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CONFIGURATIONS OPTIMIZATION OF A TUG SHIP PROPULSION SYSTEM: A LIFE CYCLE ASSESSMENT CASE STUDY

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TABLE OF CONTENTS

INTRODUCTION 3

1. LITERATURE REVIEW 4

2. METHODOLOGY 6

   2.1. LCA METHOD 6

   2.2. FORMULA GOVERNING 8

3. LCA ANALYSIS AND DISCUSSION 10

   3.1. AIM AND SCOPE 10

   3.2. LIFE CYCLE INVENTORY ANALYSIS: GLOBAL WARMING AND ACIDIFICATION POTENTIAL 11

   3.3. LIFE CYCLE IMPACT ANALYSIS 12

4. CONCLUSIONS AND FUTURE WORK 16

REFERENCE 17

INTRODUCTION

Nowadays, global warming has been attracting researchers and scientists' attentions due to the severity of its environmental impacts. The global warming effect is mainly caused by CO_2 from the consumption of fossil fuel. Not only CO_2 has drawn the attention from scientists but also acid gases have, such as SO_x and NO_x which will lead to acid rains after released into the atmosphere. All these pollutions are a result of burning fossil fuels; therefore, the control and reduction of emissions from human activities is one of the most interesting topics all over the world. There are many solutions proposed or tested to meet the demands, such as alternative fuel, hybrid system and route optimizations. They all are trying to increase energy efficiency and reduce the emission generated and released. The selection of alternative fuel with a reduced content of sulphur will generate less amount of SO_x. Also, the usage of liquefied natural gas will help reduce emissions too, such as NO_x, SO_x and CO_2. Some vessels apply bio-fuel engines on board which is considered to be able to reduce the carbon emissions as the fuel is generated from the plants who are continuously absorbing CO_2 from the atmosphere. The hybrid system, which is another way to mitigate the air pollutions, either uses renewable energy or power from the power plant (bulk energy provider) whose emission will be much lower than traditional power systems. With the rising of the forecasting technologies and databases, the sea conditions of vessel route (wind, wave, tidal) can be predicted and the optimal route with lowest fuel consumption but an acceptable schedule can be determined. All these technologies will help mitigate the current global warming and acidification situations. However, there is only a few discussions or research work carried out on the ship power output management from the perspective of emission control and environmental protection. This paper will focus on a tugboat power output management to find out the optimal engine configurations and engine output according to the power demand of the vessel. The optimal configurations will enable the engine to be operated under most effective loads with lowest fuel oil consumption and NO_x emissions. To expand the analysis and consider the whole life span of a vessel, the life cycle assessment will be carried out to indicate the performance of ship power output management through the vessel's whole service life.

1. LITERATURE REVIEW

There are many applications of emission control technologies on marine vessels but only a few of them are focusing on the tug ship. Some works are worth to mention which carried out analysis on tug ships activities and their performances. One work carried out by Burak from Turkey applied kerosene fuel blended with aspire methyl ester on a tug boat and carried out exergy analysis on the vessel to determine the environmental impacts of this application (Gökalp, 2018). It indicates the bio-fuel could help reduce the CO emission but as a drawback, the NO_x emission will be higher. The usage of bio-fuel is a good way to control the emissions but the study only focus on the operation phase which means it is lack of life cycle view. The economic analysis is not under consideration which is not a comprehensive study. It is also lack of mentioning the advantage of bio-fuel is the source of the fuel which is usually from agriculture; and with the consideration of source, it will be a more advanced analysis and could illustrate the benefits and performance of bio-fuel comprehensively.

Another research (Zhu, Chen, Wang, & Xia, 2018) on the tug ship is to equip the vessel with a hybrid system which considers both the impacts of environment and cost. It is a comparative work to use different optimization methods to determine the optimal operation performance of the hybrid propulsive system (combination of battery with conventional system) on the tug ship. However, the study shortens the life span to construction and operation which disregards of maintenance and scrapping/dismantling phases. The focus of the study is also to prove the excellence of non-dominated sorting genetic algorithm II (NSGA-II) from the single-objective genetic algorithm (SOGA). However, it is still believed that the evaluation of technology could be expanded and comprehensive.

