Study on Life Cycle Impact Assessment for Ships

by

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Abstract

We have developed LCA software to estimate the environmental impact of a ship during its life cycle. We incorporated a recently developed comprehensive life cycle impact assessment (LCIA) methodology, called LIME, which quantifies the potential environmental risk and creates a single economic index specific to Japan's conditions. Analysis was conducted on a bulk carrier based on data obtained from field studies at a shipbuilding yard and a dismantling yard and on the analysis of navigation logbooks of actual bulk carriers. The results of stage-by-stage analysis clarified that almost all the environmental impact during the ship's life cycle occurs at the operation stage and that the primary environmental impact categories are acidification, global warming, resource consumption and urban air pollution. Based on the LIME index, the result also made it clear that the emission of CO_2, NO_x, SO_x, NMVOC and PM as well as the consumption of crude oil are major environmental load items contributing to environmental impact during the ship's life cycle.

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1. Introduction and objective

The Life cycle assessment (LCA) incorporated in ISO-14040 is now gaining widespread acceptance as an effective means of measuring and evaluating the burden of products, materials and even corporate activities on the environment for their entire life cycle – from the extraction of resources, through the production of materials, product parts and product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (in effect, therefore, ‘from the cradle to the grave). The framework in the ISO standard divides the entire LCA procedure into four phases: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment and (4) Interpretation.

We have attempted to establish an LCA methodology specific to ships and to develop software to facilitate LCA analysis of ships. First, life cycle inventory (LCI) analysis, in which relevant inputs and outputs of product system under study throughout the life cycle are, as far as possible, complied and quantified, was carried out focusing on carbon dioxide (CO_2), nitrogen oxide (NO_x) and sulfur oxide (SO_x) emissions[1)-2)]. Detailed investigations were conducted on construction and recycling processes at a shipbuilding yard and a dismantling yard, and actual operational conditions of several kinds of ocean-going cargo ships in order to estimate environmental impact [3)-4)].

A comprehensive life cycle impact analysis (LCIA) methodology, called LIME [5)] (life cycle impact assessment method based on endpoint modeling), was recently developed to quantify the potential risk of environmental loads and to create a single economic index. LIME is a damage-oriented LCIA methodology, which qualifies environmental impacts induced by the occurrence of environmental loading in Japan with a high degree of transparency.

However, LCIA analysis on ships has not been performed because of complexity of quantifying its environmental loads through the life cycle. In this paper, we execute LCIA analysis using LIME by the LCA software based on the obtained investigation results and present environmental impacts caused by ship during its life cycle based on the result of LCIA analysis.

2. Goal &Scope

2.1 Goal

The step in the Goal definition phase involves stating and justifying the goal of study, explaining the aim of the study and specifying the intended use of the result. The goal of this study is to clarify the environmental impacts and major environmental loads of a ship during its life cycle.

2.2 System boundary

The Scope definition step establishes the main characteristics of an intended LCA study, covering such issues as temporal, geographical and technology coverage, the mode of analysis employed and overall level of sophistication of the study.

The system boundary shows processes related to intended study. In this study it includes the shipbuilding, ship operation, and ship dismantling & recycling stages as well as the production of fuels, materials and ship parts. Parts recovered from the dismantled ship are assumed not to subject to reuse. Waste treatment is assumed to be land filled.

2.3 Impact categories

The impact categories considered for each lifecycle stage in calculating the single index are global warming, acidification, photochemical oxidant creation, eutrophication, urban air pollution, waste and resource consumption, as shown in Table 1. The newest version of JLCA-LCA Database, Fiscal 2005 Second Edition [6] was applied to the analysis.

Table 1 Impact categories applied to the analysis of the ship model

Impact categories	Shipbuilding	Operation	Dismantling & Recycling
Global warming	○	○	○
Acidification	○	○	○
Eutrophication	○	○	○
Photochemical oxidant creation	○	△	○
Urban air pollution	×	△	×
Resource consumption	○	○	○
Waste	○	○	○

Note : △ applied to cargo handling at ports in Japan

3. Method and conditions of analysis

3.1 LCA software for ships

The LCA software for ships was used for LCI analysis and LCIA. The main screen of the LCA software is shown in Fig. 1. The software consists of a database with ship specifications and parts on board, and the LCA database. LCA analysis is performed at each lifecycle stage as well as over the entire life cycle, and includes the production of fuels, materials and ship parts at each stage.

