Journal of
Marine Science and Engineering

MDPI

Technical Note

Comparative Life Cycle Assessment of Marine Insulation Materials

Hayoung Jang [1], Yoonwon Jang [2], Byongug Jeong [1] and Nak-Kyun Cho [2,*]

[1] Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK; Hayoung.jang@strath.ac.uk (H.J.); byongug.jeong@strath.ac.uk (B.J.)
[2] Department of Manufacturing Systems and Design Engineering, Seoul National University of Science and Technology (SeoulTech), Seoul 01811, Korea; ywj820@seoultech.ac.kr
* Correspondence: nkcho@seoultech.ac.kr

Abstract: This study aimed to reduce the holistic environmental impacts of insulation materials proposed for the accommodation of a marine cargo ship, and suggest the optimal option for cleaner ship production, using life cycle assessment. With a commercial bulk carrier as a case ship, three major insulations were assessed, which were wool-based material (mineral wool or glass wool), expanded polystyrene, and polyurethane foam. The analysis was scoped based on 'from cradle to grave', while focusing on the following five representative environmental indicators: global warming potential$_{100years}$, acidification potential, eutrophication potential, ozone depletion potential, and human toxicity potential. The assessment was performed in the platform of the GaBi software. The results showed that polyurethane foam would have the greatest impacts, especially in regard to global warming, eutrophication, and human toxicity. On the other hand, expanded polystyrene and wool-based material showed better environmental performance than polyurethane foam. For example, wool-based insulation was found, in terms of GWP and HTP, to produce 2.1×10^4 kg CO_2-eq and 760.1 kg DCB-eq, respectively, and expanded polystyrene had similar results with respect to GWP, AP, and EP as 2.1×10^4 kg CO_2-eq, 23.3 kg SO_2-eq, and 2.7 kg Phosphate-eq, respectively. In fact, the research findings point out the shortcomings of current design practices in selecting insulation materials for marine vessels, while providing meaningful insights into the importance of the selection of appropriate insulation materials for marine vessels for cleaner shipping. Therefore, it is believed that this paper will make a sound contribution to enhancing future design practice and regulatory frameworks in response to environmental issues in the marine industry.

Keywords: global warming potential$_{100\ years}$; acidification potential; eutrophication potential; ozone depletion potential; human toxicity potential

check for updates

Citation: Jang, H.; Jang, Y.; Jeong, B.; Cho, N.-K. Comparative Life Cycle Assessment of Marine Insulation Materials. *J. Mar. Sci. Eng.* **2021**, *9*, 1099. https://doi.org/10.3390/jmse9101099

Academic Editor: Cristiano Fragassa

Received: 13 August 2021
Accepted: 1 October 2021
Published: 9 October 2021

1. Introduction

1.1. Background

The increase in universal environmental degradation has led entire countries to be environmentally conscious [1]. Hence, sustainability has become one of the most urgent issues across industries, including the construction and marine industry.

For example, there have been many studies on sustainable building and constructions. Ref. [2] reviewed the sustainability of green roofs for sustainable building in terms of air pollution improvement, water quality management for the environmental benefits, and economically encouraging policies and revealed the undeniable environmental benefits and economic feasibility of green roofs. Studies on the sustainability of green materials, such as cork as a building material for acoustic treatment used in buildings [3], have also been conducted. In order to reduce the greenhouse gas emissions of concrete, ref. [4] conducted a comparative life cycle sustainability analysis by substituting fly ash for Portland cement, and concluded that it is difficult to improve environmental performance in the short term by using fly ash, but it improves sustainability in the long term. These green materials have contributed a lot to building a more sustainable society as an alternative to improving the eco-friendliness of traditional synthetic materials.

As a part of this green movement, the marine industry has been making a lot of effort to improve sustainability. To achieve this goal, environmental control is being strengthened. For instance, International Maritime Organization (IMO) has set environmental regulations regarding sulphur oxide and greenhouse gas emissions, which can negatively affect the environment with respect to acidification and climate change. Besides, eutrophication harms marine ecosystems, some emissions could have a negative effect on human health, and many other detrimental environmental impacts exist as well. Owing to the environmental issues, LCA has been developed rapidly over the last few decades since it is possible to evaluate impact indicators in the whole life cycle of services, products, materials, processes, and others [5,6]. Due to its versatility, numerous studies, in a variety of industries, such as marine, automotive, construction, and others, have adopted LCA as a primary methodology to investigate the holistic environmental impacts of particular designs, systems, and products [7].

For instance, with the motivation of a series of international maritime environmental regulations, many studies have been carried out to investigate the holistic environmental impacts of marine industry [8–10]. Jeong et al. conducted comparative LCA of marine diesel and electricity and derived the result that the ship using a battery had reduced environmental impact potentials [11]. Additionally, there has been research about LCA of ship hull maintenance strategies of a ship to identify the optimal method from an environmental perspective as well [12]. Besides, several works have carried out comparative analysis of LCA and practicality, such as weight and cost. For example, Katsiropoulos et al. analyzed not only the environmental impacts of various production scenarios but also the cost of material, recycling, labor, and energy [13]. Additionally, there is a study about a comparative LCA and financial analysis of mixed culture polyhydroxyalkanoate (PHA) and biogas production. Based on their results, they concluded that the production process of mixed culture PHA should be optimized, for instance, process costs and environmental impact [14].

It can be concluded that all of the LCA studies used in marine research actively point out the importance of LCA and the necessity of its introduction as a standard emission measurement.

1.2. Current Issues in Marine Industry

Despite several academic studies as mentioned above, LCA has been far less used than it ought to have been in the marine industry. It means the current industrial practices and regulations for ship design and construction have overlooked the potential environmental harms caused by improperly selected ship materials or construction processes. Moreover, shipyards are choosing ship materials without paying sufficient attention to the environment but paying too much attention to the economy. Due to the shortfall for maritime regulations, the only criterion considered in the business is 'cost'.

As a result, the marine industry cannot answer the fundamental question of how sustainable is a ship construction? A number of products probably exist and some of them will be adopted. The problem is that those products are not the same in terms of their environmental impacts.

Although LCA has been proven to be effective in answering that question, this method has not been standardized in the shipbuilding sector. Despite voluminous studies in maritime environmental protection of shipping activities, few attempts have been made to investigate the emission levels associated with ship construction.

1.3. Direction to Contribution

This paper was motivated to offer a proper LCA guideline for ship construction field by conducting a comparative analysis of marine insulation materials. In the building construction field, there are a number of studies that have used comparative LCA analysis of different insulation materials to distinguish the sustainable one. According to Llantoy et al., they developed a comparative LCA of different insulation materials for buildings, such as polyurethane, mineral wool, and extruded polystyrene (XPS), and derived the result that mineral wool showed the best environmental performance [15]. In addition, Li et al. investigated the environmental impacts of rock wool board and expanded polystyrene (EPS) board, using impact categories, such as global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), and eutrophication potential (EP). The result of comparative LCA indicated that EPS board obtained better outcomes with respect to the GWP, AP, POCP, and EP [16].

However, relevant studies of marine insulation materials with respect to environmental performance and practicality are lacking; thus, it is still hard to confirm what materials will be most appropriate for marine applications. Given this, the LCA was conducted to offer a better suggestion of insulation material use among wool-based insulation (mineral wool, glass wool), polyurethane foam, and expanded polystyrene.

A case study was carried out, using the data of a 50,000 dead weight tonnage (DWT) bulk carrier. The material recommendation based on the results, which will be given in the paper, could assist in choosing an insulation material with better sustainability and practicality. In addition to this, the research findings suggest the necessity of standardization of LCA in the shipbuilding sector to ensure a huge decrement in environmental impacts [17,18].

2. Methodology (Life Cycle Assessment)

For a few decades, LCA has been known as a methodology to achieve sustainable development and has been used in the marine industry since the 1990s, being applied to a number of studies related to ship structures, fuels, materials, etc. [19]. The LCA is used to calculate indicators of various potential environmental impacts, which are emitted from products at the overall life cycle stages as shown in Figure 1 [20]. Therefore, it has the advantage that it is possible to suggest ways to reduce the environmental impact at a desired stage of a product or a system while avoiding effects on other stages [21].

