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Life Cycle Assessment of Port Projects -Preliminary modeling of elementary process-

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Abstract

The increasingly apparent limitations to resources and the environment demand a changeover to a recycling-oriented society with low environmental load. Infrastructure construction and port services consume large quantities of materials and energy, and efforts must be made to minimize environmental load when carrying out port projects. To realize this, appropriate environmental impact assessment methods are required through all stages of project life cycles. Moreover, it is also necessary to refine practical methods of estimating environmental load applicable to ports. This paper describes the development of a system for estimating energy consumption and CO_2 emission in projects implemented to improve container cargo transportation through ports. The numerical values and functions forming the basis for calculations are also described.

KEYWORDS: *Life Cycle Assessment, Energy Consumption, CO_2 Emission, Container Cargo Transportation*

1. Introduction

Today, as resource and environmental limitations become increasingly apparent, a changeover to a recycling-based society with low environmental load is demanded. Infrastructure construction and port services consume large quantities of materials and energy, and efforts must be made to minimize environmental load when carrying out port projects. To realize this, appropriate environmental impact assessment methods are required through all stages of project life cycles. Moreover, it is also necessary to refine practical methods of estimating environmental load applicable to port projects. Therefore, an integrated system of techniques was developed for estimating energy consumption and carbon dioxide (CO_2) emission associated with projects implemented to improve container cargo transportation through ports. Concepts for establishing the basic conditions in individual manufacturing/use processes were formulated in order to improve the system's practicality, and the numerical values and calculation methods forming the basis for calculations are developed.

The Life Cycle Assessment (LCA) technique is a representative framework for estimating and assessing environmental impacts in the processes from manufacture to end-of-life disposal of

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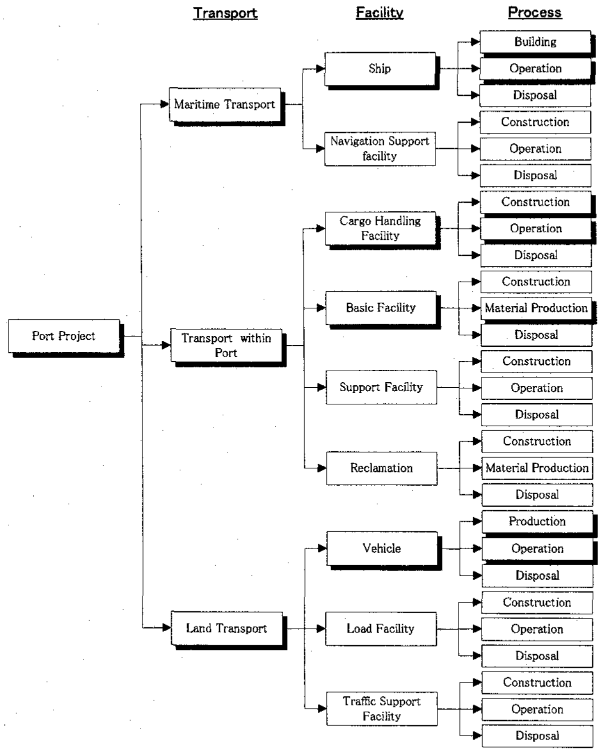
products and services. In addition to the establishment of LCA standards under the ISO (International Organization for Standardization) and JIS (Japanese Industrial Standard), a great deal of research on LCA has also been accumulated, which provided basic information for estimating the environmental load associated with port projects. When implementing LCA, extensive information and data is required on manufacturing-related fields, but it is extremely difficult to do this on an original basis. Therefore, this study aimed to develop a calculation system based on research from other fields, and to collect and organize information specifically related to port projects.

2. Basic Concepts for Estimating Environmental Impacts of Port Projects

According to ISO (1997), an LCA comprises (1) Establishment of the purposes of the LCA and the system boundaries; (2) Inventory analysis; (3) Impact assessment; and (4) Interpretation. Estimation and assessment of the total impact of environmental load over the entire life cycle of the object product or service is the basic concept of an LCA.



Note: Solid lines show ideal items of LCI analysis. Shaded boxes are objects of this research.

Figure 1 Study scope for LCI of port projects

Energy consumption and CO_2 emission are treated as objects of estimation of environmental load, because the magnitude of environmental impact can be measured by the total value of environmental load. The mechanisms whereby energy consumption and CO_2 emission impact energy resource depletion and climate change are complex, as are the societal effects of the impact. For this reason, it was considered difficult to implement impact assessment in the composition of the LCA, and therefore, the Life Cycle Inventory (LCI), which excludes impact assessment, was adopted as the scope of the study.