Zhen’s team (Zhen, Wang, Wang, & Qu, 2018) also focuses their research on the tug ship but on its scheduling which will be optimized barge assignment of the tug vessel to minimize the required tugs. The model established is also validated by experiment. This work is also a good start to assess the performance of tug ship operation scheduling which is optimized not only to minimize the number of tug vessels involved but also reduce the operation cost and related emission release.

These works are current researches focusing on the tug vessels which is apparently lack of comprehensive analysis. This paper will strive to assess the performance of a tug ship from both the impact of environmental and cost. As a promising topic, the on board propulsion system configuration is one way to reduce the energy consumption so that reduce the emission from the ship exhaust. However, as a fact of lack of evaluation method, the performance of most promising techniques or approaches is underestimated or misevaluated. Life cycle assessment is considered to be a comprehensive process to consider from the cradle to grave of a system or product to quantify its impact on the environment.

2. METHODOLOGY

This section of the methodology will not only state the life cycle assessment with its processes but also present the formula related to LCA assessment.

2.1. LCA METHOD

ISO standard indicates LCA analysis should fundamentally include four processes: the definition of research/analysis objectives and boundaries, life cycle inventory analysis (LCI), life cycle impact analysis (LCIA) and life cycle interpretation (ISO, 2006a, 2006b). Figure 1 presents the flowchart and relationships between phases.

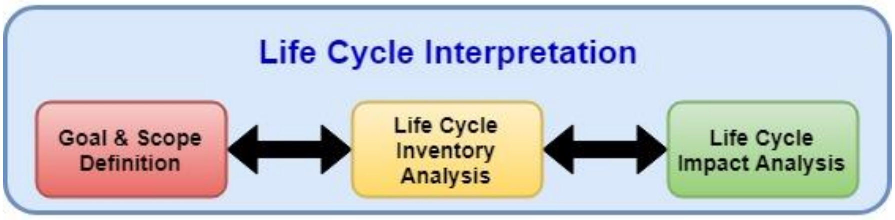

Figure 1 The schematic chart of life cycle assessment

The first step to conduct an LCA analysis is to define the objectives and boundaries. A typical objective of research study is to determine a specific performance or cost of a system or product and similarly, LCA study is to obtain the environmental impact. However, there are so many different environmental impacts existing, for example, global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP); hence it is essential to set up the purpose of the study. Next, the scope and boundary should be considered and as the goal is set up, the selection and consideration of certain types of potential (e.g. GWP, AP or EP) should be carried out based on the goal. There will be many emissions and pollutions under evaluation, so that many others have been neglected as they have insignificant impacts on the primary goal. After the potentials selected, a functional unit should be set up as a standard to carry out the evaluation and comparisons of different scenarios. Then a normalization process will be conducted, which converts emissions contributing to different potentials into one indicating emission. According to the CML database (CML, 2016), all the emissions which make contributions to global warming will be normalized and converted into an equivalent quantity of CO_2 and the unit is kg CO_2 equivalent. Similarly, for AP and EP, the fundamental pollutions are sulphur dioxide and phosphate (SO_2 and PO_4^{3-}). Usually, a functional unit could be the quantified ship performance during its service but they can always be set up by the end users based on their objective. The normalization processes help to simplify the set up process which usually is based on the normalized units or their extensions. Definition of the system boundary is also an important part. Not only constraining the scope by the relevant emissions, but also identifying the differences between alternatives could also help limit the LCA scope which can be extremely complex, so that a compact but adequate LCA model can be established without considering repeated, redundant and less effective parts of the system or product. Therefore, a reasonable scope should be made in order to neglect these unnecessary parts. Furthermore, assumptions should be made as well in order to progress the analysis because sometimes real data cannot be retrieved or provided. Usually assumptions should be made or advised by the system or product owners, manufacturers and operators.