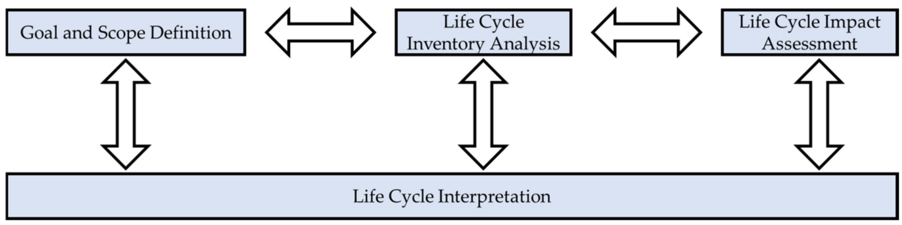

Figure 1. A schematic view of LCA processes.

For using the LCA, four major processes should be followed and these four processes are indicated in the ISO standards [22]. They are the goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope definition describe the system of a product with respect to the functional unit and the system boundaries. The functional unit enables alternative insulation materials to be compared with wool-based material in this study and the designated system boundary shows which phases of a product's life cycle will be analyzed during research [20].

After the first step, inventory analysis must be carried out to identify and quantify the inputs and outputs for a product right through from the cradle to the grave. Raw materials, water, and energy are included in inputs and substances that are emitted into the environment, such as emissions, are called outputs. The process involves data collection to develop a flow diagram of each product's processes, including inputs and outputs [23,24]. By using the results of the inventory analysis flow, the impact assessment stage evaluates the life cycle of a product by means of ReCiPe, CML, Ecoindicator, and so on. The ReCiPe is one of several methods of the impact assessment phase of LCA. Within the ReCiPe method, 18 midpoint indicators and 3 endpoint indicators exist to assess the environmental impacts [25]. In addition, the CML stands for the Centrum voor Milieukunde Leiden (the Center of Environmental Science, Leiden University, The Netherlands) [26]. This methodology was developed by the Institute of Environmental Science of the University of Leiden. Amongst the various methods, the CML method was used in the study. The CML is used to evaluate the environmental impacts that are caused by a product. Various impact indicators are included in the CML method, for instance, acidification potential, global warming potential, aquatic ecotoxicity, human toxicity, etc. [27].

Lastly, life cycle interpretation plays a role in the identification, quantification, and evaluation of the results from the inventory analysis and the impact assessment then provides recommendations and conclusions, or limitations are given in this phase eventually [28]. The study was conducted along with the aforementioned processes discussed in the sections below.

3. Goal and Scope

3.1. System Boundary

The first step of the LCA is to define the system boundaries and goals. The aim of the study was to evaluate the environmental impact indicators of three different insulation materials for comparison. Moreover, as it can be seen in Figure 2, GaBi software, which is a well-known tool to assess environmental analysis, was adopted. It is a graphical user interface software that offers users convenience in conducting LCA, whereas providing thousands of verified LCA data that is easily fitted to user-designed LCA models. In addition to the LCA GaBi data, this paper obtained LCA data from a variety of resources, such as communicating with different diverse stakeholders and adopting different industry standards and literature and past publications, etc. In particular, the operational framework of GaBi software is based on a master database, engineering consulting knowledge, and a specialized software environment. Thus, the GaBi software automatically includes extensive knowledge of the expert and technical expertise of LCA methodologies. Users can track all material, energy, and emission flows based on this data and knowledge. By modeling complex processes and various production options through the collected data, dozens of environmental impact categories, such as GWP, AP, and EP, can be instantly calculated and schematized using various LCIA methodologies, such as CML and ReCiPe, ultimately resulting in comprehensive environmental assessment. Based on it, the boundary was set from the raw material phase to the disposal phase in this paper. All processes can be divided into two major phases, which are the manufacturing phase and end of life (EOL) phase. The operation phase is not included within the boundary since emissions are not directly emitted from marine insulation during operation. For the goal of the study, environmental emissions were quantified in five impact categories at the impact assessment stage: GWP, AP, EP, ODP, and HTP. GWP was selected because global warming results in serious climate change worldwide these days. Furthermore, AP, EP, and ODP were chosen to demonstrate the impact of each material in terms of ecosystems on earth. Lastly, HTP was selected to examine the potential risk of each process of the material with respect to human health.

3.2. Functional Unit

The functional unit of the study was defined as a mass of each material in kg; therefore, three different materials were compared based on each one's total mass. The density (kg/m^3) and thickness (m) of each material are given by various insulation companies; therefore, the volume (m^3) of each insulation material could be calculated by multiplying the thickness and area (m^2) of insulation placed in the case ship. Hence, when the density and volume of insulation were multiplied, a mass of each insulation material was identified and used as the input data of GaBi software to derive results. The specification of each wool-based material was collected from the structural fire protection plan of Hyundai Mipo dockyard's 50,000 DWT bulk carrier. In addition, the specifications of expanded polystyrene and polyurethane foam were obtained from the GaBi software database.

3.3. Assumptions

Several assumptions were set before the comparative analysis in the study. First, all transportations occurred in South Korea; therefore, a truck was selected as the vehicle for transportation of each material. Moreover, diesel fuel was used as the energy for trucks as it can be seen in Figure 2. During modelling of the disposal phase, it was not classified specifically in different methods, for example, recycling, incineration, and landfill. Recycling, recovery, or reuse processes were not included in the EOL phase in accordance with the collected data from published environmental product declarations, which will be further discussed and cited in Section 4.2. As it can be seen in the flow diagram modelling section, the EOL phase was classified as transportation to the disposal site and the overall disposal process. Lastly, the operation phase was not included since there is no emission from insulations during the operation phase; thus, the outline of the LCA analysis was divided into two major processes, such as the manufacturing phase and EOL phase.

3.4. Impact Categories

The aforementioned five impact categories were GWP, AP, EP, ODP, and HTP, indicating environmental impacts, such as climate change, acidification, eutrophication, ozone depletion, and toxicological stress on human health [20].

Greenhouse gases cause global warming on Earth, which is related to climate change, and each gas has a specific GWP, indicating by kg CO_2 equivalent [30]. GWP measures the amount of energy that a gas will absorb based on a certain period of time. Here, 100 years and 20 years are typically used as the period. Acidification is one of the environmental impacts that could seriously affect ecosystems, especially within aquatic communities. It occurs in surface soils, oceans, rivers, and lakes when acids are emitted into the environment [31]. There are several factors of acidification, such as SO_2, NO_x, HCl, NH_3, and HF. Therefore, these emissions are expressed as kg SO_2 equivalent when it comes to AP [32].Eutrophication can have effects on water due to an excessive enrichment of nutrients, which can lead to imbalances in marine ecosystems [33]. Owing to eutrophication, water quality can deteriorate and benthic habitats are destroyed by excessive precipitation [34]. The level of emissions is expressed in kg phosphate equivalent. ODP indicates the effectiveness of a given product in ozone depletion, being expressed as kg CFC-11 (R-11) equivalent. Interestingly, ozone depletion not only harms human health and the ecosystems of water and terrestrial communities but also affects climate changes. Besides, air quality could be worsened and some materials could be degraded by ultraviolet radiation as well [35]. The impact category of human toxicity has relevance with human health risks. HTP is expressed by the level of kg dichlorobenzene (DCB) equivalent [36]. The measure of HTP is used to evaluate the potential health risks of a product's life cycle [37].

As mentioned above, all five chosen impact categories can measure significant environmental impacts in advance. Therefore, all emissions from each insulation material's system boundary were converted to the five indicators. The results and interpretation are stated in the section of impact assessment.