Here, the port projects analyzed by LCI are measures taken to improve container transportation. In maritime transportation, various navigation support facilities are necessary, including the Global Positioning System (GPS), traffic monitoring radar, lighthouses, buoys, and navigation channels. Likewise, in land transportation, trucks, road pavement, banks, slope protection, bridges, tunnels, and other infrastructure facilities, as well as ventilation facilities, drainage facilities, lighting, signs, traffic signals, control centers, and other traffic support facilities are necessary. Transportation within the port requires cargo handling equipment, yards for cargo handling, transit sheds, warehouses, and other cargo handling and storage facilities, channels, berths, breakwaters, quays, harbor roads, and other infrastructure facilities, lighting, reefer plugs, control buildings, and other auxiliary facilities, and reclamation land. All information/data on these facilities that has a high degree of specificity to ports and is considered to have a large effect on the estimation results was collected and arranged. Figure 1 shows the objects of this research.

2.1 Method of Calculating Environmental Load

The methods for calculating environmental load are principally categorized into two types: (1) the "process approach", in which all of the main manufacturing processes for the product or service are listed, the inputs/outputs in each manufacturing process are estimated, and then the environmental load is estimated from the processes; and (2) the "input/output (I/O) table approach", in which each process is assumed to correspond to a sector of the I/O table, the input/output of products or services are estimated through the table, and then the environmental load is estimated (Imura, 2001).

In the process approach, it is not realistically possible to estimate the environmental load accompanying the production from all departments. On the other hand, in the I/O table approach, there are a number of cases where it is not possible to see any difference in the elements that the user wishes to assess, because the number of production departments and product types is limited. Therefore, for a certain part, a method is adopted in which production-derived load is estimated based on specific data for the product or service, while for another part, production-derived load is estimated from a modeled inter-industry input relationship obtained from the I/O table. Then, the unit environmental load is multiplied by the result. This method is called the "hybrid approach" (Imura, 2001) and is the basis of the method proposed in this research.

2.2 Basic Transportation Conditions

In modeling container cargo transportation, the following assumptions were adopted in order to reduce the complexity of the model.

(1) The ratio of the number of 20-ft and 40-ft containers is constant in all transportation

situations.

(2) The gross weight per loaded container, empty container, loaded semi-trailer, and empty semi-trailer is constant in all situations.

3. Maritime Transportation Model

The basic concepts for constructing a model for estimating environmental load associated with maritime transportation are defined here.

In foreign trade by container cargos, the main mode of transportation is by lift on/lift off (LOLO)-type full container ships without shipboard cranes. Therefore, for foreign trade, the object of the model is transportation by this type of container ship (hereinafter simply referred to as "container ship").

For example, Figure 2 shows a case where the object port (KK) is a feeder port, and feeder transportation is performed to the main port (P). The cargo is reloaded onto an oceangoing ship at Port P. Figure 3 shows a case where Port KK is the oceangoing ship's port of call. Assuming the object cargo transportation is between Port KK and Europe, the difference in maritime transportation between the cases "with" and "without" is feeder transportation between Port KK and Port P and oceangoing ship transportation from Port P to Port K in the "without" case. In contrast, the difference in the "with" case is transportation by oceangoing ship from Port P to Port KK and from Port KK to Port K. Thus, it is possible to compare the two cases simply by calculating the differences in the "with" and "without" cases.

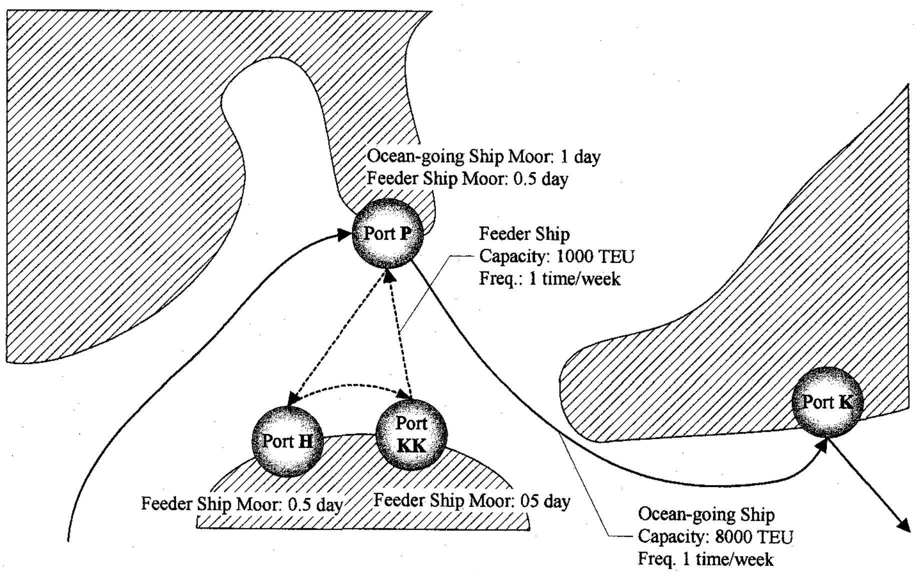


Figure 2 Schematic diagram of maritime transportation route ("without")