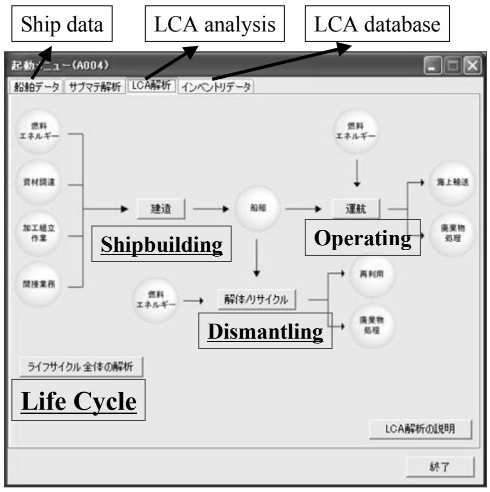


Fig.1 Main screen of LCA software for ships

The software analysis functions include those of LCI analysis, LCIA and sensitivity analysis. An interface incorporated in the software links the actual categorization of activities in shipbuilding, ship operation and ship dismantling & recycling to the process data of the software. Environmental impacts are quantified using the matrix method based on the processes, that is, the smallest technical units or systems where economic or environmental input and output data is available, such as fuel production, material processing and machinery operation. Database installed in the software prepares not only highly reliable data on material processing such as welding, cutting and painting, and operation of machinery such as diesel engines and boilers, but also background data such as production of materials and energy, etc.

LIME impact assessment data incorporated in the software is used to estimate the environmental impact of a ship during its lifecycle and to indicate environmental contributions in different lifecycle stages such as shipbuilding, ship operation and ship dismantling & recycling.

3.2 Ship model

A Panamax bulk carrier with a cargo capacity of 76,000 tons was selected as the ship model for LCA analysis since it is one of the most popular types of ships in operation. A photograph of the ship is shown in Fig. 2 and the principal particulars of the ship are listed in Table 2. The total weight of the ship is about 11,000 tons, with an approximate distribution of 82% for the hull, 10% for out-fittings and 8% for other machinery including electric parts. The ship is equipped with a main diesel engine of 8,830 kW, three diesel generators and an auxiliary boiler.

3.3 Process quantities

Data on the processes in the shipbuilding and dismantling stages was obtained from field studies at a shipbuilding yard and a dismantling yard.[4] Load factors for the main engine, diesel generator and auxiliary boiler in the operation stage were based on data obtained from the analysis of navigation logbooks of actual bulk carriers.[4]

3.4 Process data

Inventory data on the production of materials and fuels was derived from representative LCA database[6)-7)] data. Material processing data on cutting, welding, painting and bending was prepared according to the investigation at the shipbuilding yard and by calculation based on a products catalog. Emission factors for the main engine, diesel generator and auxiliary boiler in the operation stage were calculated based on IPCC guidelines, etc.[8)-9)]

4. Shipbuilding

4.1 Analysis model

The shipbuilding system used at the investigated yard is the block erecting system, that is, a ship is built by erecting blocks for the hull using cranes in a dry dock. Materials and ship parts are transported to the shipbuilding yard by ship or truck. Ship parts are installed during or after construction of the hull. Steel plates are subject to such processes as cutting, welding and painting, and assembly to hull blocks. Before delivery to the ship owner, the ship undergoes a sea trial to examine performance characteristics such as maximum speed and fuel consumption.

4.2 System boundary for shipbuilding

The system boundary for the shipbuilding stage is shown in Fig. 3. Transportation of material and ship parts to the shipbuilding yard was taken into consideration in the analysis. Inventory data on the production of ship parts such as the main engine and diesel generators was regarded as that of materials mainly contained in the parts

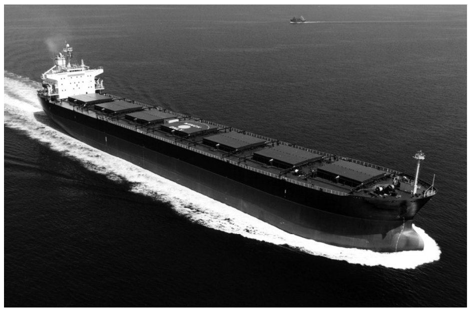


Fig. 2 Photograph of the ship model (Panamax bulker

Table 2 Principal particulars of the ship model

Classification	Item	Quantity	Unit
Size	Length	225.00	m
	Breadth	32.26	m
	Depth	19.30	m
	Draft	14.40	m
Tonnage	Dead weight	76,300	t
	Gross tonnage	40,100	GT
Speed	Service speed	15.50	knt
Main engine	Type	7S50-MC-C	
	MCR	8,830	kW
Generator	Output	400 × 3 set	kW
Aux. Boiler	Output	1.3	t/h