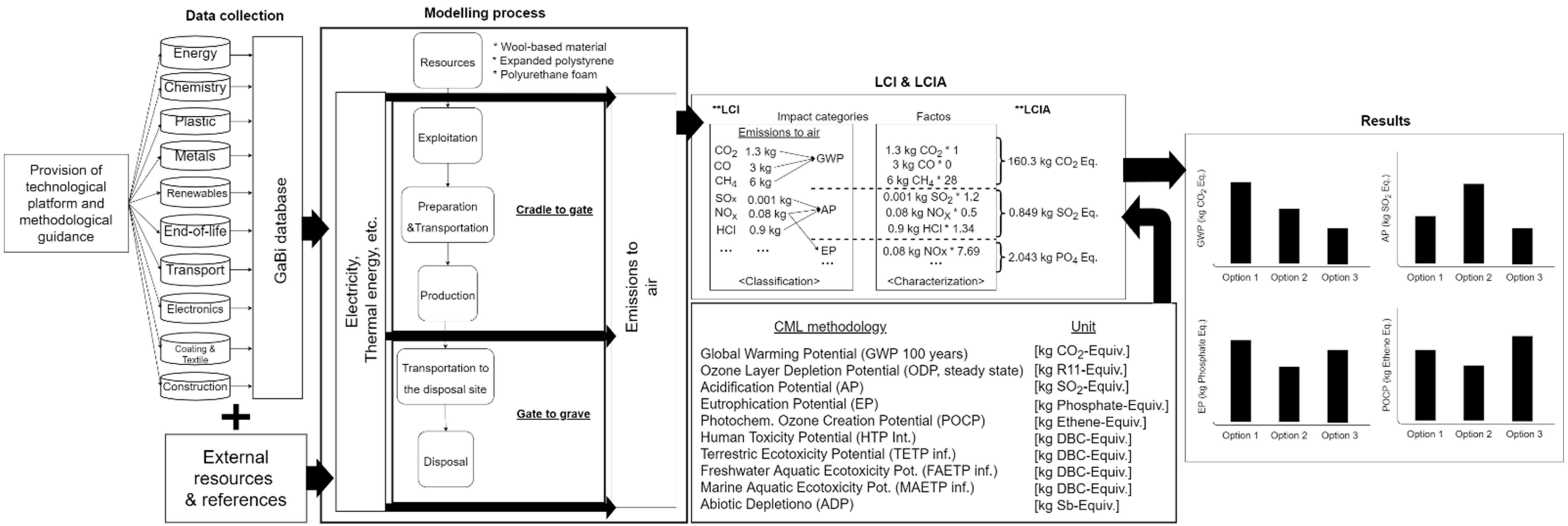

Figure 2. A schematic view of an outline of the LCA analysis [29].

4. Inventory Analysis

4.1. Case Ship and Material Analysis

In this study, a 50,000 DWT class bulk carrier from the company named 'Hyundai Mipo Dockyard' was analyzed to demonstrate the material that accounts for the majority of the total insulation volume within it. Inventory analysis of the case ship was carried out based on the structural fire protection plan that is given by the ship company and five decks were used for the research. The specifications of each deck are summarized in Table 1, which were also sourced from the structural fire protection plan. Based on the information, the total volume of constructed insulation materials was figured out and it turned out that the wool-based insulation material accounts for 72.5% of the insulation volume in the sample ship as it can be seen in Table 2.

Table 1. Deck specifications.

Deck	Height (m)	Width (m)	Length (m)
Upper	3.90	21.60	23.02
A	2.85	20.00	23.02
B	2.85	10.66	23.02
C	3.00	10.40	23.02
Navigation	2.90	11.07	13.44

Table 2. Inventory analysis results of wool-based material.

Deck	Total Volume (m^3)	Volume of Wool-Based Material (m^3)	Total Percentage of Wool-Based Material
Upper	58.54	37.58	
A	39.34	27.37	
B	32.78	23.65	72.50%
C	43.21	32.96	
Navigation	20.90	19.66	

The authors calculated the weight and volume of wool-based insulation material in the decks by analyzing the structural fire protection plan of the case ship as it can be seen in the conceptual schematic view in Figure 3. Since the wool-based material constitutes 72.5% of the case bulk carrier's decks, it was selected as the object of comparative LCA. Moreover, polyurethane foam and expanded polystyrene were chosen as alternatives to the wool-based material to be compared and the specifications of each material are in Table 3, which were sourced from the GaBi software database. These two materials were selected as substitutions due to the following conditions: good thermal performance, good fire protection, decent acoustic control performance, excellent humidity control that is a significant qualification for ships, and reasonable cost for being constructed in bulk carriers.

Figure 3 shows the conceptual description of the case ship's fire protection plan. The left-side of the figure depicts how the fire protection plan contains information about the insulation in each deck. Each deck is divided into several rooms and consists of various insulation materials. As it can be seen in Figure 3, the bulkhead, deck, and ceiling are symbolized in a number of ways, depending on the thickness, material, company, etc. Examples of symbols for division are included in the figure. Therefore, computation of the volume of each insulation material was derived based on the information from the fire protection plan of the case bulk carrier.

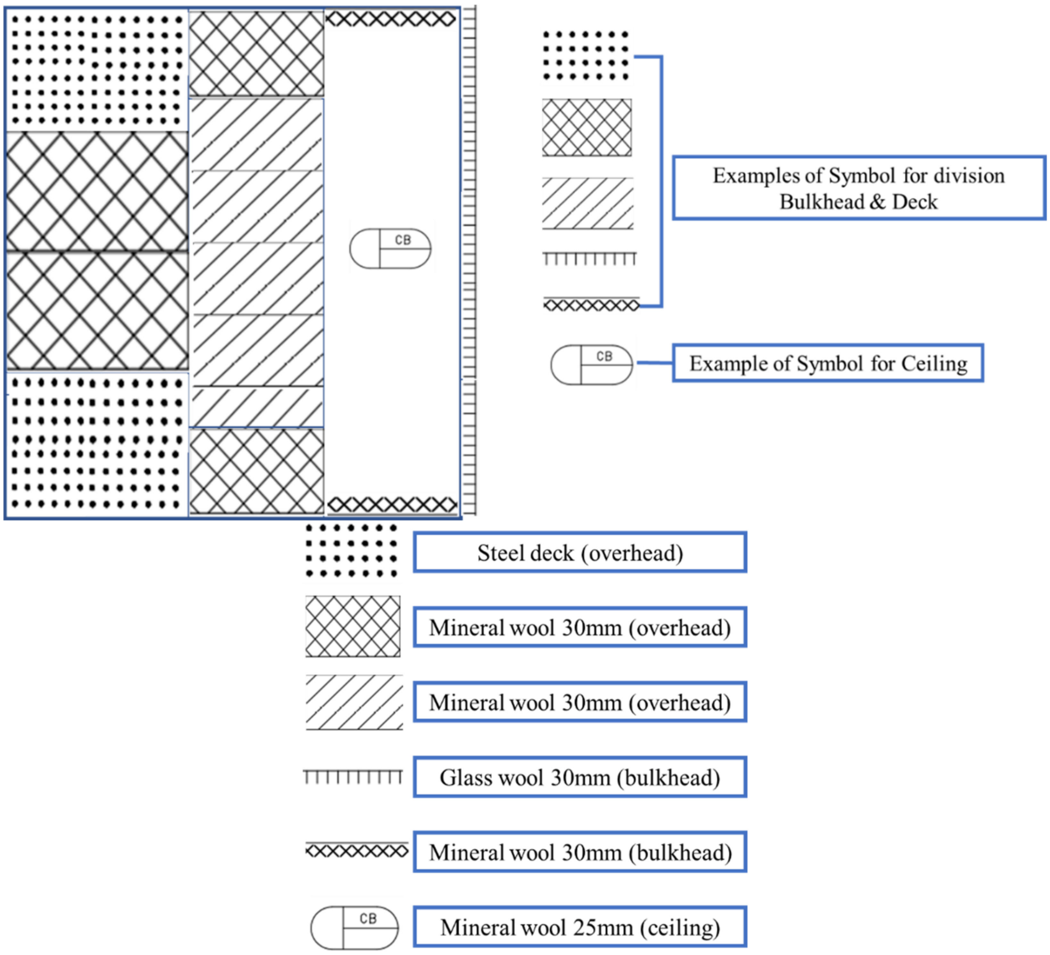

Figure 3. Conceptual example of the case ship's fire protection plan.

Table 3. Material specifications.