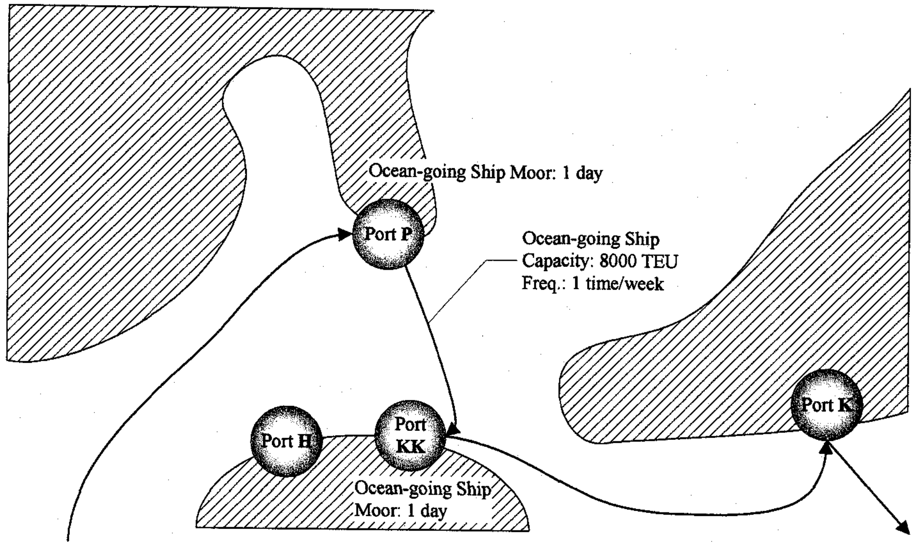


Figure 3 Schematic diagram of maritime transportation route ("with")

3.1 Ship Navigation and Mooring

Environmental load from ships is caused by power used for sailing and for onboard machinery, and general electrical power for the kitchen, lighting, etc. generated by an internal combustion engine, as well as heating for crew quarters and fuel generated by a fired boiler. If the amount of fuel consumption can be obtained, the amount of resultant energy consumption and CO_2 emission can be obtained. The fuel consumption in container ships can be broadly classified into three classes, i.e., consumption during navigation, when entering/leaving port, and while moored. For simplicity, entering/leaving port is included in navigation.

(1) During navigation

Ships convert the combustion of fuel into propulsive force and for moving the hull. Normally, wind resistance is not particularly large. Therefore, the fuel consumption per unit of time necessary to navigate the ship is proportional to the amount of work per unit of time to overcome the fluid resistance of the seawater acting on the ship. The main components of the fluid resistance of seawater are frictional resistance and wave-making resistance. Frictional resistance is proportional to the product of the cross section and the third power of the speed. Wave-making resistance is generally designed to be below a certain value; under this condition, it is roughly proportional to the product of the cross section and the third power of the speed. Ships of the same type have roughly the same hull shape; therefore, the cross section is considered to be proportional to the second/third power of the ship's displacement. Furthermore, because the ship's draft changes in cases where the load changes, the cross section is proportional to the percentage of displacement during navigation relative to displacement when fully loaded. Summarizing the above, the fuel consumption of a ship's main engine is as shown by the following equation:

$$FO_{i-j}^{s,nav} = K_{FO}^{s,nav} \cdot \left(FDT^{s,nav} - \left(1 - LF_{i-j}^{s,nav}\right) \cdot DWT^{s,nav}\right) \cdot \left(FDT^{s,nav}\right)^{-1/3} \cdot \left(V_{i-j}^{s,nav}\right)^3 \quad (1)$$

$FO^{s,nav}_{i-j}$ is the fuel oil consumption of the ship's main engine during navigation between Port i and Port j (kg/h), $K^{s,nav}_{FO}$ is the fuel consumption coefficient, $FDT^{s,nav}$ is the ship's displacement when fully loaded (t), $DWT^{s,nav}$ is the weight of the ship's full load (t), $LF^{s,nav}_{i-j}$ is the loss factor between Port i and Port j, and $V^{s,nav}_{i-j}$ is the velocity of navigation between Port i and Port j.

Assuming this equation, $K^{s,nav}_{FO}$ was obtained from actual data on container ship fuel consumption in 2003 available from shipping companies. The results are as shown in Table 1.