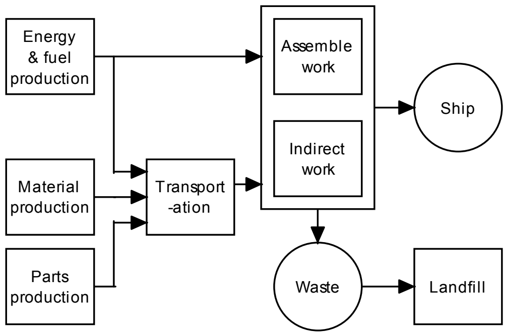


Fig.3 System boundary of shipbuilding

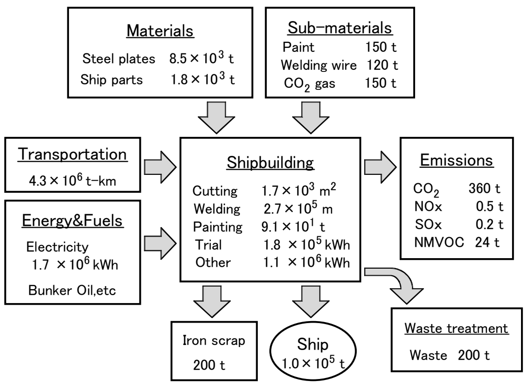


Fig.4 Input and output at the shipbuilding yard on the ship model

and did not include manufacturing processes for the sake of simplicity.[10] Urban air pollution was not considered in the impact categories shown in Table 1 because most shipbuilding yards are not located in urban areas.

4.3 Shipbuilding work processes

Investigation on input/output at the shipbuilding stage and work processes for the ship model was conducted. The result of the investigation is shown at Fig. 4. Electricity consumption for building the ship model at the yard was 1.7 million kWh, based on the average.

Transportation of purchased parts and equipment accounted for 4.3 million t-km : 82% for domestic coastal shipping, 12% for ocean-going shipping and 6% for transportation by truck.[4]

4.4 Results of analysis

4.4.1 Shipbuilding of the model

The impact assessment analysis on building the ship model indicates an environmental impact of 7.8×10^7 yen in the LIME single index, and includes the effect of the production of fuels and such materials as steel plates and ship parts.

Fig. 5 shows the proportion of the environmental impact in terms of impact categories and indicates that the impact of shipbuilding is mainly attributable to resource consumption, global warming and photochemical oxidant creation, but not to acidification, eutrophication or waste. The impact of photochemical oxidant creation is mainly in terms of the painting process, and includes the effect of paint production.

Fig. 6 shows the proportion of the environmental impact in terms of shipbuilding processes. Steel production has the largest environmental impact in the shipbuilding stage, followed by shipbuilding work, that is, such work processes as welding, painting and sea trials. The total environmental impact from both the work processes and

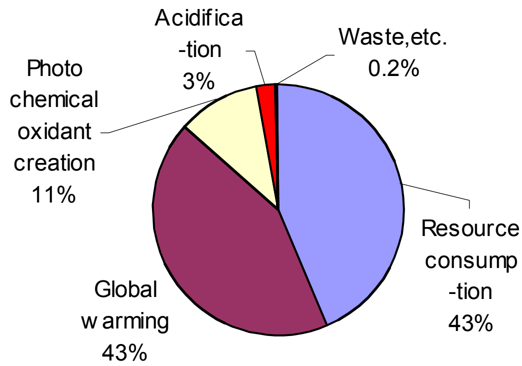


Fig.5 Impact categories caused by shipbuilding including production of materials and ship parts, etc