Material	Density (kg/m^3)	Thickness (mm)	Total Weight (kg)
Mineral wool	140	253,060	13,000
Glass wool	45	30, 50	2000
EPS	30	24	3300
PU	60	22	6000

4.2. Data Collection

Data collection is one of the most significant things for LCA since it is required for completing a desired model. In this study, data collection was done using three methods: the fire protection plan of the case ship, GaBi software database, and literature. The fire protection plan was used for demonstration of the specifications of each deck and identification of the object material, which was revealed as wool-based insulation in the previous section. The density and thickness of mineral wool and glass wool were mentioned in the structural fire protection plan of Hyundai Mipo dockyard's 50,000 DWT class bulk carrier. In addition, the GaBi software database was used as one of the data collection methods. GaBi software is one of many LCA software tools and it possesses an extensive database with relatively good quality when it is compared with other LCA software tools [38]. Therefore, GaBi software was selected as the main platform to progress the comparative LCA analysis.

Figures 4 and 5 depict flow diagrams of the cradle-to-gate phase of each material from the GaBi software database. These data were used for modelling in the software.

However, the database was used only for the cradle-to-gate phase due to the scarcity of data for defining the environmental impacts in the disposal phase. For the disposal phase, published environmental product declarations from a number of companies were used as data sources [39–42]. The data from the information from companies were used for modelling the disposal process of each type of insulation in the GaBi software for the impact assessment. Each material's data were adjusted based on the functional unit (kg).

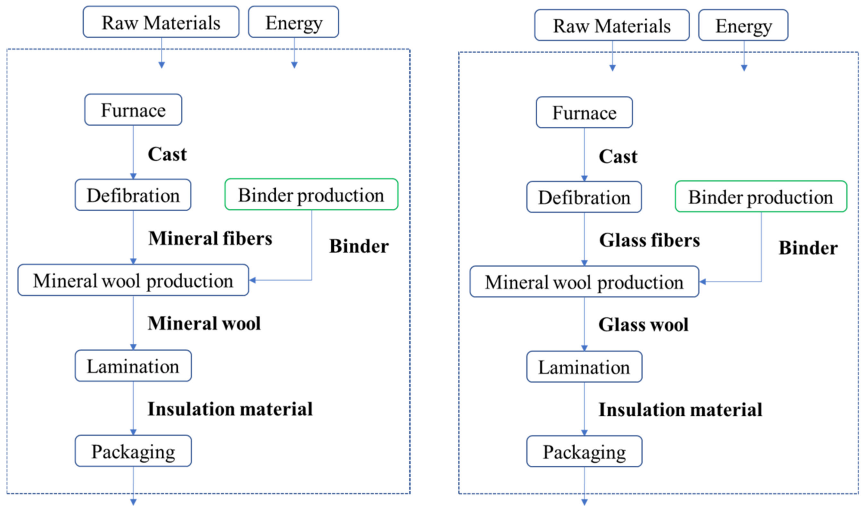

Figure 4. Cradle-to-gate flow diagram of wool-based material.

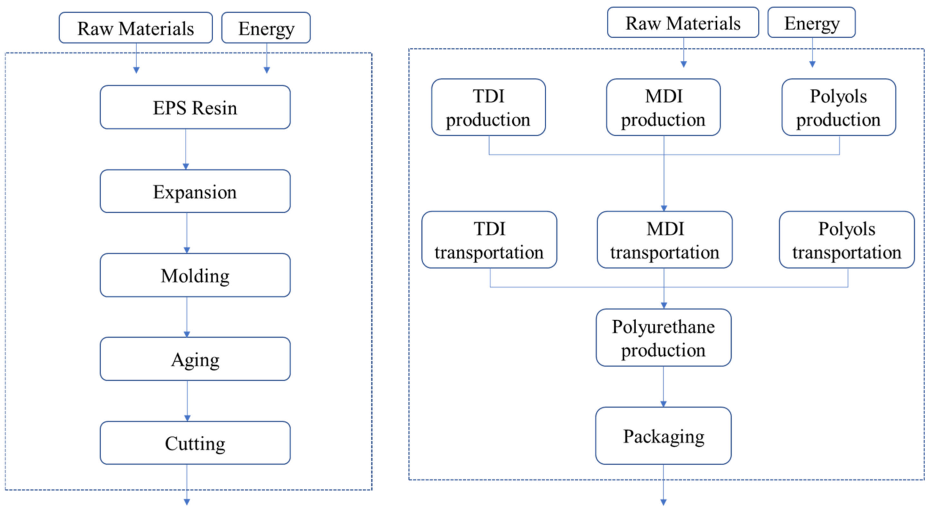

Figure 5. Cradle-to-gate flow diagram of EPS and polyurethane foam.

4.3. Flow Diagram Modelling

Figure 6 shows a schematic view of the flow diagram of mineral wool to describe how it was modelled in GaBi software. First, the manufacturing phase consists of the process of the cradle-to-gate phase of mineral wool as in Figure 4, which is offered by the GaBi software database, transportation to the construction site, and the diesel fuel refinery process for the truck. Second, the EOL phase modelling starts from the transportation process to the disposal site. The distribution phase to a disposal area needs a diesel refinery process and then the created scrapping process using data from the environmental product declaration is connected with the transportation process. Finally, the flow diagram of the whole life cycle is completed when two phases are connected as the schematic view. Moreover, Figures 7–9 show the modelled flow diagram of each material and they all have the same structure as the overall flow diagram of mineral wool except the cradle-to-gate process for each one of them.

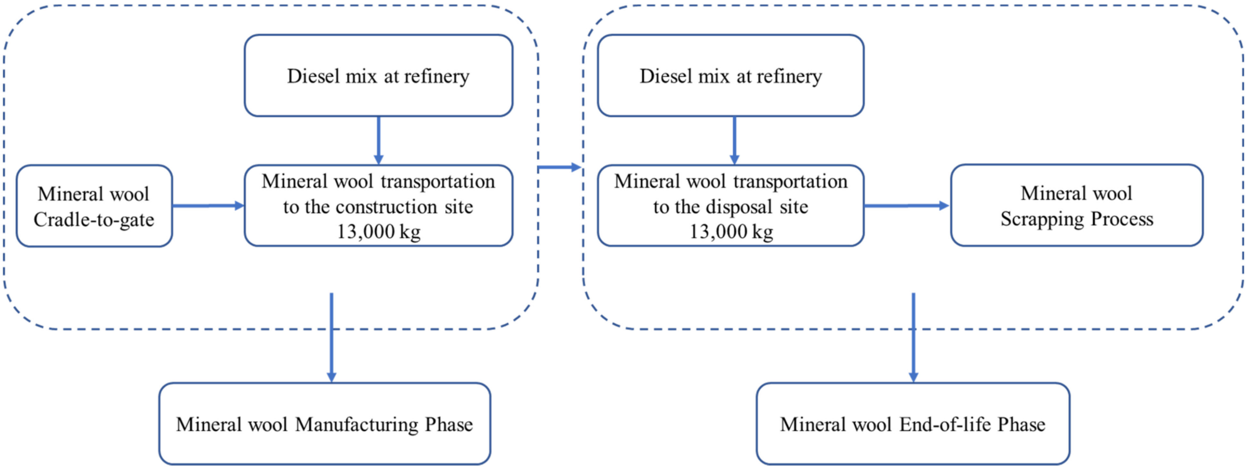

Figure 6. Flow diagram of mineral wool.