After the definition of goal and scope, life cycle inventory analysis can be conducted as shown in the schematic diagram in Figure 2. It starts with the defined goal and scope in the previous step where an initial LCA plan has been selected and determined. With this plan, data involved in the plan could be collected, normalized and aggregated so that initial outcomes could be determined. However, the scope of the LCA analysis will be expanded or trimmed because of the availability of the relevant data. After adjusting the scope based on data availability, similar processes of data collection, normalization and aggregation will be conducted so that a modified but complete inventory of an LCA analysis can be obtained.

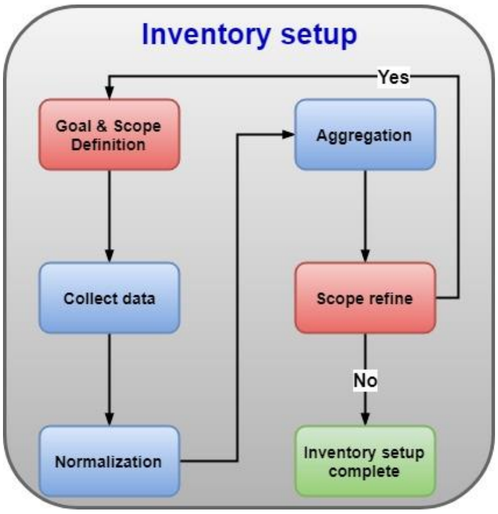

Figure 2 Schematic chart of life cycle inventory analysis

The LCI analysis will be used as a fundamental for LCIA analysis which consists of three main steps:

a. Selection: impact categories chosen including indicators and characterization models;
b. Classification: LCI results assigned to the selected impact categories;
c. Characterization: calculation using LCI results as input and characterization models to determine results based on category indicator.

In the last phase - life cycle interpretation -, sensitivity analysis will be carried out to evaluate impacts of the selected inputs on the established LCA processes and results, i.e. midterm and final results. These inputs are selected based on their significance, availability, and uncertainty.

The results will indicate the significant performances based on the LCI and LCIA analysis which usually provide end users recommendations on the selections of different alternatives. Furthermore, the conclusions, limitations and recommendations of the LCA analysis should be provided in this interpretation processes which illustrate not only the decisions made but also the constraints of the analysis.

2.2. FORMULA GOVERNING

As this paper will mainly focus on the main engine and their related activity, the fuel oil consumption during the operation phase of vessels is considered and a general equation could be used to calculate the fuel oil consumption under both conditions (1):

$$FC = \sum_{i=1}^{n} \mathrm{Pe_i} \times \mathrm{SFOC}_i \times \mathrm{H}_i\mathrm{i} \times \mathrm{LS} \quad (1)$$

Where,

FC is the annual fuel consumptions [g];

Pe is the power requirement during vessel operation [kW];

SFOC is the specific fuel oil consumptions of the engine under specific engine output [g/kWh];

H is the hours of operation in a year [hours];

LS is the years of vessel life span [years];

N is the total number of operation conditions under consideration;

i represents number of different vessel operation conditions under different engine loads.

Due to the engine load variation under different operating conditions, the SFOC adjustment of the engine will be considered based on the engine project guide data shown in Figure 3. Equation (2) gives the interpolation curve of this figure (Dedes, 2013):

$$SFOC = 378.8-387.2\times EL^3+880.2\times EL^2-657.3\times EL \quad (2\text{-}1)$$

$$Q_{NOx} = 8.56-9.392\times EL^3+8.522\times EL^2+4.235\times EL \quad (2\text{-}2)$$

Where,

SFOC is the specific fuel consumption under a certain engine load [g/kWh];

Q_{NOx} is the specific NO_x emission under a certain engine load [g/kWh];

EL is the engine load under a certain operation conditions [%];