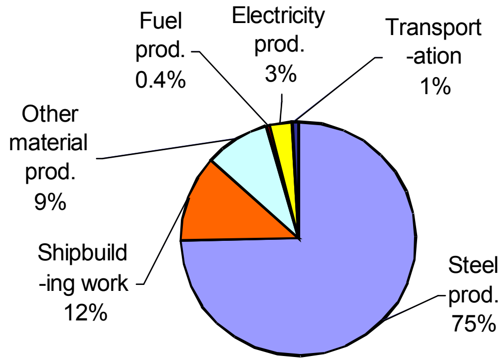


Fig.6 Shipbuilding processes causing environmental impact

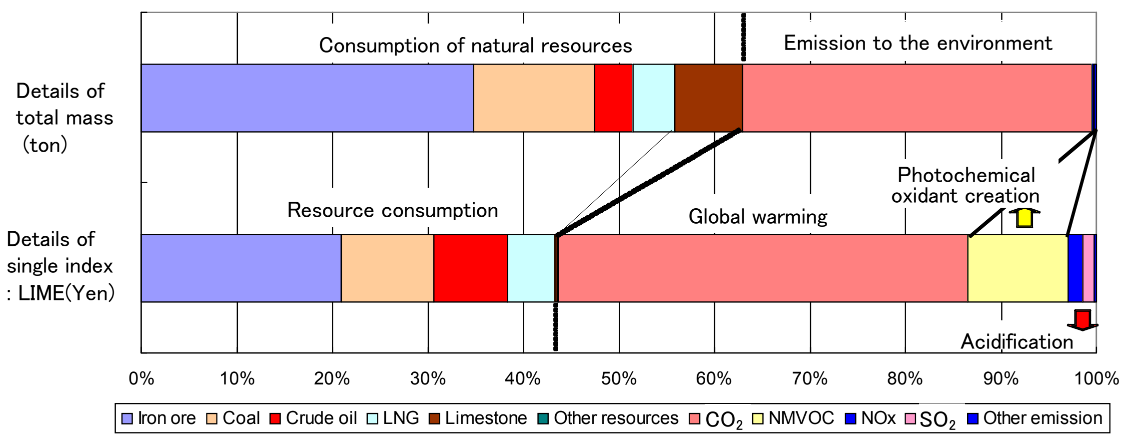


Fig.7 Effect of load items on environmental impacts caused by shipbuilding.
Upper horizontal bar: share of total mass including consumption or emissions of load items
Lower horizontal bar: share of environmental impacts based on LIME

the production of materials and fuels associated with the processes, accounts for about 24% of the total environmental impact from shipbuilding. This is discussed further in the next section.

The mass proportion of input and output in the shipbuilding stage is shown in the upper bar of Fig. 7, that is, natural resource consumption and environmental emission, and the lower bar illustrates the details of the impact categories as per the LIME index. The highest contribution to environmental impact is in the global warming category and most of that is attributable to CO_2 emission. The contribution of resource consumption is almost the same as that of global warming and is mainly attributable to the consumption of iron ore, coal, crude oil and LNG; only slightly to the consumption of limestone. NMVOC (non-methane volatile organic compounds), NOx, and SOx are emitted very little in mass, but their contribution to the environmental impact is meaningful in terms of photochemical oxidant creation and acidification.

4.4.2 Work processes at the shipbuilding yard

The environmental impact attributed to work processes at the shipbuilding yard accounts for about 1.9×10^7 yen, and corresponds to about 24% of the total impact throughout the shipbuilding process, where the associated production of materials such as paints and oils is included but the production of steel plates and ship parts is not. The proportion of the impact from the work processes in terms of impact categories is shown in Fig. 8, which indicates that the main contributing categories are photochemical oxidant creation, resource consumption and global warming.

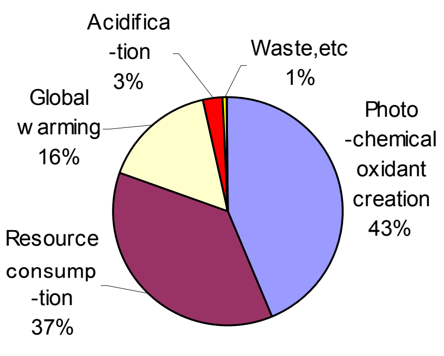


Fig.8 Impact categories caused by the work processes at the shipbuilding yard

Fig. 9 shows the proportion of the impact in terms of the contribution of materials and fuels consumed in the work processes and environmental emissions discharged during the work processes. The total contribution of purchased materials and energy accounts for 52% of the environmental impact, and includes up-stream processes such as production of electricity and consumption of crude

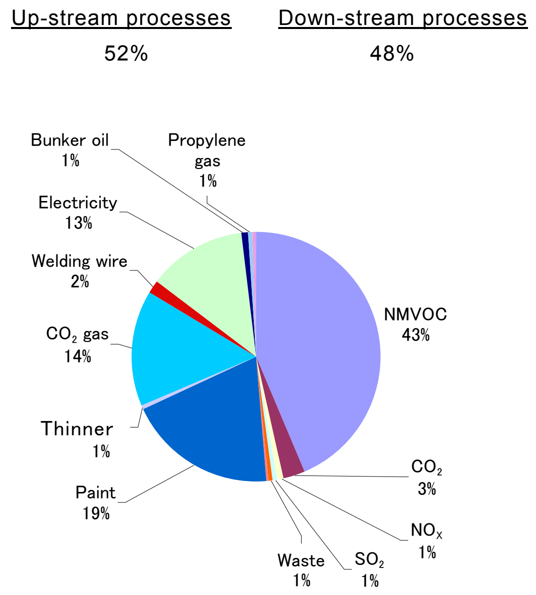


Fig.9 Effect of the purchased materials & energies and emissions directly caused by the work processes

materials. The contribution of emissions directly discharged from the work processes accounts for 48% of the impact, and includes down-stream processes such as landfill of waste.

