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A new life cycle impact assessment approach for buildings

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Abstract

This study examines factors resulting in an environment burden (local EB) in the region where a building is located, and suggests a method for assessing it. The environmental burden (attached EB) caused by the expansion of infrastructures, such as, roads and parking lots for supporting buildings is also considered. An integrated life cycle impact assessment approach is proposed for buildings based on social cost account, called a region-type life cycle impact assessment (R-LCIA) here, which can give not only the total environment burden on a global scale but also the environment burden in a region scale and the attached EB. Furthermore, as an example of the R-LCIA, the environmental impact of a store building is assessed, and the effects of its location, structural type, and energy system are discussed.

Keywords: Building; Life cycle impact assessment; Local environmental burden; Attached environmental burden; Social cost

1. Introduction

In the life cycle of a building, various natural resources are consumed, including energy resources, water, land, and minerals, and many kinds of pollutants are released back to the global/regional environment. These environmental inputs and outputs result in global warming, acidification, air pollution, etc., which inflict damage on human health, primary production, natural resources and biodiversity. The building sector, constituting 30–40% of the society's total energy demand and approximately 44% of the total material use as well as roughly 1/3 of the total CO_2 emission [1,2], has been identified as one of the main factors of greenhouse gas emissions. There is no doubt that reducing the environmental burden of the construction industry is indispensable to sustainable development. In particular, now that the "Kyoto Protocol" has already gone into effect, this is an urgent assignment.

Environmental life cycle assessment (LCA) can not only quantify the environmental burden (EB) caused by buildings, but can also show reduction measures. However, building LCA examples reported so far have several problems or limitations [2,3], e.g., (1) most of the LCA examples remain in the stage of inventory analysis of environmental input and output such as energy consumption amount and CO_2 emission, or the stage of characterizing EB factors such as global warming and acidification, and thus do not give a single index through an integrated impact assessment, (2) the whole EB imposed on the global environment is assessed, but the portion (local EB) imposed on the region where the building is located is not determined, (3) the EB caused by the building itself is estimated, but the EB (called attached EB in this study) associated with the infrastructures such as roads and parking lots supporting the building's functions is not considered, and (4) discussion on reducing the building's EB is mainly concentrated on the use of recycled materials, prolongation of service life, and selection of low- or non-pollution energy

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systems, etc., and does not include the effects of the location and structural form of the building, etc. These limitations result in an underestimate of the building's EB, so that insufficient information is provided for regional environment protection measures and urban planning.

This paper proposes a new LCA approach for buildings, called a region-type life cycle impact assessment (R-LCIA) in this study, which not only gives total EB on a global scale but also the EB in a region scale and attached EB. The methods for estimating local EB and attached EB caused during the life cycle of a building are first examined. An integrated impact assessment method is then given for buildings based on an end-point LCA approach and a social cost account. Finally, a case study of a building's R-LCIA is conducted to assess the EB of a store building, and the effects of its location, structural type, and energy supply on its EB are discussed.

2. Region-type life cycle impact assessment approach

2.1. Local environmental burden

During the life cycle of a building, part of the resource input is directly from the region where it is located, and a proportion of the pollutants are directly released back to the same region. The environmental burden resulting from a building can be classified into two parts, inside and outside the region. The former is called a local environmental burden. Most of the concrete measures to preserve the regional environmental are planned and taken by local governments. Thus, the building's LCA should also clarify the local environmental burden, and not only the total EB. Here, the region refers to the range of a municipality such as city, town, or village.

The processes producing a local EB are considered to include transportation of materials, production of building materials in the region, operation of construction machines, fossil fuels consumption during the building's service phase, collection and treatment of solid wastes and sewage, and consumption of exhaustible resource acquired from region. The resource input and pollutant output in these processes will result in a local EB. To estimate the pollutant output directly released to the region, a database of local emission intensity is necessary for production of various building materials, vehicle traveling, waste disposal, and consumption of fossil fuels. Energy input and consumption of purchased electricity are not considered to result in a local EB because energy sources such as oil and coal are not obtained from urban areas, although they are exhaustible ones, and purchased electricity is generally generated away from urban areas. Of course, if the building taken as the object of study is located within or near a mine site or power plant, the local EB caused by the energy input and consumption of electricity should be considered.