Table 1 Results of estimation of $K^{s,nav}_{FO}$

$K^{s,nav}_{FO}$	Fit index	N	DWT	Vs	Yb
53.4×10^{-6}	35 0.977	25	17,700 74,400 45,300 18,030	25.0 42.0 35.2 4.5	1977 2003 1992 6.76

Note 1: The fit index in the upper row is the t value; that in the lower row is the correlation coefficient of the actual results and estimation.
Note 2: N is the sample size, DWT is (t), Vs is navigation velocity (km/h), and Yb is the year built.
Note 3: In order from the top row, DWT, Vs, and Yb show the minimum, maximum, average, and standard deviation.

Fuel consumption of the auxiliary engine due to use of general electricity changes very little in relation to the size of the ship. Therefore, 2.42 kg/h is assumed based on data from shipping companies. If reefer power consumption is added to this, auxiliary engine fuel consumption is as shown by the following equation:

$$DO_{i-j}^{s,nav} = DO_{general}^{s,nav} + DO_{reefer}^{s,nav} \cdot NR_{i-j}^{s,nav} \quad (2)$$

$DO^{s,nav}_{i-j}$ is fuel (diesel oil) consumption of the auxiliary engine during navigation between Port i and Port j (kg/h), $DO^{s,nav}_{general}$ is fuel consumption for general electricity (kg/h), $DO^{s,nav}_{reefer}$ is fuel consumption for reefers (kg/h/TEU), and $NR^{s,nav}_{i-j}$ is the number of reefers carried between Port i and Port j (TEU).

(2) Mooring

During anchorage, the main engine is usually stopped and only the auxiliary engine is operated. Because fuel consumption of the boiler is extremely small, it is ignored in these calculations. From the viewpoint of auxiliary engine functions, fuel consumption is as shown by the following equation:

$$DO_j^{s,mor} = DO_{general}^{s,nav} + DO_{reefer}^{s,nav} \cdot \frac{NR_{i-j}^{s,nav} + NR_{j-k}^{s,nav}}{2} \quad (3)$$

$DO^{s,mor}_j$ is fuel consumption of the auxiliary engine while moored at Port j (kg/h), $DO^{s,nav}_{general}$ is fuel consumption for general electricity (kg/h), $DO^{s,nav}_{reefer}$ is fuel consumption for reefers (kg/h), and

$NR^{s,nav}_{i\text{-}j}$ is the number of reefers carried between Port *i* and Port *j* (TEU).

3.2 Shipbuilding

In order to obtain the energy consumption and CO_2 emission accompanying the construction of a container ship, the general ship specifications are assumed based on the following data on ships designed or planned in 2001.

Table 2 Main specifications of container ships

	Panamax type	Post Panamax type	Super Panamax type
Load capacity of container	4,000 TEU	6,600 TEU	12,000 TEU
Length x breadth	294 × 32.2 m	347 × 42.8 m	380 × 54.4 m
Full load draft	13 m	14.5 m	14.8 m
Full load displacement	78,000 t	142,800 t	207,000 t
Loading weight in tons	56,000 t	105,000 t	157,000 t

4. Land Transportation Model

Here, the basic concept is defined for constructing a model for estimating the energy consumption and CO_2 emission accompanying land transportation.

The object cargo is transported by land either from its point of origin to the loading port, or from the unloading port to its destination.

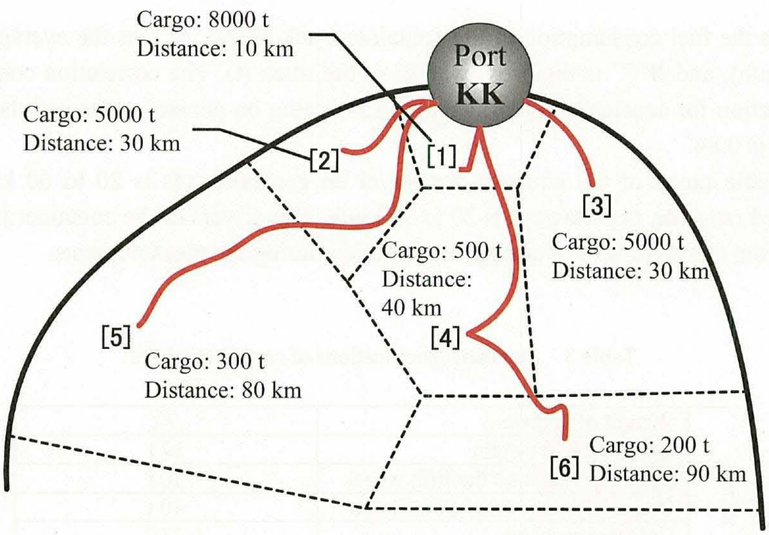


Figure 4 Schematic diagram of land transportation routes

In order to obtain the environmental load accompanying land transportation and to reduce the complexity of the model, land transportation is considered as follows: First, the region is divided into several appropriate zones, with representative points assigned to each one. Next, only one suitable transportation route is set between each representative point and the object port. All cargo generated and concentrated in each zone is considered to be transported between the object port and the representative point in the zone concerned, and furthermore, all cargo is considered to pass along the set route.