The contribution of the painting process accounts for about 62% of the environmental impact caused by work processes at the shipbuilding yard, when production of paints and thinner emission are included as well as NMVOC.

5. Ship operation

5.1 Analysis model

The ship was assumed to periodically carry coal from Australia to Japan over a lifecycle of 25 years, where the total number of round trip voyages is 272. The cargo-loading plan for the ship model is shown in Table 3. The assumed service speeds and load factors for the main

Table 3 Navigation and cargo-loading plan

Kind of cargo	Coal
Export port	Newcastle
Export country	Australlia
Distance (nautical mile)	4,286
Stowage factor（S.F.）	40
Cargo specific gravity (t/m^3)*	0.898
Cargo weight（mt）	74,000
Load factor to DWT（%）	97
Cargo volume（m^3）	82,451
Load factor to hold capacity（%）	90.3

Note：*Apparent specific gravity (t/m^3)=35.9/S.F.

engine (M/E), diesel generator (D/G) and auxiliary boiler (BLR) are shown in Table 4. The voyage bound for Australia was assumed to be in ballast and the voyage for Japan to be fully loaded. A 75% share of the ship's life cycle was allocated to running at sea and a 25% share to cargo handling at port.

Table 4 Load factors of machinery

Condition	Running at sea		Cargo handling at port	
	Loaded	Ballasted	Loading	Unloading
Speed (knt) / Cargo handling speed (t/h)	14.5	15.2	713	786
Main engine (%)	90**	90**	0	0
Diesel generator (%kWh)*	74	74	104	104
Aux. boiler (%)	0	0	93	93

Note：*Load factor of D/G is ratio to one D/G capacity (400kW)
　** Load factor at design

5.2 System boundary for ship operation

The system boundary for the ship operation stage is shown in Fig. 10. M/E, D/G and BLR operations during running at sea and cargo handling at port are the main processes of the ship operation stage. Scheduled painting at a shipbuilding yard was considered as a maintenance process, and anti-fouling paint dissolved into the water was considered as an environmental load item contributing to eutrophication.

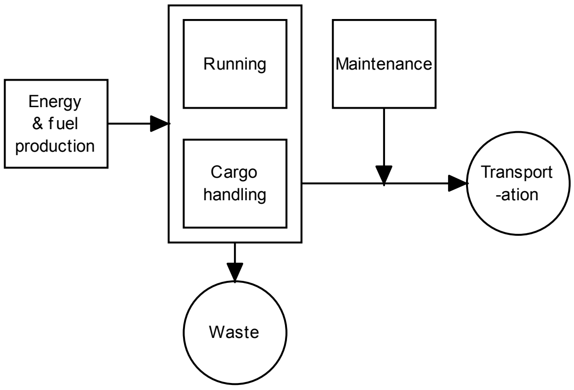


Fig.10 System boundary of ship operating

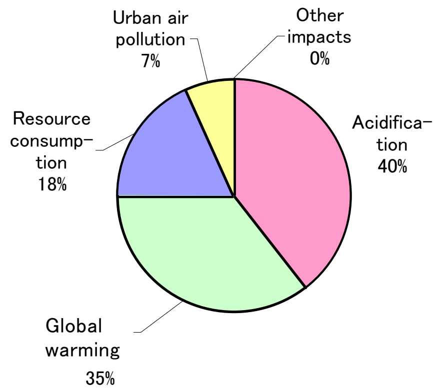
The process of cargo unloading only at ports in Japan was taken into consideration in order to evaluate the impact attributable to urban air pollution and photochemical oxidant creation. However, the use of port facilities, such as cranes, for cargo handling and the incineration of sludge for waste treatment, was not included in the process, because theses activities are done at the land and the environmental impacts caused by them are generally small.

In this analysis, emissions into the air such as leakage of refrigerant from refrigerators, NMVOC emission during fuel oil bunkering, and emissions from incinerators were not taken into consideration, because these emissions are generally small and depend on specific conditions such as ship type, ship equipment and navigation route, etc. Emissions into the sea such as electrolyzed plate for cathodic protection, oily water from oil separators and chemicals for boiler water treatment were not considered either because of the same reason mentioned above.