Local emission intensity data have been obtained for production of some materials from actual surveys [4] and using a "Bottom up Method" based on energy input [5], as shown in Table 1. Local emission intensities of fossil fuel consumption during a building's operation service phase, operation of construction machines, traveling of various vehicles, and treatment of wastes and sewage have also been estimated [6]. Using the local emission intensity data, the local environmental burden caused during the building's life cycle can be assessed.

2.2. Attached environmental burden

To construct a building and to support its functions, a building site needs to be prepared, and infrastructure facilities around it such as roads and parking lots need to be constructed and maintained. Moreover, accessing the building by car will result in an increase in traffic on surrounding roads. The environmental burden caused by the necessary infrastructure facilities and traveling of vehicles is relevant to the building, and is called attached environmental burden (EB_a) in this study. The magnitude of the EB_a depends on the building's use, location, scale, etc. From a systematic standpoint, it should be considered that the EB_a is caused during the life cycle of the building. Thus, when assessing the EB of a building and determining how to reduce it, the EB_a should be seriously noted, especially for large-scale buildings.

Table 1
Local emission intensities of some building materials

Building material	CO_2 (g)	SO_x (g)	NO_x(g)	SPM (g)	COD (g)	T-N (g)	T-P (g)	Solid waste (g)
Crushed gravel (kg)	3.51	1.78E − 4	1.10E − 3	2.44E − 3	7.4E − 4	6.70E − 4	8.00E − 5	3.39
Portland cement (kg)	3.35E + 2	0.102	1.50	4.00E − 2	0.227	8.1E − 2	9.90E − 2	−1.49E + 2
Blast furnace slag B type cement (kg)	2.02E + 2	0.067	8.75E − 1	2.4E − 2	0.217	7.80E − 2	9.50E − 2	−4.99E + 2
Fly ash B type cement (kg)	2.77E + 2	0.085	1.23	3.30E − 2	0.230	8.20E − 2	1.01E − 1	−2.93E + 2
Ready-mix concrete (m^3)	1.41E + 4	4.41E − 1	9.20	9.31	0.183	1.22E − 1	1.19E − 1	4.00E + 3
PC pile (kg)	3.81E + 1	1.08E − 1	1.09E − 1	3.61E − 2	0.486	2.93E − 1	2.69E − 1	6.93E − 1
PC product (kg)	3.05E − 2	6.52E − 2	2.52E − 2	1.50E − 2	0.891	5.39E − 1	4.93E − 1	1.27

Table 2
Considered infrastructure facilities causing EB_a and scope to be evaluated

Infrastructure facility	Evaluated scope		
	Construction stage	Service stage	Demolition and disposal stage
Formation of building site (including regulating pond ages)	○	×	×
Road (including traveling of vehicles)	○	○	×
Green land, park, parking lot, square	○	○	×

Note: Evaluated service term of facility is the same to that of building.

Infrastructures resulting in an attached environmental burden of a building and the evaluated scope of each facility are shown in Table 2. In this study, only newly constructed infrastructure facilities and increase in traffic on main roads for accessing the building are taken as objects of EB_a evaluation. The evaluated service period of the infrastructure facilities is set to the same as that of the building they support. Furthermore, the EB_a caused by the infrastructure facilities in the abandoned stage is not considered.

If more than one building is served by an infrastructure facility such as a park, the EB_a caused by this facility is allocated among the buildings according to the numbers of people using them. The EB_a associated with access to the building by vehicles is evaluated from the traveling distances and the traffic on main access roads. The traveling distances should be determined from traffic surveys or predictions, but for convenience, the lengths of main access roads within a radius of 500 m from the edges of parking lots are considered to be the traveling distances of vehicles accessing the building, referencing to the set-up of the geographic range for estimating benefits of regional development [7]. The EB_a is also classified into the local portion and the outside-regional portion.

2.3. Integrated impact assessment method

The life cycle inventory (LCI) can quantify the requirements of energy and raw materials taken from the environment, and the output released back into the environment throughout the life cycle of building. However, in most cases, based only on separate LCI results, it is difficult to make an EB comparison between different buildings, and to understand the impacts on the environment. A comprehensive impact assessment is therefore necessary to translate inventory data to damage to safeguard subjects of human health, public assets, biodiversity, and primary productivity, and further express all the damage with a single EB indicator.