4.1 Truck Travel

To obtain estimation equations for fuel consumption of container trucks, the running speed and fuel consumption while traveling on general roads (mainly in the port zone) and expressways (Metropolitan Expressway and Joban Expressway) were measured in October 2002 and January 2003, using the Ohi Wharf on Tokyo Bay as the point of origin and destination, and fuel consumption was set as follows based on the measured values (Murano and Suzuki, 2003; Suzuki, 2004):

Travel on general roads

$$FO^{t,run} = \frac{(453\cdot e^{-0.019\cdot V^{t,run}}+98)\cdot W^{t,run}+7.9\cdot (V^{t,run})^{1.2}}{18000} \tag{4a}$$

Travel on expressways

$$FO^{t,run} = \frac{(170\cdot e^{-0.0097\cdot V^{t,run}}+98)\cdot W^{t,run}+7.9\cdot (V^{t,run})^{1.2}}{18000} \tag{4b}$$

where $FO^{t,run}$ is the fuel consumption of the container truck (*l*/km), $V^{t,run}$ is the average speed within the section (km/h), and $W^{t,run}$ is the gross weight of the truck (t). The correlation coefficient for the estimation equation for acceleration resistance when running on general roads and the energy of the consumed fuel is 0.84.

The applicable range of the equation for travel on general roads is 20 to 60 km/h, while the applicable speed range on expressways is 20 to 90 km/h. The drivers of the container trucks practiced good driving from the viewpoint of energy conservation during the measurements.

Table 3 Standard specifications of container trucks

Tractor	Weight of vehicle	7 t
	Gross vehicle weight	17 t
	Loading weight on the fifth wheel	10 t
	Connected total weight of vehicle	40 t
	Cylinder capacity	13 *l*
	Fuel	Gas oil
Semi-trailer car weight		3.7 t (40 ft) / 3.5 t (20 ft)
Container car weight		3.8 t (40 ft) / 2.3 t (20 ft)

4.2 Manufacture of Trucks

The environmental load accompanying the manufacture of trucks is estimated from the truck weight. The general container truck specifications were obtained based on automobile manufacturing company catalogues from 2003.

5. Port Model

Ports are considered to comprise facilities for breakwaters, channels, anchorages, mooring facilities, pavement, reclaimed land, and cargo handling equipment. The form of mooring facility is assumed to be a quay, and its caisson type. Quay cranes are assumed to be gantry cranes for container cargo handling, and transfer cranes are assumed for cargo handling in the yard. For the breakwaters and quays, equations are prepared for obtaining the main specifications and weight of facilities used from the water depth and design seismic coefficient. Using the material weight, it is possible to obtain the environmental load in the material manufacturing stage. Because the main materials in channels, anchorages, and reclaimed land are earth and sand, the amounts used can be easily calculated. Excluded are the environmental load during execution of construction work, to be estimated based on the main specifications of each facility, the amount of materials used, and the installation conditions of the facility. In order to estimate total environmental load accompanying operation of cargo handling equipment, the unit values of environmental load of cargo handling equipment are defined.

5.1 Breakwaters

The method of estimating the main specifications for standard breakwaters is based on data on the breakwaters designed by the District Port Construction Bureaus of the Ministry of Transport between 1991 and 2001.

The mainstream in frontline breakwaters for ports in Japan is the composite breakwater covered with wave-dissipating blocks or the upright caisson breakwater. Therefore, models are prepared assuming these structural types.

(1) Caisson height

Caisson height is proportional to the water depth at the installation position. This relationship is described by the following equation:

$$H_{caisson} = a_{00} \cdot D_{sea} \tag{5}$$

where $H_{caisson}$ is the height of the caisson (m), a_{00} is a constant, and D_{sea} is the water depth of the natural ground at the breakwater (m). Estimating a_{00} by the least squares method using this equation gives 0.826. Here, the sample size used in the estimation is 90, the multiple correlation coefficient is 0.98, and the t value of a_{00} is 49.