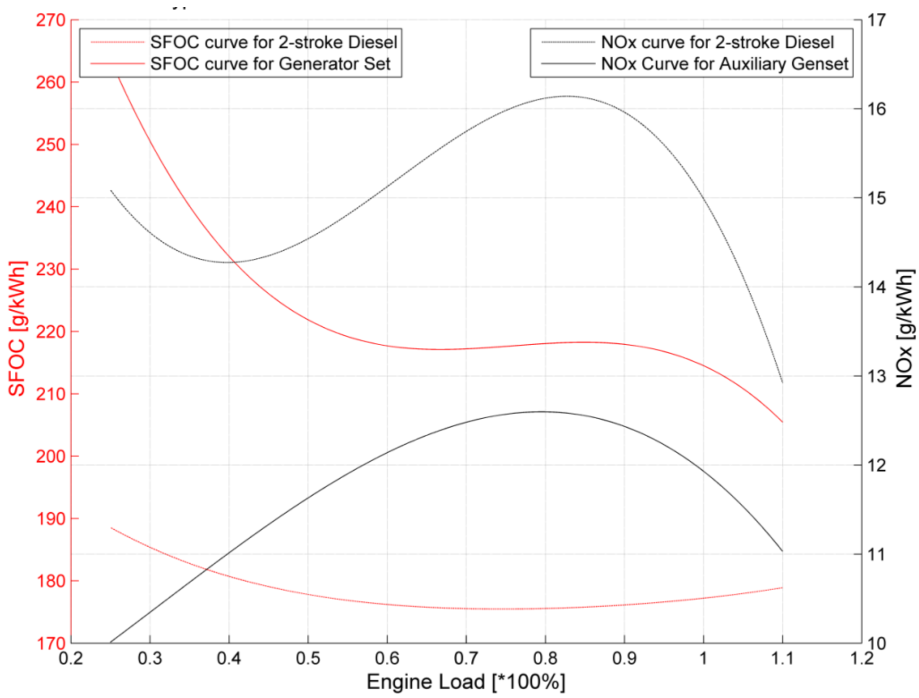

Figure 3 Typical SFOC curves and NO_x emission curves for M/E and A/E

Emission can be theoretically estimated based on emission factors and fuel consumption (3):

$$Q_e = C_f \times FC \quad (3)$$

Where,

Q_e is the quantity of emission from engine operation [g];

C_f is the emission factors of fuel burnt in the engine [g/g].

3. LCA ANALYSIS AND DISCUSSION

In this section, the LCA analysis will be carried out, starting from the aim and scope definition, followed by a life cycle inventory setup and impact assessment.

3.1. AIM AND SCOPE

The aim of this research has been stated in the introduction to explore the impacts of engine configurations on tugboat fuel saving and emission reduction performances. A case ship is selected for this purpose shown in Table 1 and Table 2. The research is focusing on the engine configuration so that the following assumptions are made before carrying out the analysis:

a. Only main engine and their related activities are involved (Figure 4);
b. Carbon emissions from engine fuel consumption are calculated based on emission factors provided by the International Maritime Organization (Smith et al., 2015);
c. The scrapping processes are referred from Ling-Chin and Roskilly's research (Ling-Chin & Roskilly, 2016);
d. The manufacturing process of engines are regarded out of scope;
e. The changes in fuel consumption due to engine load variation are estimated using the relationship for typical engines shown in Figure 3;
f. Properties of electricity and transportation are determined based on published papers and GaBi database(GaBi, 2018);
g. Machinery maintenance is regarded out of scope;
h. Environmental impact assessment is limited to the GWP and AP that is regarded as the most crucial marine contributor to deteriorating the global environment.

In the next section, the LCA model for this ship is established and presented which will be used as a benchmark in the life cycle impact analysis.