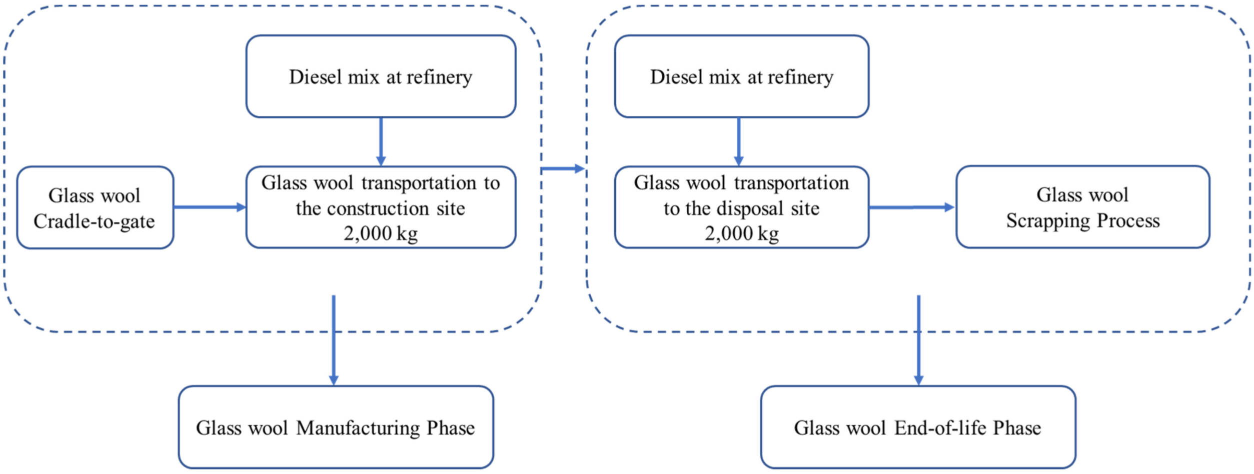

Figure 7. Flow diagram of glass wool.

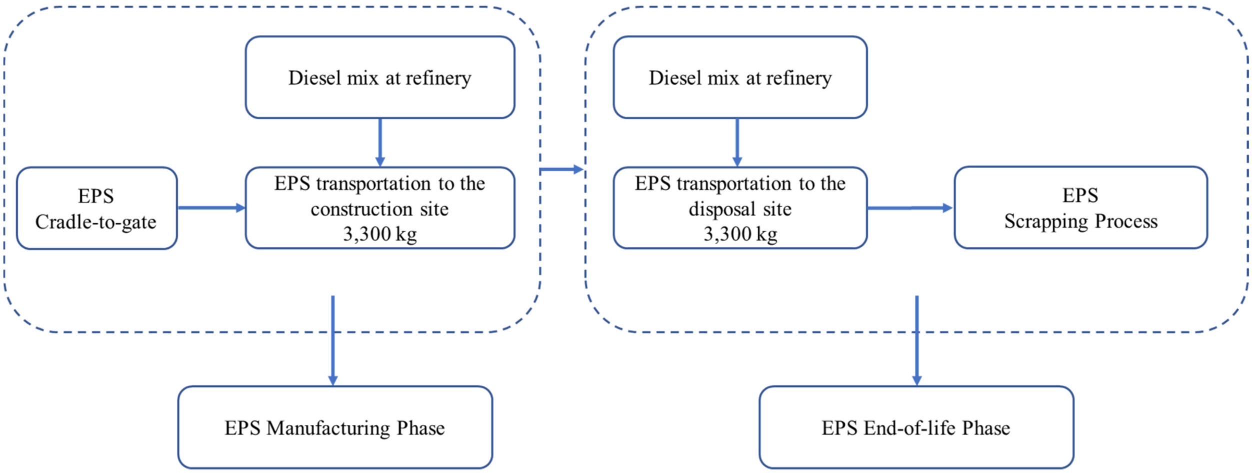

Figure 8. Flow diagram of EPS.

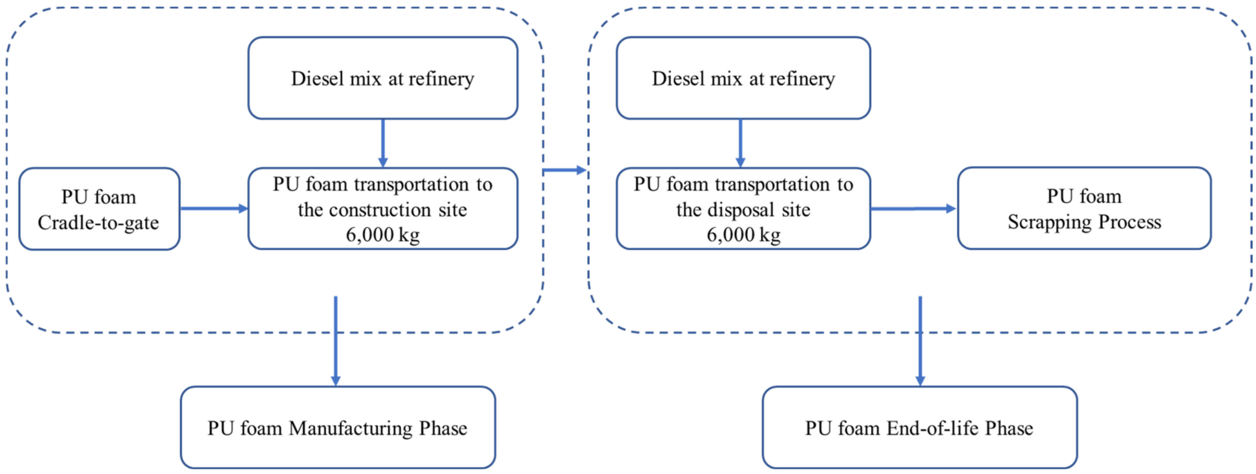

Figure 9. Flow diagram of PU foam.

5. Results (Impact Assessment)

In this paper, impact assessment proceeded based on three different perspectives: cradle-to-gate, disposal phase, and cradle-to-grave. Figure 10 indicates each impact category from three different points of view, respectively. The values of each impact category were derived by GaBi software, in accordance with CML 2001. The GaBi software is useful software to derive the impact assessment of products or systems by using its database and various functions, such as a new process or plan generation. Depending on the input data such as the amount of raw material or product, distance from site to site, and so on, the results will differ.

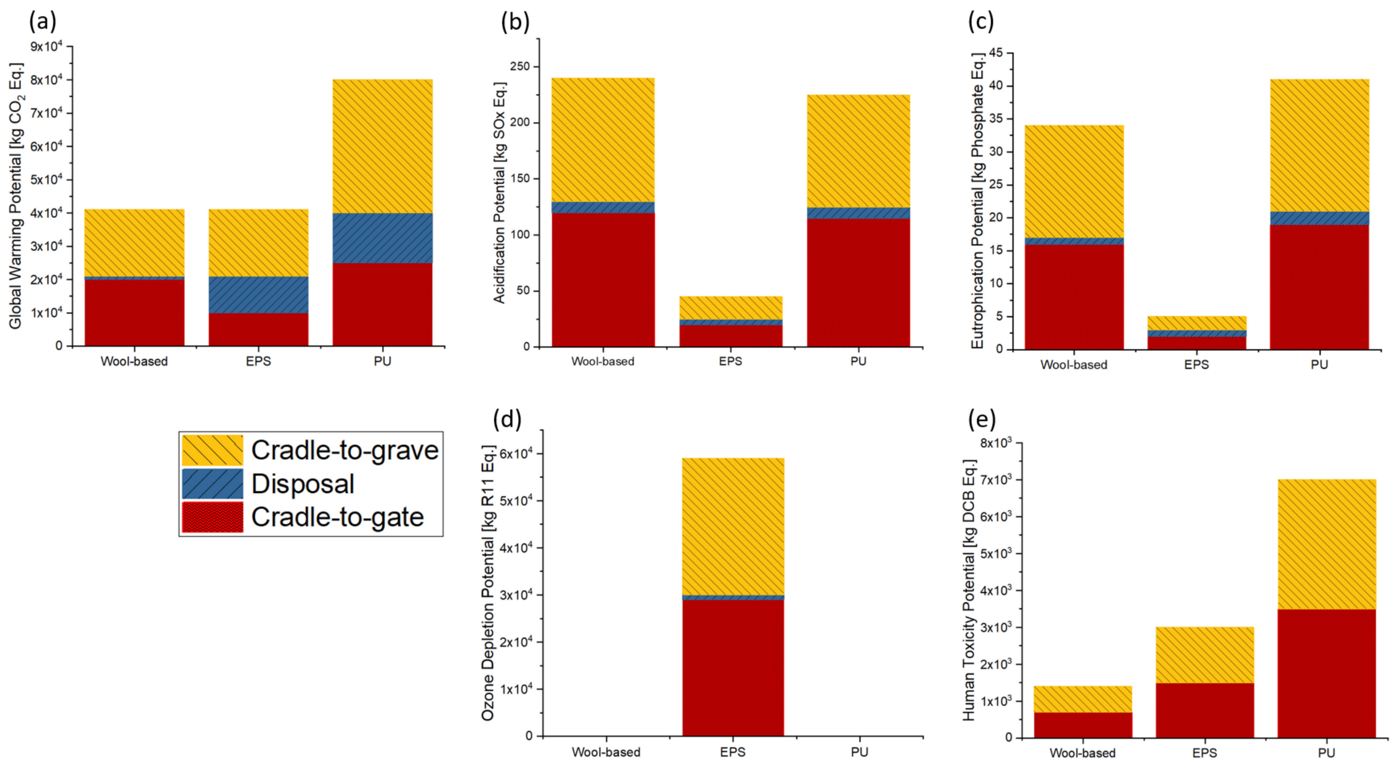

Figure 10. Results of life cycle assessment: (**a**) GWP, (**b**) AP, (**c**) EP, (**d**) ODP, (**e**) HTP.