(2) Caisson breadth

Caisson breadth differs between the open sea and enclosed bays, but can be considered proportional to the water depth of the natural ground. This relationship is described by the following equation:

$$B_{caisson} = a_{01} \cdot D_{sea} \tag{6}$$

where $B_{caisson}$ is the breadth of the caisson (m), a_{01} is a constant, and D_{sea} is the water depth of the natural ground at the breakwater (m). Estimating a_{01} by the least squares method using this equation gives 0.889 (open sea) and 0.558 (bay). The sample sizes used in the estimation are 67 (open sea) and 15 (bay), the multiple correlation coefficients are 0.94 (open sea) and 0.96 (bay), and the t values of a_{01} are 23 (open sea) and 12 (bay).

(3) Caisson weight

Caisson weight (self-weight) differs between the open sea and enclosed bays, but can be considered proportional to the cross section of the caisson. This relationship is described by the following equation:

$$a_{02} = \frac{W_{caisson}}{H_{caisson} \cdot B_{caisson}} \tag{7}$$

where a_{02} is the ratio of the self-weight of the caisson to its cross section (t/m^2), $W_{caisson}$ is the weight of the caisson (t/m), $H_{caisson}$ is the height of the caisson (m), and $B_{caisson}$ is the breadth of the caisson (m). The average value of a_{02} is 0.600 (open sea) and 0.701 (bay). The standard deviation at this time is 0.086 (open sea) and 0.102 (bay). The sample sizes used in the estimation are 61 (open sea) and 14 (bay).

(4) Mound volume

Mound volume can be considered proportional to the power of the water depth of the natural ground. This relationship is described by the following equation:

$$\ln(V_{mound}) = a_{031} \cdot \ln(D_{sea}) + a_{032} \tag{8}$$

where V_{mound} is the volume of the mound (m^3/m), a_{031} and a_{032} are constants, and D_{sea} is the water depth of the natural ground at the breakwater (m). Estimating a_{031} and a_{032} by the least squares method using this equation gives 1.57 and 1.09, respectively. The sample size used in the estimation is 77, the multiple correlation coefficient is 0.73, and the t values of a_{031} and a_{032} are 9.3 and 2.3, respectively.

(5) Volume of wave-dissipating blocks

In virtually all of the examples collected here, wave-dissipating blocks were only used on breakwaters in the open sea. Therefore, use in the case of open sea is assumed here. The volume of wave-dissipating blocks can be considered proportional to the second power of the caisson height. This relationship is described by the following equation:

$$\ln(V_{block}) = 2 \cdot \ln(H_{caisson}) + a_{04} \tag{9}$$

where V_{block} is the volume of wave-dissipating blocks (m³), a_{04} is a constant, and $H_{caisson}$ is the height of the caisson (m). Estimating a_{04} by the least squares method using this equation gives 0.408. Here, the sample size used in the estimation is 45, the multiple correlation coefficient is 0.70, and the t value of a_{04} is 6.2.

5.2 Quays

The method of estimating the main specifications for standard quays is based on data on quays designed by the District Port Construction Bureau of the Ministry of Transport between 1991 and 2001.

The representative quay structural types are the caisson, sheet pile, and jetty type. Among these, the caisson type is introduced here. The caisson is assumed to be an *in-situ* poured RC structure, including ones in which the buttresses are not large and ones in which lightweight mixed soil, premixed treated soil, etc. are not used as backfill, with ground improvement achieved by the SCP method. The following analysis is performed per meter of quay length.

(1) Caisson height

Caisson height is generally the total of the water depth at the quay and the excess crown height above the water level. The relationship between these is expressed by the following equation:

$$H_{caisson} = a_{10} + D_{quay} \tag{10}$$

where $H_{caisson}$ is the height of the caisson (m), a_{10} is a constant, and D_{quay} is the water depth at the quay (m). Estimating a_{10} by the least squares method using this equation gives 2.16. The sample size used in the estimation is 83, the multiple correlation coefficient is 0.95, and the t value of a_{10} is 22.

(2) Caisson weight

As conditions for the sliding stability of a caisson, the frictional resistance of the caisson bottom surface, the horizontal force of the caisson during an earthquake, and the earth pressure at the back side of the caisson during an earthquake must be equal at a condition multiplied by a safety factor. The frictional resistance at the caisson bottom is proportional to the caisson gross weight. The horizontal force of the caisson during an earthquake is proportional to the product of the caisson gross weight and the design seismic coefficient.