Table 1 Case study vessel information

Vessel specification		
Name	Salvation 21	
Flag	Korea	
LOA	32.3	meter
B	10	meter
Gross tonnage	156	tonne
Fuel type	HFO	
Annual operation days	313	days
Engine power	1518×2	kW
Life span	30	year

Table 2 Case study vessel operational profile

Category	Sailing	Manoeuvring	Port	Unit
Operation profile	6	0.6	3	hours
Engine Load	74%	33%	0	percentage
Power required	2250	1000	0	kW
SFOC	191	194	0	g/kWh

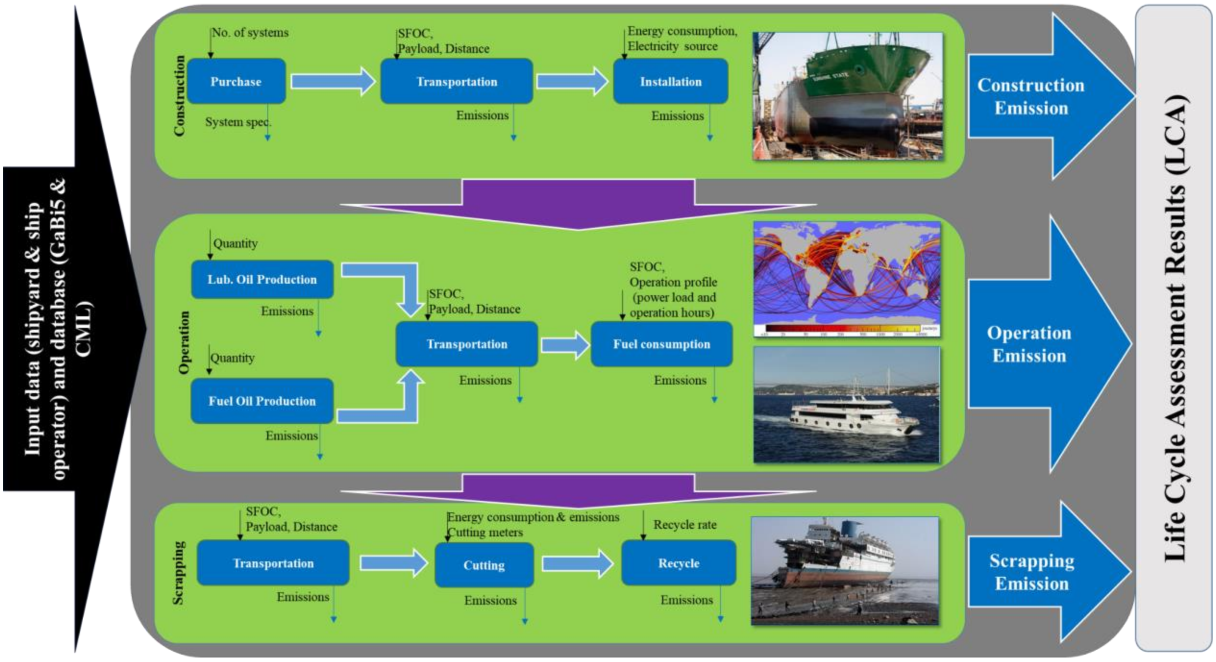

Figure 4 Activity consideration and flow

3.2. Life Cycle Inventory Analysis: Global Warming and Acidification Potential

Based on the aim and the scope established in the previous section, an LCA model was built and presented in Figure 5. The figure includes the flow of the main engine from construction (purchase, transportation and installation), to operation phase (fuel consumption and transportation) and to scrapping of engine (disassembling, transportation, recovery etc.). Blue represents the flow of engines; the fuel for ship operation is highlighted in red colour and fuel for transportation is in black; green lines show the supply of electricity.

With this model and the application of GaBi software and database, the emission inventory is set up and shown in Table 3. As two emission categories are considered in this study (GWP and AP), the emission release breakdowns are presented in the figure. It is apparent that the operation of the vessel contributes the most of emission through the life span.

The way to estimate the emissions, apart from ship operation, is based on the database and empirical equation from GaBi which estimates the material used and emission generated of many activities (not usually considered in ship industry), such as fuel oil production and transportation. The GWP and AP impacts considered in this paper will cover both these seldom considered activities and engine related ones.

