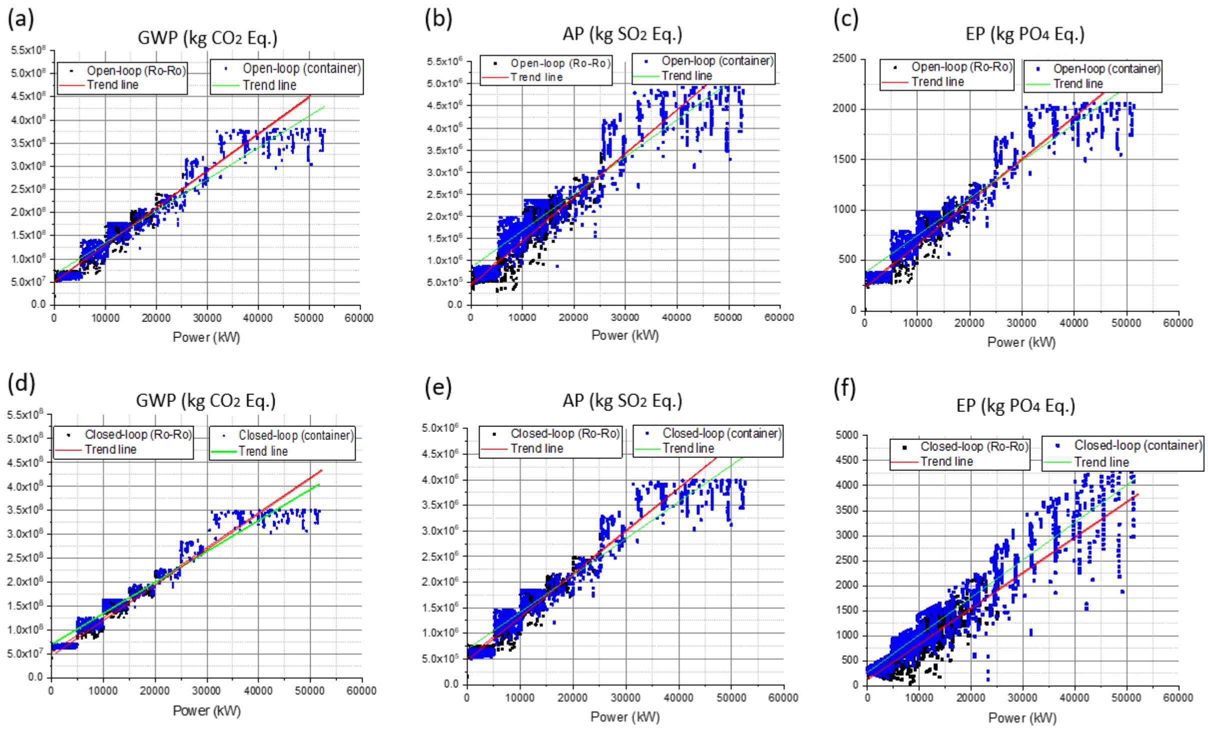

Figure 14: Results of PT-LCA for open-loop scrubber systems and closed-loop scrubber systems describing environmental impacts according to power [kW] with the 4,166 container vessels comparing to the results of Ro-Ro vessels: (a) GWP of open-loop system according to power (kW), (b) AP of open-loop system according to power (kW) and (c) EP of open-loop system according to power (kW), (d) GWP of closed-loop system according to power (kW) , (e) AP of closed-loop system according to power (kW) and (f) EP of closed-loop system according to power (kW) (Red line: results of Ro-Ro vessels, Green line: results of container vessels)

Figure 14 shows the comparative analysis between the results of PT-LCA for Ro-Ro vessels and 4,166 container vessels (*by courtesy of Lloyd's register*). Except for Figure 14 (f), the results from Figure 14 (a) to Figure 14 (e) present that container vessels are more sensitive to environmental impact by power than Ro-Ro vessels. This could be one of the examples that PT-LCA is also possible to estimate the environmental impact of the subject systems in accordance with non-linear parameters such as ship types. Nevertheless, a prerequisite interpretation and re-formatting of those parameters is required to be suitable for PT-LCA platform. Those parts will be investigated in the future studies.

5. Discussion

Given that scrubber systems were developed as one of the most viable measures to comply with IMO SO_x regulations, the environmental research has been required to confirm whether they are completely eco-friendly without no doubt. Although there have been several environmental studies of scrubber systems, the holistic LCA for SO_x scrubber systems was not implemented prior to this research. Thus, the primary novelty of this paper herein can be placed on the assessment of the overall environmental impacts of the scrubber systems throughout the entire life cycle.

In addition, this paper addressed the shortcomings of conventional LCA practices; their results are case-specific so that general observation could be hardly achieved. On the other hand, the shipping industry often necessitates a more general understanding of eco-friendly systems for proper decision-making and regulatory frameworks than the results obtained in specific cases that cannot represent the entire fleet.