5.1. Global Warming Potential (GWP)

Figure 10 shows the GWP of the three materials with the level of CO_2 equivalent. From all three perspectives, polyurethane foam has the highest GWP, which means that it affects climate change the most, compared with the other two materials. Although the expanded polystyrene produces the least amount of GWP at the cradle-to-gate phase, the wool-based material shows the lowest GWP value in the disposal phase. Interestingly, both materials emit 2.1×10^4 kg CO_2 equivalent from the whole life cycle point of view. Moreover, the amount of CO_2 equivalent difference between polyurethane foam and the other two materials is 1.8×10^4 kg.

5.2. Acidification Potential (AP)

As it can be seen in Figure 10b, the wool-based material is expected to contribute to the most acidification in all three phases. However, there are only 8.4, 2.5, and 10.9 kg differences with the values of polyurethane foam from the three different phases so it can be said that wool-based insulation and polyurethane foam could produce similar amounts of acidification. Moreover, the disposal phase indicates a much lower level of SO_2 equivalent, compared with the other two boundaries; therefore, a reduction of the acidification potential could be targeted in the manufacturing phase and then both the cradle-to-gate and cradle-to-grave processes would present decreased acidification. In addition, the expanded polystyrene creates the lowest emission level of SO_2 equivalent in all three phases. Thus, the expanded polystyrene is estimated to affect the environment the least in terms of acidification.

5.3. Eutrophication Potential (EP)

Unlike the tendency of AP, polyurethane foam shows the biggest environmental impact when it comes to EP as it can be seen in Figure 10c. However, the differences in the values between wool-based material and polyurethane foam are within only 3.6 kg. Hence, both materials are suggested to reduce emissions regarding eutrophication in the manufacturing phase, thus it will lead to a reduction of EP from the cradle-to-grave perspective as well. Meanwhile, the expanded polystyrene produces the least amount of EP; therefore, it is expected to impact the environment less than the other two materials with reference to the eutrophication.

5.4. Ozone Depletion Potential (ODP)

The result of ODP indicates a different trend with the results of GWP, AP, and EP since expanded polystyrene shows the biggest value in terms of ODP. In Figure 10d, the results of wool-based material, polyurethane foam, and expanded polystyrene in the disposal phase are barely in sight because they produce a minimal amount of R 11 equivalent when they are compared with 2.9×10^{-4} kg R 11 equivalent, which is the result of expanded polystyrene's ODP in the disposal phase and cradle-to-grave phase. However, ozone depletion is estimated as a minor impact since it shows smaller values among the five impact categories. The exact results can be seen in Tables 4–6.

5.5. Human Toxicity Potential (HTP)

Figure 10e indicates the level of HTP. As it can be seen in Figure 10e, HTP has the second highest values after GWP' thus, human toxicity could be one priority that should be reduced. Amongst the three materials, polyurethane foam is expected to result in the greatest human toxicity. Especially, the HTP values of polyurethane foam in the cradle-to-gate and cradle-to-grave phase are 3.44×10^3 and 3.444×10^3 kg DCB equivalent, respectively, which are followed sequentially by the expanded polystyrene and wool-based material. The HTP of wool-based material is 741 kg DCB equivalent in the manufacturing phase and 760.1 kg DCB equivalent from the whole life cycle point of view, being measured as the smallest value among the three cases. Meanwhile, in the disposal phase, HTP measures lower than 20 kg DCB equivalent in regard to the three materials; therefore, it is barely visible in Figure 10e. Hence, HTP needs to be cut down with respect to the manufacturing phase regarding all three materials.

Table 4. Cradle-to-gate (manufacturing phase).

	GWP (kg CO_2-eq.)	AP (kg SO_2-eq.)	EP (kg Phosphate-eq.)	ODP (kg R 11-eq.)	HTP (kg DCB-eq.)
Wool-based	2.0×10^4	117.4	16.0	1.9×10^{-10}	741.0
EPS	1.0×10^4	22.5	2.4	2.9×10^{-4}	1.5×10^3
PU foam	2.6×10^4	109.0	19.0	1.5×10^{-14}	3.4×10^3

Note: Global warming potential: Polyurethane foam > Mineral wool + Glass wool > Expanded Polystyrene. Acidification potential: Mineral wool + Glass wool > Polyurethane foam > Expanded Polystyrene. Eutrophication potential: Polyurethane foam > Mineral wool + Glass wool > Expanded Polystyrene. Ozone depletion potential: Expanded Polystyrene > Mineral wool + Glass wool > Polyurethane foam. Human toxicity potential: Polyurethane foam > Expanded Polystyrene > Mineral wool + Glass wool.

Table 5. Disposal phase.

	GWP (kg CO_2-eq.)	AP (kg SO_2-eq.)	EP (kg Phosphate-eq.)	ODP (kg R 11-eq.)	HTP (kg DCB-eq.)
Wool-based	1.0×10^3	3.5	0.9	7.0×10^{-10}	19.1
EPS	1.1×10^4	0.8	0.3	2.0×10^{-8}	4.2
PU foam	1.3×10^4	1.0	1.5	1.3×10^{-7}	4.4

Note: Global warming potential: Polyurethane foam > Mineral wool + Glass wool > Expanded Polystyrene. Acidification potential: Mineral wool + Glass wool > Polyurethane foam > Expanded Polystyrene. Eutrophication potential: Polyurethane foam > Mineral wool + Glass wool > Expanded Polystyrene. Ozone depletion potential: Expanded Polystyrene > Mineral wool + Glass wool > Polyurethane foam. Human toxicity potential: Mineral wool + Glass wool > Polyurethane foam > Expanded Polystyrene.

Table 6. Cradle-to-grave.

	GWP (kg CO_2-eq.)	AP (kg SO_2-eq.)	EP (kg Phosphate-eq.)	ODP (kg R 11-eq.)	HTP (kg DCB-eq.)
Wool-based	2.1×10^4	120.9	16.9	8.9×10^{-10}	760.1
EPS	2.1×10^4	23.3	2.7	2.9×10^{-4}	1.5×10^3
PU foam	3.9×10^4	110.0	20.5	1.3×10^{-7}	3.4×10^3

Note: Global warming potential: Polyurethane foam > Mineral wool + Glass wool ≥ Expanded Polystyrene. Acidification potential: Mineral wool + Glass wool > Polyurethane foam > Expanded Polystyrene. Eutrophication potential: Polyurethane foam > Mineral wool + Glass wool > Expanded Polystyrene. Ozone depletion potential: Expanded Polystyrene > Mineral wool + Glass wool > Polyurethane foam. Human toxicity potential: Polyurethane foam > Expanded Polystyrene > Mineral wool + Glass wool.

5.6. Material Suggestion

The results of the environmental impact are summarized in Tables 4–6 depending on each phase. Since polyurethane foam has poor environmental performance, compared with the other two materials, it is not recommended as a marine insulation material in this paper. First, expanded polystyrene could be suggested from the cradle-to-gate perspective due to its decent environmental performance, which can be seen by the results of GWP, AP, and EP. Particularly, GWP shows a huge gap, which is measured as 1.0×10^4 and 1.6×10^4 kg CO_2 equivalent between expanded polystyrene and the other two materials, respectively. However, when it comes to the human toxicity problem, the wool-based material is recommended as well if the manufacturer does not consider GWP.