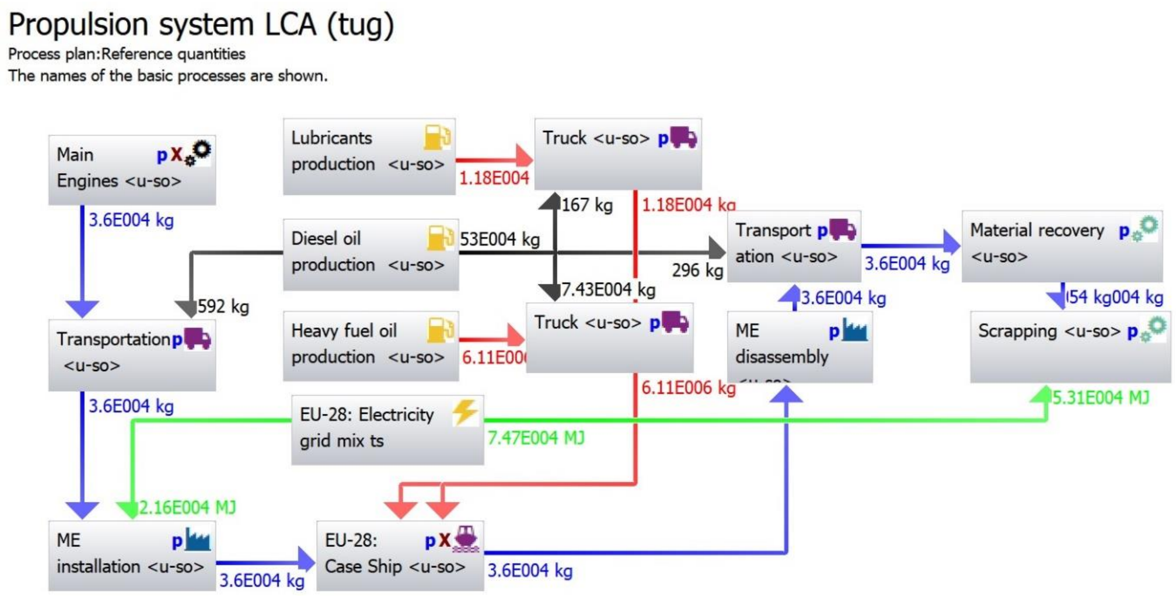

Figure 5 LCA model of the case ship

Table 3 Emission inventory of life cycle assessment

Module name	**Emission category**	
	Global Warming Potential (kg CO_2 eq.)	Acidification Potential (kg SO_2 eq.)
Transportation	9.32×10^5	1.11×10^3
Heavy Fuel oil production	1.14×10^7	4.94×10^4
Lubricating oil production	9.14×10^4	393
Diesel oil production	1.48×10^5	590
Tug ship operation	7.92×10^7	2.70×10^6
Other activities	1.24×10^4	23.2
Total	9.17×10^7	2.76×10^6

3.3. LIFE CYCLE IMPACT ANALYSIS

To test and analyse the impact of engine configurations on vessel performances, five scenarios are under assessment based on the model established and mentioned in the previous section. Five scenarios are listed:

1. Scenario 1 (Benchmark): two large engines running – 1518kW×2

This is the benchmark study in the inventory setup. The engines are operated at 74% engine load (at sea) and 33% (manoeuvring);

2. Scenario 2: three medium engines running – 1062kW×3

In scenario 2, 3 medium engines replace 2 large engine. The engines are operated at 71% engine load (at sea) and 31% (manoeuvring);

3. Scenario 3: two medium engines running – 1062kW×2

This scenario has the same engine type as Scenario 2 but only 2 other than 3 medium engines are running. The engines are operated at 106% engine load (at sea) and 47% (manoeuvring); under the sailing condition, the engines are overloaded. The operation concept suggests this as infeasible already but it is still under consideration to find out whether emission released will be improved.

4. Scenario 4: four small engines running – 761kW×4

In scenario 4, 4 small engines are equipped on the vessel. The engines are operated at 74% engine load (at sea) and 33% (manoeuvring);

5. Scenario 5: three small engines running – 761kW×3

This scenario has the same engine type as Scenario 4 but only 3 other than4 small engines are running. The engines are operated at 99% engine load (at sea) and 44% (manoeuvring); under the sailing condition, the engines are nearly fully loaded.