In this case, assuming the most representative RC-type caisson, the caisson weight (self-weight) is considered to be proportional to the caisson gross weight. If the friction coefficient of concrete and ballast is 0.6 (Port and Harbor Bureau, Ministry of Land, Infrastructure and Transport, 1999), the caisson weight is:

$$W_{caisson} = a_{11} \cdot \frac{1+k_{eq}}{0.6-k_{eq}} \cdot H_{caisson}^2 \tag{11}$$

where $W_{caisson}$ is the weight of the caisson (t/m), a_{11} is a constant, k_{eq} is the design seismic coefficient, and $H_{caisson}$ is the height of the caisson (m). Estimating a_{11} by the least squares method using this equation gives 0.179. The sample size used in the estimation is 72, the multiple correlation coefficient is 0.98, and the t value of a_{11} is 40.

(3) Caisson breadth

The weight of the caisson is considered to be proportional to the cross section of the caisson. Therefore, the caisson breadth is considered to be in a proportional relationship to caisson weight/caisson height, as expressed by the following equation:

$$B_{caisson} = a_{12} \cdot W_{caisson} / H_{caisson} \tag{12}$$

where $B_{caisson}$ is the breadth of the caisson (m), a_{12} is a constant, $W_{caisson}$ is the weight of the caisson (t/m), and $H_{caisson}$ is the height of the caisson (m). Estimating a_{12} of an RC-type caisson by the least squares method using this equation gives 1.75. The sample size used in the estimation is 72, the multiple correlation coefficient is 0.98, and the t value of a_{12} is 46.

(4) Mound volume

Mound volume differs between when the water depth of the natural ground is shallower than the quay water depth and when the ground water depth is deeper.

When the water depth of the natural ground is shallower than the quay water depth, the mound is placed by digging the natural ground the minimum necessary amount from the caisson installation water depth. This case is assumed to take a value of 3.97 (mound volume, 52.8 m^3/m), which is equal to the average value obtained by logarithmic conversion of the mound volume (m^3/m). The standard deviation in this case is 0.81, and the sample size is 42.

When the natural ground is deeper, the mound volume is considered to be proportional to the power of the difference between the water depth of the natural ground and that of the quay; therefore, parameters are estimated assuming the following equation:

$$\ln(V_{mound}) = a_{131} \cdot \ln(D_{sea} - D_{quay}) + a_{132} \tag{13}$$

where V_{mound} is the volume of the mound (m^3/m), a_{131} and a_{132} are constants, D_{sea} is the water depth of the natural ground (m), and D_{quay} is the water depth of the quay (m). Estimating a_{131} and a_{132} by the least squares method using this equation gives 1.30 and 3.18, respectively. The t values of the respective estimation variables are 10 and 19. The multiple correlation coefficient is 0.95, and the sample size is 13.

5.3 Cargo Handling Equipment

A single-trolley gantry crane with wire rope hoist for container cargo handing is assumed as the quay crane. The yard cargo handling equipment is considered to comprise a transfer crane and yard trailer. For the transfer crane, RTG (rubber tire gantry) is assumed.

(1) Quay crane

Referring to several designs of quay cranes used in Japan, 3 cases, namely, the Panamax type (P type), Post Panamax type (PP type), and Super Panamax type (SP type) were arranged. In carrying out this analysis, a survey of the design specifications of quay cranes throughout Japan and of the actual cargo handling conditions were carried out in 2000 (Suzuki and Sato, 2003). Considering the knowledge obtained and the trend toward larger-scale container ships, the specifications of each size of quay crane are assumed as shown in Table 4.

Table 4 Specifications of quay cranes

Item	Type P	Type PP	Type SP
Rated load	30.5 t	40.6 t	50.0 t
Outreach	37 m	47 m	62 m
Rail span	16 m	30 m	30 m
Back reach	11 m	15 m	16 m
Hoisting height above rail	30 m	36 m	39 m
Hoisting speed	50–120 m/min	60–150 m/min	70–150 m/min
Traversing speed	150 m/min	180 m/min	210 m/min
Traveling speed	45 m/min	45 m/min	45 m/min

Note: Rated load shows the case for containers.

a) Cargo handling

Power consumption per total weight of the containers handled by P-type and PP-type quay cranes was obtained by dividing the annual power consumption of the cranes concerned by the total weight of containers handled by the cranes, using data from 2000 for No. 2 and No. 5 quay cranes at Shimizu Port Sodeshi Pier No. 1. The environmental load per weight of cargo handled was considered to be equal. As a result, power consumption per unit weight of containers handled by quay cranes was 0.462 kWh/t for the P type and 0.243 kWh/t for the PP type.