Second, the wool-based material is suggested in the disposal phase for two reasons. The first reason is that the environmental impact will barely happen during the phase in accordance with the results. For instance, the amount of emissions related to AP and EP of all materials is less than 3.5 and 20 kg for HTP. ODP indicates minimal values in particular, being measured in the range of 7.0×10^{-10} to 1.3×10^{-7} kg R 11 equivalent. However, GWP still shows relatively large values when it is compared with other impact categories, which are from 1.0×10^3 to 1.3×10^3 kg CO_2 equivalent; therefore, global warming could be treated as the major environmental impact during the disposal phase. Hence, it is reasonable that the wool-based material is recommended due to its 10 times smaller GWP than the other two materials during scrapping.

Lastly, the expanded polystyrene and the wool-based material would both be excellent marine insulation materials, depending on different viewpoints. From the environmental point of view, these two materials evenly turned out to be sustainable marine insulation materials. Expanded polystyrene has the lowest environmental impact regarding global warming, acidification, and eutrophication. Additionally, wool-based insulation produces the least in terms of GWP and HTP. Thus, manufacturers of ships could select either one based on their own considerations. The second viewpoint is efficiency. As it is mentioned above, expanded polystyrene weighs 3300 kg, whereas the wool-based insulation's weight is 15,000 kg. Thus, expanded polystyrene will offer better efficiency of time and energy during distribution or construction of marine insulation. Therefore, expanded polystyrene should be used in the marine industry when the practicality and environmental performance are involved in the consideration.

From the given interpretations, comparisons of the results in Tables 4–6, and material suggestion for the marine insulation sector, the industry could accomplish a reduction of environmental impacts. As it is mentioned, the selection of wool-based insulation and expanded polystyrene would contribute to better sustainability. In more detail, wool-based insulation is recommended in terms of human health and climate change. Moreover, expanded polystyrene is expected to offer sustainable results with respect to ecosystems on Earth and climate change. In addition to the environmental performance, the practicality of expanded polystyrene could be a factor of such a recommendation as well. Since its weight is relatively light, compared with wool-based insulation's weight, better efficiency when it comes to the distribution phase and construction phase on the ship is estimated. Moreover, the manufacturing phase seems to have greater environmental impacts when it is compared with the disposal phase and it shows a similar tendency with the overall life cycle stage in most cases, which means that the production phase contributes to the environmental characteristic of each material the most. Hence, the study recommends that sustainable production processes should be developed.

6. Discussion

This paper was strongly motivated by the strong industrial demands in response to cleaner production and greener shipping. While current maritime regulations and current practices regarding maritime environmental protection are largely skewed towards propulsion systems, the equivalent impacts associated with ship design and manufacturing processes have been overlooked.

Under this culture, a fundamental argument raised by this paper is the importance of applying LCA to ship building sectors as common practice. The research findings distinctively illustrate the strengths of this novel approach and the limitations of the current environmental indicators. In fact, the current indicators tell us absolutely nothing about the environmental impacts on ship building, but LCA identifies optimal methods in terms of cleaner production from a holistic view.

With regard to this, LCA's implementation for decision-making regarding insulation materials in this paper can give meaningful insight into how we should apply this method for ship construction. LCA is still under-used in the marine industry because there are no standardized guidelines developed yet, although presently stakeholders have started to recognize its necessity. Considering this, this paper provides useful guidance regarding which can be used for more extensive studies on various aspects of shipbuilding as well as future regulatory frameworks. Therefore, it is strongly believed that this paper will contribute to enhancing maritime environment issues.

To be specific, the analysis results suggest proper selection of insulation material used for ship superstructure. By using expanded polystyrene, ecocide can be reduced owing to the smaller values of AP and EP than the wool-based material case. Additionally, due to the same value of GWP from both materials, expanded polystyrene could replace wool-based insulation without an increase of the impact on climate change. Furthermore, this paper indicates that the development of sustainable production processes will contribute significantly to cleaner ship production. Moreover, expanded polystyrene offers better efficiency during the ship building process with regard to the distribution and construction phase due to its light weight.

The insulation materials under comparison in this paper were carefully selected as the most feasible options in consideration of the material costs and the process based on the industrial knowledge of the authors. On the other hand, there is still a need to extend the investigation to other types of materials, such as green materials, to understand the optimal solution for environmental perseverance. In fact, similar results can be expected in this paper as there is a case study in which green materials were found to be more eco-friendly compared to existing materials from of life cycle perspective [43]. Nevertheless, this investigation should be considered as future work as it is not yet applicable to the ship and shipbuilding market. The authors strongly believe that it makes no sense to further investigate other materials without potential market use in the marine sector.

In short, the original contribution of this research can be summarized into two main points. First, by means of the advantages of LCA, the comparative analysis clearly confirms expanded polystyrene as an alternative to wool-based material, which can reduce the emission levels to some large extent, compared to the conventional material. Second, it presented a practical LCA approach for evaluating the holistic environmental impacts for the ship building process by using marine insulation materials as a demonstrative work.

On the other hand, some limitations of the paper are acknowledged, for instance, optimization of the thickness of insulation materials or division of the disposal phase were not included in the research. By optimizing the thickness of each material, a lighter weight will be achieved, and it can lead to better environmental performance and efficiency at once. Additionally, if the disposal phase is divided in detail, such as recycling, landfill, incineration, and others, more strict results would have been given in the paper.

7. Conclusions

According to the results, the research findings can be summarized as follows:

1) Most environmental impacts were attributed to the manufacturing phase, indicating the importance of developing proper production processes of insulation materials to contribute to cleaner shipbuilding.
2) Although polyurethane foam showed the greatest impact among the three different materials, expanded polystyrene and wool-based insulation were considered as eco-friendly materials with relatively low environmental impact. To be brief, wool-based insulation has the lowest results in terms of GWP and HTP as 2.1×10^4 kg CO_2-eq and 760.1 kg DCB-eq, respectively. Expanded polystyrene has the lowest impact with respect to GWP, AP, and EP as 2.1×10^4 kg CO_2-eq, 23.3 kg SO_2-eq, and 2.7 kg Phosphate-eq, respectively. In addition to the results regarding environmental performance, when the practicality is considered, since only 3300 kg of expanded polystyrene is needed to replace 15,000 kg of wool-based insulation material, the former is suggested due to its light weight. As a result of the substitution of wool-based material with expanded polystyrene, better efficiency is achieved when it comes to the distribution stage and construction stage. Therefore, expanded polystyrene should be used in the marine industry as both the environmental performance and weight were considered in the study.
3) As a proven methodology, this comparative LCA research will aid the marine industry to achieve sustainability by suggesting expanded polystyrene as a replacing material based on the results. By using the material as a marine insulation, environmental impacts regarding global warming, acidification, and eutrophication will be reduced. Since many sectors, including the marine industry, are struggling with curtailing

various environmental issues, such as ecocide and climate change, this research is expected to provide a useful option, which can contribute to the current task.