To narrow this gap, this paper introduced an improved approach called 'Parametric Trend LCA (PT-LCA)' with which numerous case studies can be performed simultaneously while explaining trends and correlations between each input parameter and output related to environmental performance of subject systems. To emphasize this, the PT-LCA proposed in this paper, was designed to investigate the environmental impacts of the scrubber systems according to rule-makers' point of view. Too case-specific studies (using designers' approach) may fail to provide general observations, and those case-oriented results may be subject to a question of general applicability. On the other hand, the functionality of the parametric trend analysis proposed in this paper can offer a great deal of information to stakeholders by enabling them capable of understanding the holistic environmental impact of their fleets with very little information they own. For example, our research output can straightforwardly advise that closed-loop scrubber is the most environmentally suitable for a shipowner who has a 10-year-old vessel with 20MW power. This fact can be a considerably serviceable for establishing regulatory/decision-making guidelines. It is worth noting that the application of PT-LCA cannot be limited to scrubber systems or marine-related tasks but is suitable for any area which requires a general understanding of life cycle emissions for particular systems.

Turning to case study results, SO_x scrubber manufacturers often advertise a 97% reduction in SO_x emissions during operation (ABS, 2017). However, this research has shown that the actual effects of scrubber systems would be averaged at 23.7% of AP in terms of whole life cycle perspective (see Table 5). It means that the life cycle processes and activities pertinent to scrubber systems have contributed significantly to emissions.

Study results also deliver a crucial message regarding the application of scrubber systems for marine vessels. Although scrubber systems were proven excellent in removing SO_x, it was found that the ultimate maritime goal to reduce AP might cannot be achievable if the scrubber systems are not able to eliminate the other emissions - particularly, NOx and HCI - that negatively affect AP.

Research findings have shown that additional energy consumption to run scrubber systems can contribute to increasing the environmental impacts other than AP. Considering this fact, one may raise a doubt on whether the SO_x reduction could prevail over the increment in other emissions in particular, CO_2, NO_x and HCl. In view of that, it is relevant to conclude the case studies through PT-LCA cannot guarantee that SO_x scrubber systems are more environmentally friendly than simply using HFO alone. To answer this argument, further research is still needed to determine whether GWP (or EP) can outweigh AP or vice versa.

In fact, like other LCA research, the series of case studies with the PT-LCA were also encountered with the challenges relative to limited and incomplete information and data. Consequently, the case study results may differ somewhat from actual emission measurements. Nevertheless, it is highly believed that such potential deviations do not jeopardise the research results, findings and a meaningful indicator of proper system selection as well as the pathway that the SO_x scrubber systems should take.

In addition, it is worth noting that this paper does not present emission levels at each life stage of scrubber systems. One of reasons is that a series of past research has demonstrated that the operating phase of the marine systems has the greatest contribution (as high as 99%) to the overall environmental impacts (Jeong et al., 2019). It is because the operating phase has much extensive energy consumption and longer service time compared to construction, maintenance and scrapping. The same phenomenon lies in scrubber systems. Secondly, as dealing with the LCA of more than 1,000 ships rather than a single vessel, the nature of this research is not to present case-oriented results but to reveal general guidelines applicable to whole fleets. Thus, it is more convinced that this paper should guide more on understanding of the correlations between the overall environmental impacts and ship characteristics than quantifying emissions at each life stage of each ship.

6. Conclusions

Based on the research work discussed in this paper, the following conclusions can be drawn:

1) Although contributing to the AP reduction, SO_x scrubber systems were shown to exacerbate other environmental impacts such as GWP and EP. The study results of Case 1 can be summarised as below:
   - In *HFO only*: 1.44E+12 kg CO_2 Eq. for GWP; 5.28E+10 kg SO_2 Eq. for AP; 9.62E+06 kg PO_4 Eq. for EP.
   - In *HFO with Open-loop scrubber*: 1.98E+12 kg CO_2 Eq. for GWP; 4.03E+10 kg SO_2 Eq. for AP; 1.29E+07 kg PO_4 Eq. for EP.

   To answer the question on whether scrubber system is ultimately contributing to cleaner production and operation in the maritime industry or not, there needs a future study to prioritise those impacts.
2) Closed-loop scrubbers are more environmentally friendly than open-loop scrubbers in terms of GWP and AP, whereas the opposite trend is found in EP. It could be equally applied when adopting hybrid scrubber systems. Results of Case 2 can be abridged as below:
   - In Open-loop scrubber; 2.1E+11 kg CO_2 Eq. for GWP; 2.54E+09 kg SO_2 Eq. for AP; 1.11E+06 kg PO_4 Eq. for EP.
   - In Closed-loop scrubber; 2.0E+11 kg CO_2 Eq. for GWP; 2.22E+09 kg SO_2 Eq. for AP; 1.61E+06 kg PO_4 Eq. for EP
3) Ship age and power are found dominant parameters which have a great influence on the holistic environmental impacts of SO_x scrubber systems. Such correlations (functional units) are formulated into general equations (see Table 7).

4) Throughout the case studies, the PT-LCA has been proven an effective tool for evaluating emission levels and for contributing to developing rules or guidelines for proper system selection in environmental perspectives. Although this paper has limited use of the PT-LCA with scrubber systems, it can be widely utilised wherever general environmental instructions are required.

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