Table 5 Consumption of materials required in the manufacture of quay crane

Category	Material type	Unit	Type P	Type PP	Type SP
Structure part	Steel	t	580.9	971.5	1,284.3
Machine part	Machinery equipment	t	165.6	108.6	123.2
Electric part	Motor	t	8.0	16.5	19.0
	Controller	t	11.0	25.0	28.8
	Lighting equipment	k¥	24,620	25,817	29,690
	Cables	t	8.0	12.0	13.8
	Wiring material	t	2.0	3.0	3.5
Painting	Paint	t	10.0	11.9	15.8
Crane weight		t	670	1,060	1,400

b) Manufacture of cargo handling equipment

Material consumption by size required to manufacture one quay crane is assumed as shown in Table 5, referring to example estimates of quay cranes in 2001. Because energy consumption for maritime transportation from the works to the site varies greatly depending on the transportation distance, this item must be estimated separately.

(2) RTG

The method of cargo handling within the container terminal is assumed to be transfer crane. RTG is assumed for the transfer crane, as this type has been adopted in many terminals.

a) Cargo handling

The fuel consumption of RTG is proportional to the total weight of containers handled. This is because the largest part of the energy consumed by RTG is used in operating the spreader. Therefore, for a suitable container terminal, fuel consumption per total weight of containers handled by RTG is obtained by dividing the annual fuel consumption by the total weight of all containers handled during the year, including empty containers. According to the data for the Shimizu Port Container Terminal for 2000, fuel consumption per total weight of containers handled by RTG was 0.0967 *l*/t.

b) Manufacture

The weight of materials required to manufacture one RTG was set as shown in Table 6, referring to example estimates of RTG in 2001. The specifications assumed for these estimations are rated load: 40.6 t, lift: 23.5 m, hoisting speed: 20–50 m/min, traversing speed: 70 m/min, traveling speed: 135 m/min, and control method: inverter.

Table 6 Consumption of materials required in the manufacture of RTG

Category	Material type	Unit	Quantity
Structure part	Steel	t	55.2
Machine part	Machinery equipment	t	38.5
	Tires	t	2.6
Electric part	Motor	t	3.5
	Controller	t	4.5
	Engine	t	1.6
	Motor	t	2.2
	Lighting equipment	k¥	502
	Cables	t	2.7
	Wiring material	t	0.3
Painting	Paint	t	1.0

6. Discussion

The accuracy and practicality of estimating energy consumption and CO_2 emission accompanying the transportation of container cargos through ports can be improved. However, there are also considerable portions of this work where concepts and information/data were not set due to limitations on information and labor; these must be left to other researchers. Verification of accuracy by comparing the knowledge obtained in this research with actual cases was not done. Improvement of parameters and subsystems that are overly sensitive or lack explanatory power was not done. And, addition of important parameters and subsystems was not done. These are important tasks that must be carried out.

To directly ascertain which information/data would have a significant effect on the estimation results is difficult. For this reason, the items adopted are ones assumed to have a large effect based on empirical knowledge and related literature. Although these items constitute the scope of this research, it is possible to identify inadequacies and inappropriate arrangement/modeling by investigating the consistency between the estimated values of environmental load and actual environmental load. If these points can be found, it would then be possible to add or arrange information/data to cover inadequacies and correct inappropriate arrangement and modeling. An estimation system with a high degree of completeness can be created by repeating this process. The efforts introduced herein should be regarded as a first step in carrying out this process.

7. Summary

The concepts for setting basic conditions were defined in order to enhance the reliability and practicality of methods for estimating the environmental load, and the values forming the basis for calculations were set targeting energy consumption and CO_2 emission associated with marine transportation of container cargo. Concretely, this work included arrangement of the composition of the basic subsystems, arrangement of the concepts and representative estimation equations for modeling each subsystem and setting conditions, and collection and arrangement of basic information/data to aid in establishing the concepts and values for the explanatory variables and parameters.

The objects of the systems can be broadly divided into a maritime transportation model, land transportation model, and port model. Concepts that express the standard conditions of each, and representative values such as relational expressions, parameter values, explanatory variables, etc. were arranged.

For the maritime transportation model, concepts for setting ship navigation routes, and functions to estimate fuel consumption by ship navigation based on measured values were arranged. To obtain the environmental load during shipbuilding, the specifications and material composition of representative ships were also arranged.

For the land transportation model, methods for setting transportation distances and average travel speeds for each origin-destination (OD) cargo, and functions to estimate fuel consumption by container truck traveling based on measured values were arranged. To obtain the environmental load during the manufacture of container trucks, the specifications and material composition of representative container trucks were arranged.

In the port model, the object facilities were breakwaters, quays, quay cranes, and transfer cranes. To simplify these calculations, functions to estimate the necessary specifications of breakwaters and quays from some basic conditions were arranged based on their installation conditions. For cargo handling equipment, the material composition was arranged by size. For environmental load during operation, unit values for obtaining the environmental load from cargo handling conditions were arranged.

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