Author Contributions: H.J.: methodology, validation, data curation, writing—original draft preparation, Y.J.: Conceptualization, software, formal analysis, writing—original draft preparation, B.J.: investigation, resources, writing—review and editing, N.-K.C.: investigation, resources, writing—review and editing, supervision, All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Weng, Y.; Hsu, K.-C.; Liu, B.J. Increasing worldwide environmental consciousness and environmental policy adjustment. *Q. Rev. Econ. Financ.* **2019**, *71*, 205–210. [CrossRef]
2. Berardi, U.; GhaffarianHoseini, A.; GhaffarianHoseini, A. State-of-the-art analysis of the environmental benefits of green roofs. *Appl. Energy* **2014**, *115*, 411–428. [CrossRef]
3. Iannace, G.; Ciaburro, G.; Guerriero, L.; Trematerra, A. Use of cork sheets for room acoustic correction. *J. Green Build.* **2020**, *15*, 45–55. [CrossRef]
4. Wang, J.; Wang, Y.; Sun, Y.; Tingley, D.D.; Zhang, Y. Life cycle sustainability assessment of fly ash concrete structures. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1162–1174. [CrossRef]
5. Guinee, J.B.; Heijungs, R.; Huppes, G.; Zamagni, A.; Masoni, P.; Buonamici, R.; Ekvall, T.; Rydberg, T. *Life Cycle Assessment: Past, Present, and Future*; ACS Publications: Wasington, DC, USA, 2011.
6. Hwang, S.S.; Gil, S.J.; Lee, G.N.; Lee, J.W.; Park, H.; Jung, K.H.; Suh, S.B. Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. *J. Mar. Sci. Eng.* **2020**, *8*, 660. [CrossRef]
7. Vita, A.; Castorani, V.; Germani, M.; Marconi, M. Comparative life cycle assessment of low-pressure RTM, compression RTM and high-pressure RTM manufacturing processes to produce CFRP car hoods. *Procedia CIRP* **2019**, *80*, 352–357. [CrossRef]
8. Hwang, S.; Jeong, B.; Jung, K.; Kim, M.; Zhou, P. Life cycle assessment of lng fueled vessel in domestic services. *J. Mar. Sci. Eng.* **2019**, *7*, 359. [CrossRef]
9. Joung, T.-H.; Kang, S.-G.; Lee, J.-K.; Ahn, J. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. *J. Int. Marit. Saf. Environ. Aff. Shipp.* **2020**, *4*, 1–7. [CrossRef]
10. International Maritime Organization. *Sulphur 2020—Cutting Sulphur Oxide Emissions*; International Maritime Organization: London, UK, 2020.
11. Jeong, B.; Jeon, H.; Kim, S.; Kim, J.; Zhou, P. Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity. *J. Mar. Sci. Eng.* **2020**, *8*, 580. [CrossRef]
12. Wang, H.; Oguz, E.; Jeong, B.; Zhou, P. Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry. *Ocean Eng.* **2018**, *161*, 20–28.
13. Katsiropoulos, C.V.; Loukopoulos, A.; Pantelakis, S.G. Comparative Environmental and Cost Analysis of Alternative Production Scenarios Associated with a Helicopter's Canopy. *Aerospace* **2019**, *6*, 3. [CrossRef]
14. Gurieff, N.; Lant, P. Comparative life cycle assessment and financial analysis of mixed culture polyhydroxyalkanoate production. *Bioresour. Technol.* **2007**, *98*, 3393–3403. [CrossRef]
15. Llantoy, N.; Chàfer, M.; Cabeza, L.F. A comparative Life Cycle Assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. *Energy Build.* **2020**, *225*, 110323. [CrossRef]
16. Li, Z.; Gong, X.Z.; Wang, Z.H.; Liu, Y.; Ma, L.P.; Wang, S.P.; Guo, J. Life cycle assessment of rock wool board and EPS board. In *Materials Science Forum*; Trans Tech Publications Ltd.: Kapellweg, Switzerland, 2014; pp. 106–110.
17. Schmidt, A.C.; Jensen, A.A.; Clausen, A.U.; Kamstrup, O.; Postlethwaite, D. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. *Int. J. Life Cycle Assess.* **2004**, *9*, 53–66. [CrossRef]
18. Shama, M. Life cycle assessment of ships. *Marit. Transp. Exploit. Ocean Coast. Resour.* **2005**, *1*, 1751–1758.
19. Jeong, B.; Jang, H.; Zhou, P.; Lee, J.-U. Investigation on marine LNG propulsion systems for LNG carriers through an enhanced hybrid decision making model. *J. Clean. Prod.* **2019**, *230*, 98–115. [CrossRef]
20. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef] [PubMed]

21. Menoufi, K.; Castell, A.; Navarro, L.; Pérez, G.; Boer, D.; Cabeza, L.F. Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase. *Appl. Energy* **2012**, *92*, 534–544.
22. ISO Standardization. *Environmental Management: Life Cycle Assessment; Principles and Framework*; ISO: Geneva, Switzerland, 2006.
23. Cao, C. *Sustainability and Life Assessment of High Strength Natural Fibre Composites in Construction, Advanced High Strength Natural Fibre Composites in Construction*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 529–544.
24. Muthu, S. *Estimating the Overall Environmental Impact of Textile Processing: Life Cycle Assessment (LCA) of Textile Products. Assessing the Environmental Impact of Textiles and the Clothing Supply Chain*; Elsevier: Amsterdam, The Netherlands, 2014; p. 105e131.
25. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; Van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
26. Gabathuler, H. LCA History: Centrum voor Milieukunde Leiden (CML) The CML Story How Environmental Sciences Entered the Debate on LCA Special Issue to Helias A. Udo de Haes. *Int. J. Life Cycle Assess.* **2006**, *2*, 127–132. [CrossRef]
27. Mohan, M. *Perovskite Photovoltaics: Life Cycle Assessment, Perovskite Photovoltaics*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 447–480.
28. Hernandez, P.; Oregi, X.; Longo, S.; Cellura, M. *Life-Cycle Assessment of Buildings, Handbook of Energy Efficiency in Buildings*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 207–261.
29. PE-International. *GaBi Paper Clip Tutorial: Handbook for Life Cycle Assessment, Using the GaBi Software*; PE International GmbH and Universität Stuttgart: Stuttgart, Germany, 2011.
30. Vallero, D.A. *Air Pollution Calculations: Quantifying Pollutant Formation, Transport, Transformation, Fate and Risks*; Elsevier: Amsterdam, The Netherlands, 2019.
31. Tagliarolo, M. Acidification in Aquatic Systems. In *Encyclopedia of Ecology*; Elsevier: Amsterdam, The Netherlands, 2018; Volume 6.
32. La Rosa, A. *Life Cycle Assessment of Biopolymers, Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 57–78.
33. Lemley, D.A.; Adams, J.B.; Rishworth, G.M.; Bouland, C. Phytoplankton responses to adaptive management interventions in eutrophic urban estuaries. *Sci. Total Environ.* **2019**, *693*, 133601.
34. Dorgham, M.M. *Effects of Eutrophication, Eutrophication: Causes, Consequences and Control*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 29–44.
35. Poulopoulos, S. *Atmospheric Environment, Environment and Development*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 45–136.
36. Durante, S.; Comoglio, M.; Ridgway, N. Chapter 34-Life Cycle Assessment in Nanotechnology, Materials and Manufacturing A2-Qin, Yi. In *Micromanufacturing Engineering and Technology*; William Andrew Publishing: Boston, MA, USA, 2015.
37. Singh, V.; Dincer, I.; Rosen, M.A. *Life Cycle Assessment of Ammonia Production Methods, Exergetic, Energetic and Environmental Dimensions*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 935–959.
38. Spatari, S.; Betz, M.; Florin, H.; Baitz, M.; Faltenbacher, M. Using GaBi 3 to perform life cycle assessment and life cycle engineering. *Int. J. Life Cycle Assess.* **2001**, *6*, 81. [CrossRef]
39. *Environmental Product Declaration (Glass Mineral Wool 036-037-038 Unfaced Rolls Classic 037, Expert IPR 037, KI Fit 037, Naturoll 037, Decibel, TI 140T, TI 140W, Ultracoustic R, Unifit 037, TP 115 with ECOSE Technology), 13.07.2015 ed.*; Institut Bauen und Umwelt e.V. (IBU): Berlin, Germany, 2015.
40. *Environmental Product Declaration (Expanded Polystyrene (EPS) Foam Insulation (Density 30 kg/m^3)), 20.04.2017 ed.*; Institut Bauen und Umwelt e.V. (IBU): Berlin, Germany, 2017.
41. *Environmental Product Declaration (Light and Heavy Density Mineral Wool Board), 07.11.2018 ed.*; UL Environment, North American Insulation Manufacturers Association: Alexandria, VA, USA, 2018.
42. *Environmental Product Declaration (Polyurethane Thermal Insulation Spray Foam (Blowing Agent HFO; Density 40 kg/m^3), 26.02.2019 ed.*; Institut Bauen und Umwelt e.V. (IBU): Berlin, Germany, 2019.
43. Kosareo, L.; Ries, R. Comparative environmental life cycle assessment of green roofs. *Build. Environ.* **2007**, *42*, 2606–2613. [CrossRef]