The LCA National Project [5] suggested a Japanese version of the damage-oriented life cycle impact assessment method, named LIME. In this project, a link was first established from EB substances such as CO_2 to environmental impact categories such as global warming, in addition to the safeguard subjects. Then, external diseconomy resulting from damage caused by EB substances to the safeguarded subjects were estimated through a conjoint analysis, which was used to estimate how much people would be willing to pay to preserve the safeguarded subjects. The relative importance of each of the safeguard subjects is clarified. Furthermore, after estimating the contributions of each of the EB substances or factors to the damage to the safeguarded subjects, social costs embedded per unit of various EB substances or factors were measured to clarify their integrated assessment coefficients.

Based on the integrated assessment coefficients of various EB substances or factors, i.e. social cost intensities, integrated impact assessment can be conducted after doing an inventory analysis. Social cost intensities of a proportion of EB substances are shown in Table 3. Social cost intensities of SO_x and NO_x differ among areas that have different population densities (e.g. in urban or suburb), from which they are emitted, and release forms whether spot emissions such as, at construction sites or linear emissions. SO_x and NO_x emissions along the road from traffic are considered to be linear emissions. The life cycle inventory based on currently existing emission intensity databases of materials, processes and energy only gives the SO_x emission, but since nearly all the SO_x is SO_2, the social cost intensity of SO_2 is employed to comprehensively assess the environmental impact of SO_x.

3. Case study of region-type LCIA for store building

3.1. Summary of building of accessed object

Fig. 1 is a rough sketch of a provisional plan for regional development. Stores, a hotel, a hospital and condominiums are constructed in this area of Taki town, Mie prefecture. To construct and use these buildings, building sites are prepared, and green lands, one park, one plaza, parking lots, and roads must be constructed together [6]. The scales of the planned

Table 3
Integrated assessment coefficients (social cost intensities) of EB substances and factors

Factor category	Atmospheric emissions						Waterborne releases					Resource consumption				
EB substance or factor	CO_2 (kg)	SO_2[a] (g)	NO_x (g)[b]		CH_4 (g)	N_2O (g)	SPM 2.5 (g)		COD (g)	T-N (g)	T-P (g)	Oil (g)	Coal (g)	Natural gas (g)	U (g)	Limestone or land gravel (g)
			Spot	Linear			Spot	Linear								
Social cost intensity (Yen)	1.62	1.17	2.47E − 01	6.31E − 01	3.73E − 02	4.80E − 01	2.69E − 01	1.04	6.40E − 04	8.25E − 02	9.74E − 01	1.65E − 03	4.54E − 04	1.29E − 03	1.16	20.8
EB factor category	Geo-environmental release (kg)					Land use (m^2)										
EB substance or factor	Ordinary waste	Slag	Wood chip	Wasted plastics	Sludge	Road construction	Mining of rock or soil	Final landfill construction	Urban development							
Social cost intensity (Yen)	0.396	0.201	0.554	1.29	0.388	651	163	976	163							

[a] Position-fixed emission in urban area, and sum of social costs caused by primary and secondary impacts.

[b] Sum of social costs caused by primary and secondary impacts on urban atmosphere; SPM: suspended particulate matter; COD: chemical oxygen demand; T-N: total nitrogen, T-P: total phosphorus, and U: Uranium.