5.3 Results of analysis

5.3.1 Ship operation

The impact assessment analysis on the ship operation stage indicates an impact index of 4.8×10^9 yen. Fig. 11 shows the proportion of the impact index in terms of impact categories, that is, acidification, global warming, resource consumption and urban air pollution. Urban air pollution attributable to the cargo unloading process at ports in Japan corresponds to 7% of the environmental impact at the ship operation stage. Urban air pollution,



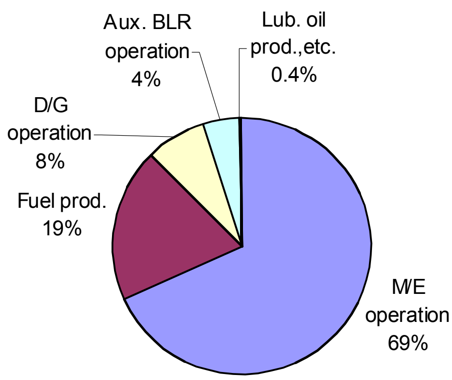


Fig.12 Ship operating processes causing environmental impact

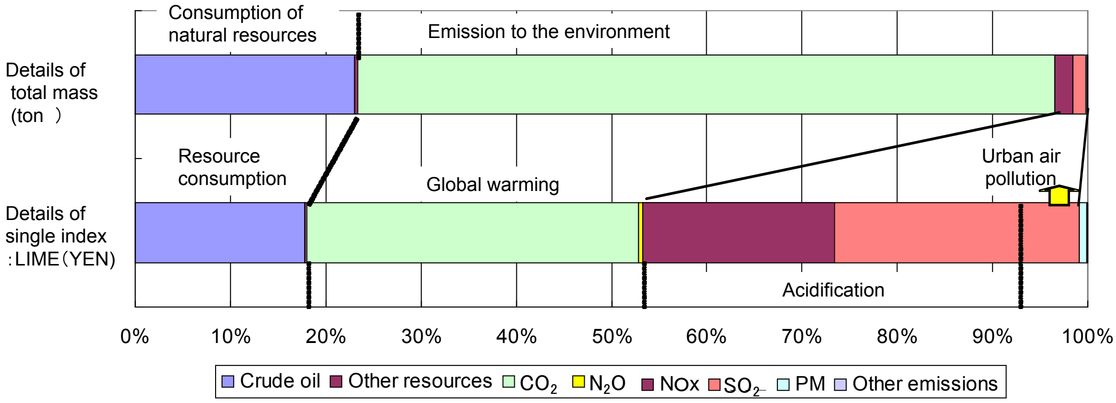


Fig.13 Effect of load items caused by ship operating.
Upper horizontal bar: share of total mass including consumption or emissions of load items
Lower horizontal bar: share of environmental impacts based on LIME

which causes such respiratory diseases as asthma, is harmful to the health of urban dwellers.

Fig. 12 illustrates the proportion of the index in terms of operation processes and indicates that the total contribution of M/E, D/G and BLR accounts for about 81%, while the production of fuels accounts for about 19% of the impact.

Fig. 13 indicates the correlation between the proportion of the impact in the LIME index and mass proportion of natural resource consumption and environmental emission at the ship operation stage. Environmental emissions have a much greater impact than consumption of natural resources such as crude oil. Emissions of NOx and SOx are very small in mass proportion, but their contribution to the environmental impact in terms of acidification is as great as that of CO_2 in global warming. PM (particulate matter) as well as SOx is emitted by D/G and BLR operation during cargo unloading and contributes to the environmental impact in terms of urban air pollution, but NOx has little impact.

5.3.2 Cargo handling at port

As indicated in the previous section, urban air pollution is 7% of the impact at the ship operation stage, which is mainly attributable to the cargo unloading process. The environmental impact caused by cargo unloading accounts for 4.1×10^8 yen and its proportion in terms of impact categories is shown in Fig. 14. The largest environmental impact is urban air pollution, which corresponds to 82% of the environmental impact caused by cargo unloading. The contribution of resource consumption is almost as much as those of global warming and acidification, but those of photochemical oxidant creation and eutrophication are very little.

Fig. 15 shows the proportion of the impact in terms of resource consumption and emissions. Contribution of SO_2 is the largest, followed by those of PM, CO_2 and NOx.