With the help of the LCA model, the emission potentials are determined and shown in Figure 6 and Figure 7. From the figure, it is obvious that the vessel operation phases are still the largest contributors under all scenarios and the proportions of emissions from different activities are similar. It is due to the use of the same model and the difference will be illustrated on the quantities not the proportions. It is also reasonable to consider to reduce the emission/fuel consumption during the operation phase to achieve better environmental protection.

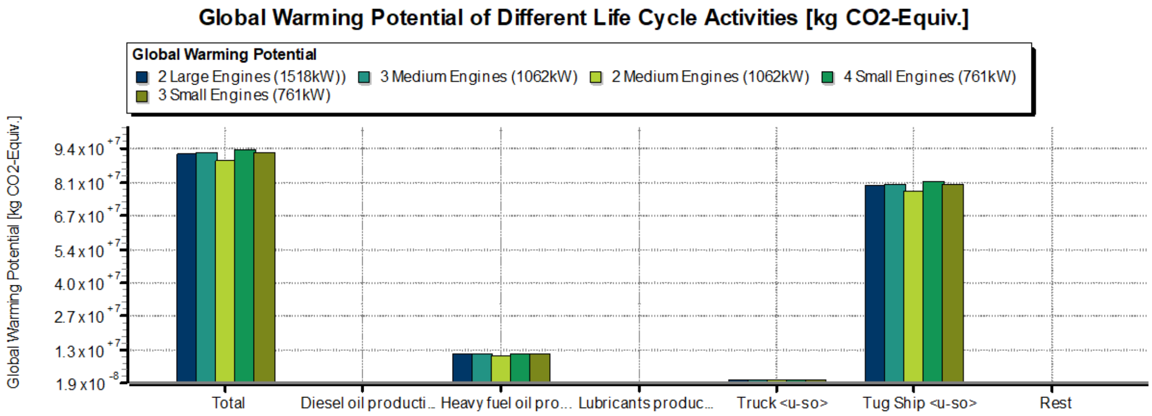

Figure 6 Global Warming Potential vs Life Cycle Activities [kg CO_2-Equiv.]

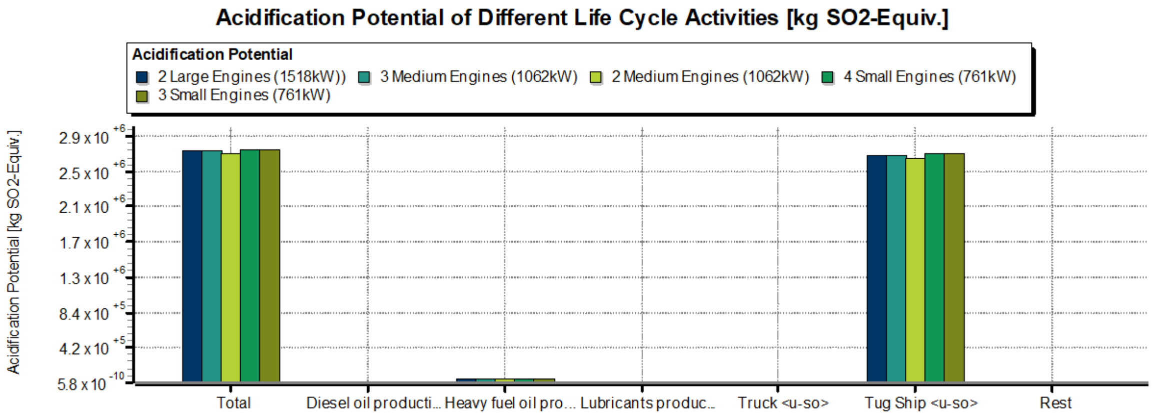

Figure 7 Acidification Potential vs Life Cycle Activities [kg SO_2-Equiv.]