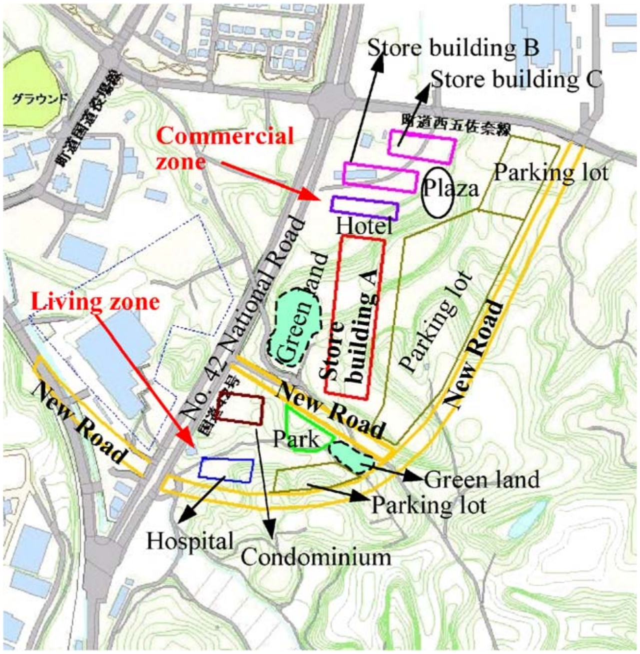

Fig. 1. Normal plan of regional development.

buildings and infrastructure facilities are shown in Table 4. It is estimated that the stores may draw 10,070 and 16,100 customers on weekdays and holidays, respectively, and shopping traffic on the newly constructed roads will be 2,149,150 cars per year. The condominiums are planned for 54 tenants.

As an example of the R-LCIA, store building A is taken as an object of R-LCIA, and its environmental burdens including whole value, local EB, and attached EB are estimated, and for comparing the variations in EB of the building caused by changes of location, structural form, and energy supply, two other scenarios are assumed by the author, as shown in Table 5 (assuming that smooth flow of traffic and geographic conditions are possible). In Case 3, the parking lots border on the No. 42 national road (Fig. 2), so the length of new roads that need to be constructed is greatly reduced, from 1000 to 200 m.

3.2. Life cycle inventory analysis

The life cycle inventory boundary is shown in Fig. 3, for estimating the direct EB of store building A itself and the attached EB of the infrastructure facilities. The considered EB substances include energy consumption and air emissions (CO_2, SO_x, and NO_x). The assessment term of the building's EB is set to 35 years.

Transport distances of materials and solid wastes are shown in Table 6 [6]. Since read-mixed concrete and macadam aggregate are available from the region, the local emissions associated with the production of these materials result in a local environmental burden.

Table 4
Outline of regional development

Building and infrastructure facility		Building area (m^2)	Total floor area (m^2)	Structural form
Store	Building A	9000	15000 (Store area: 12000)	Steel structure (Two-stores above ground)
	Building B	2000	2000	Steel structure (one-story)
	Building C	1800	1800	Steel structure (one-story)
	Parking lot	26700 on the ground and 3300 on the roof of building A		
Hotel	Building	600	2300	Steel structure (Four-stores above ground)
	Parking lot		1000 on the ground	
Hospital	Building	700	—	—
	Parking lot		1000 on the ground	
Condominiums	Buildings	900	2700	Reinforced concrete (Three-stores above ground)
	Parking lot		1400 on the ground	
Park (living zone)			2300	
New constructed blacktop road			1100	
Green land	Commercial zone		16600	
	Living zone		11900	

Table 5
Conditions of store building A and related infrastructure facilities in each case

Case 1 (Normal plan)	• Steel structure, and ordinary energy system. • One parking lot on roof of store building A. • Locations of buildings and infrastructure facilities as shown in Fig. 1.
Case 2	• Photovoltaic energy system to provide part of the energy required. • Parking lot on roof of store building A in Case 1 is built on ground. • RC structure. • Locations of buildings and infrastructure facilities as shown in Fig. 1.
Case 3	• Steel structure, and ordinary energy system. • One parking lot on roof of store building A. • Locations of buildings and infrastructure facilities are as shown in Fig. 2.

3.2.1. LCI of building itself

Kinds and amounts of materials needed to construct store building A are determined by referring to another store building that has the same scale and structural form. Energy consumption and discharges of various solid wastes in its operation service stage refer to the survey values [8,9], and the amount of solid wastes discharged during the construction and demolition stages are the values investigated by the Building Contractors Society [10]. The total EB caused by store building A from the construction stage to the demolition stage is assessed by using an LCA program developed by the Architecture Institute of Japan (AIJ). The EB caused by disposing of the solid wastes discharged in the service and demolition stages are calculated from the intensity data of energy input and air emissions [6]. In Case 2, the photovoltaic energy system produces 121.2 kWh/yr.m^2 of the electricity and supplies 278.7 MJ/yr.m^2 of heat energy to the hot-water system. Fig. 4 shows all the energy input and air emissions in global-scale during the life cycle of store building A in three cases.