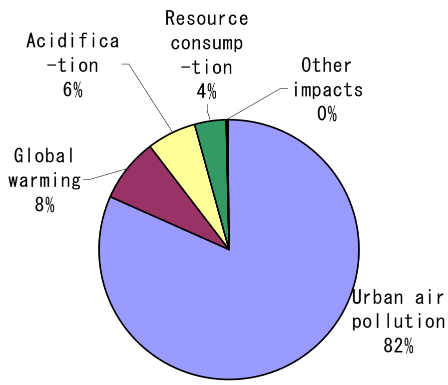


Fig.14 Environmental impact caused by cargo unloading at port

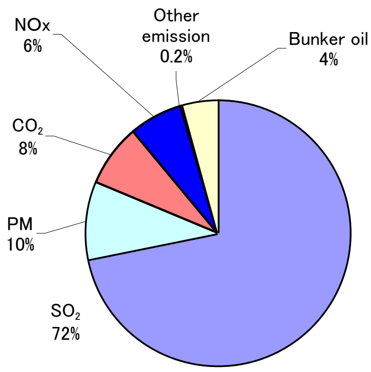


Fig.15 Effect of the fuel and emissions caused by cargo unloading at port on the environmental impacts

6. Ship dismantling & recycling

6.1 Analysis model

It was assumed that the upper part of the ship model is disassembled block by block on the water and the blocks are dismantled on land using LPG gas torches, and that the materials to be recovered and kept in the dismantling yard are steel plates, iron scrap, nonferrous metals and primary parts. The steel plates for recycling are transported to a factory by truck to be processed into steel bars used for construction, where the processes are shredding, heating and rolling and the main heating energy is subject to bunker fuel oil recovered from the ship model. Iron scrap from dismantling and recycling of the steel plates is also recovered.

6.2 System boundary for ship dismantling & recycling

The system boundary for the ship dismantling & recycling stage is shown in Fig. 16. The recycling process includes the production of steel bars, but not the recycling of iron scrap, nonferrous metals or primary parts. Waste from ship dismantling and recycling processes is assumed to be land filled without incineration. Urban air pollution was not taken into consideration in the impact categories because dismantling yards are generally not located in urban areas.

Input and output data on the dismantling & recycling processes such as cutting work and transportation was based on the data obtained by investigating the dismantling yard.[4)]

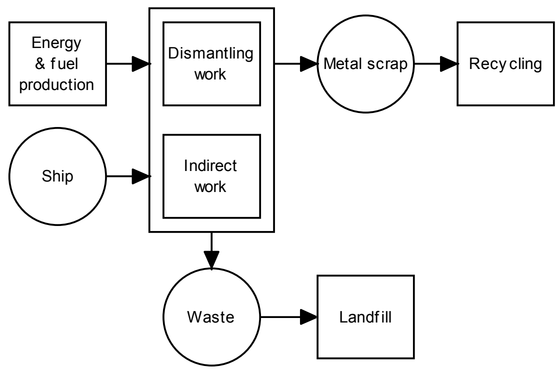


Fig.16 System boundary of ship dismantling and recycling

6.3 Results of analysis

6.3.1 Ship dismantling and recycling

The impact assessment on the ship dismantling and recycling stage indicates an impact index of 6.9×10^6 yen.

Fig. 17 shows the proportion of the impact index in terms of impact categories and indicates that resource consumption and global warming are the main impact categories at the ship dismantling & recycling stage. Fig. 18 shows the proportion of the impact in terms of the contribution of materials and energy consumption and the environmental emissions discharged in the dismantling and recycling processes. The contribution of CO_2 emission is the largest, followed by that of the consumption of bunker fuel and electricity. These contributions are subject to the consumption of LPG gas for cutting and bunker fuel for rolling in the recycling processes. The ratio of contribution for the recycling processes is about 87%, and for ship dismantling about 13%.

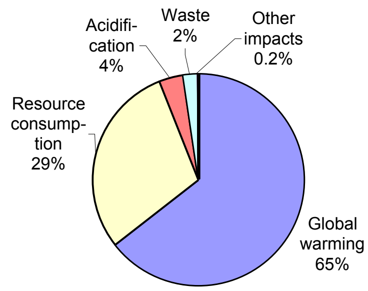


Fig.17 Impact categories caused by dismantling & recycling

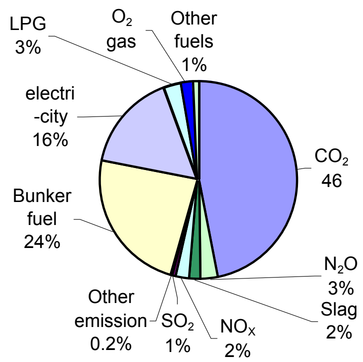


Fig.18 Effect of purchased items and emissions by ship dismantling & recycling Impact categories caused by dismantling & recycling

6.3.2 Effect of recycling

Items recovered from the dismantled ship model are shown in Table 5. When the amount of the materials listed in Table 5 is newly produced, the impact assessment analysis indicates an environmental impact of about 3.7×10^7 yen. If the amount of materials is recycled, the environmental impact is about 6.9×10^6 yen. Fig. 19 shows that the effect of ship dismantling and recycling on the environmental impact is about 3.0×10^7 yen and reduces the environmental impact by about 80%.