Among the five scenarios, scenario 3 has the lowest emission for both GWP and AP: 8.93×10^7 kg CO_2 e and 2.73×10^6 kg SO_2 e. Scenario 4 has the highest emission for both as well: 9.36×10^7 kg CO_2 e and 2.77×10^6 kg SO_2 e. Furthermore, comparing five scenarios, it is apparent that changing configuration will help to reduce the emission released but the new configurations should be assessed and compared from the aspect of emission potential in order to determine the optimal engine configuration.

Similarly, the fuel oil consumption during 30 years operation is also determined through the LCA model which is presented in Table 4. It shows while applying the third configuration the overall fuel oil consumption is the lowest.

Table 4 Fuel oil consumption for five scenarios/configurations

Scenario	**1**	**2**	**3**	**4**	**5**
Fuel oil consumption (thousand tonne)	25.36	25.61	24.68	25.89	25.56

However, under the condition of scenario 3, the engines are operated under abnormal conditions as the overloaded by 6%. It is not suggested to be run the engines under this operation condition which may increase risk and maintenance of the engines. Among five scenarios, there are three of them which have their engine running at normal conditions: scenario 1, 2 and 4. Among these three, the first configuration with two large engines has the best performance (lowest emission and fuel consumptions).

4. CONCLUSIONS AND FUTURE WORK

According to the analysis and evaluation with a limited scope in this paper, we could conclude that:

a. Operational phase contributes the most emission (about 85% of overall emissions)in the tug boat life span;
b. Changing the engine configuration has an impact on engine performances: fuel consumption and emission release;
c. A life cycle assessment could be applied and help to determine whether the impacts are positive or negative so that the optimal alternative could be obtained; this could be more accurate if holistic ship life and comprehensive activities are considered.

There are many aspects not considered in this paper and will be considered in future work:

a. Life cycle cost analysis on these engine configurations, such as engine price, fuel price, transportation fees, etc.;
b. Risk related analysis on different configurations using risk assessment method, e.g. Formal Safety Assessment (FSA), HAZOP, FMEA etc.;
c. Other emission categories could be considered such as pollution to water;
d. Last but not least, maintenance phase will be another significant focus as the numbers, hours and loads of engine operation are varied greatly so the maintenance activities (emission and cost) will give a new angle to investigate the optimal alternatives.

REFERENCE

CML. (2016). CML-IA Characterisation Factors - Leiden University. Retrieved July 18, 2018, from https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

Dedes, E. K. (2013). Investigation of Hybrid Systems for Diesel Powered Ships By. *Soton*, 324.

GaBi. (2018). Software: GaBi Software. Retrieved July 18, 2018, from http://www.gabi-software.com/uk-ireland/software/

Gökalp, B. (2018). Exergy analysis and performance of a tug boat power generator using kerosene fuel blended with aspire methly ester. *Fuel*, *229*, 180–188. https://doi.org/10.1016/J.FUEL.2018.04.095

ISO. (2006a). ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework. Retrieved July 18, 2018, from https://www.iso.org/standard/37456.html

ISO. (2006b). ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines. Retrieved July 18, 2018, from https://www.iso.org/standard/38498.html

Ling-Chin, J., & Roskilly, A. P. (2016). Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study. *Applied Energy*, *181*, 416–434. https://doi.org/10.1016/J.APENERGY.2016.08.065

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., … M., A. H. (2014). *A new scenario framework for climate change research: Background, process, and future directions*. *Climatic Change* (Vol. 122). London, UK. https://doi.org/10.1007/s10584-013-0912-3

Zhen, L., Wang, K., Wang, S., & Qu, X. (2018). Tug scheduling for hinterland barge transport: A branch-and-price approach. *European Journal of Operational Research*, *265*(1), 119–132. https://doi.org/10.1016/J.EJOR.2017.07.063

Zhu, J., Chen, L., Wang, B., & Xia, L. (2018). Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel. *Applied Energy*, *226*, 423–436. https://doi.org/10.1016/J.APENERGY.2018.05.131