In the analysis, it was assumed that the recovered iron scrap is pig iron and the non-ferrous metal scrap is crude copper. The weight of the recovered D/G was also assumed to be that of iron scrap. Japanese process data[6] for the production of pig iron, crude copper and construction materials were applied.

Table 5 Recovered items from dismantled ship & recycling

Recovered item	Quantity (t)
Iron scrap from dismantling	2.5E+03
Scrap of non-ferrous materials	2.9E+01
Reuse of D/G	3.3E+01
Construction materials	6.1E+03
Iron scrap from recycling	1.3E+03

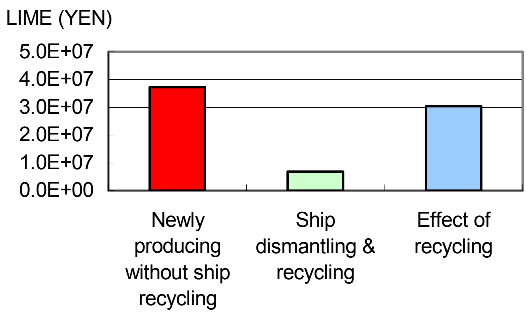


Fig.19 Effect of ship dismantling & recycling

7. Life cycle analysis

The impact assessment analysis of the ship model during its life cycle indicates an impact index of about 4.9×10^9 yen, which exceeds the delivery value of the ship model. The impact indexes for each stage are shown in Fig. 20, and the proportion of the impact index in terms of each stage is shown in Fig. 21. The contribution of ship operation over a period of 25 years accounts for about 98% of the total impact. Although the contribution of the shipbuilding stage accounts for about 1.6%, the impact can be reduced by about 60% if the recycling of materials discussed in Section 6.4.2 is taken into consideration.

Fig. 22 shows the proportion of the impact index in terms of impact categories for the ship's life cycle and reveals that acidification, global warming, resource consumption and urban air pollution are significant impact categories. The proportion of the impact categories for the ship's life cycle is almost the same as that for the ship operation stage.

8. Conclusion

The environmental impact of a ship model during its life cycle was estimated based on LIME, a comprehensive LCIA methodology. The results made it clear that almost all the environmental impact of a ship during its life cycle occurs at the operation stage and that the primary environmental impact categories are acidification, global warming, resource consumption and urban air pollution. Based on the LIME index, the results was shown that the emission of CO_2, NOx, SOx, NMVOC and PM as well as the consumption of crude oil are major environmental load items contributing to environmental impact throughout the ship's life cycle.

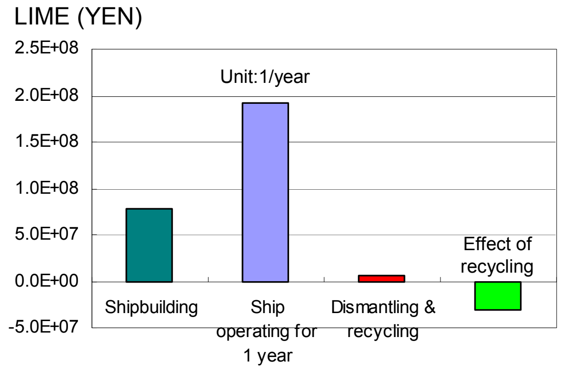


Fig.20 LIME's integrated single index for environmental impact of ship's life cycle

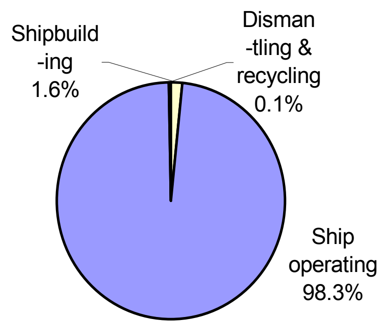


Fig.21 Stage share in the LIME's index of ship's life cycle

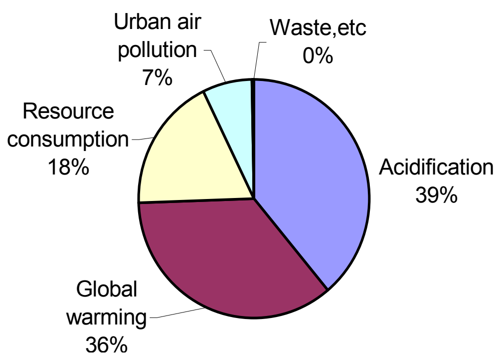


Fig.22 Impact categories share in the LIME's index of ship's life cycle

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