As shown in Fig. 4, the energy consumption and air emissions during the operation service stage are much higher than in the other two stages. Change of building location does not yield any effect on the EB of the building itself, but an RC structure results in more EB than a steel structure in the construction and demolition stages because of the use and disposal of a lot of concrete. The introduction of a photovoltaic energy system greatly reduces the energy input and air emissions in the building's service stage.

Air emissions in the region, i.e. local air emissions, caused by production of materials used in the building, operation of construction machines, transport of materials and wastes, and fuel consumption in the service stage, are estimated as shown in Fig. 5. Local air emissions during the construction stage are the least of the three stages in any case. However, the local emissions in the demolition stage are greater, contrary to the trend of the total air emissions shown in Fig. 4. This is because the machines used to pull down the building and dispose of the discharged solid wastes release a lot of air emissions. In particular, in Case 2, dismantling an RC structure and crushing waste concrete need much machine input, and thus result in the largest local air emissions. Moreover, in Case 2, the concrete is produced in the region, so local air emissions in the construction stage are the most of the three cases. However, in the service stage, the local emissions of Case 2 decrease due to the use of photovoltaic energy. Thus, to reduce the local EB of building, it is necessary to select an adequate structural form and energy system, and to adopt waste disposal methods resulting in lower EB.

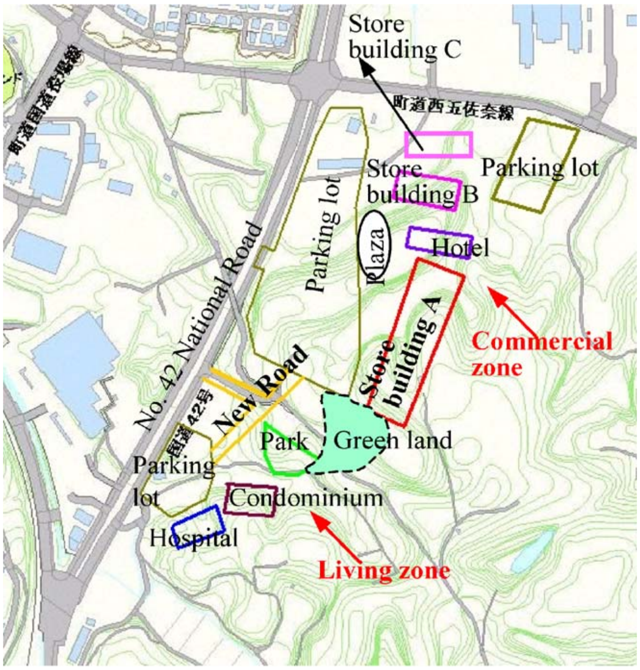

Fig. 2. Assumed alternative regional development plan.

3.2.2. LCI of infrastructure facilities supporting the building

Air emissions resulting from preparation of construction sites and construction of the park, parking lots, and greed lands and roads, as shown in Fig. 1 or Fig. 2, have been already estimated [6]. The energy input is obtained according to the database of the LCA program developed by the AIJ. It is assumed that the air emissions and energy input per year caused by maintenance in the service stage of these facilities are 3 percent of that in the construction stage. The EB caused by construction and maintenance of parking lots on the ground and greed land in the commercial zone is allocated to the three store buildings based on their floor areas, and the EB caused by the preparation of the construction sites of store building A and the allocated infrastructure facilities is obtained from the ratio of their occupation area to the total land development area. Since the number of people going to and from the condominiums, hospital and hotel is much smaller than those accessing the store, all the EB caused by construction, maintenance, and service (vehicle traveling) of the road is allocated to the three store buildings according to their areas.

Table 6
Transportation distances of construction materials and solid waste

Material or waste	Distances (km)
Read-mixed concrete	8.7
Asphalt mixtures	11.4
Roadbed materials	4.5
Rental construction machines	2.6
Concrete products	11.7
Steel materials	14.7
Other construction materials	10.8
Wasted concrete and asphalt lump	4.5

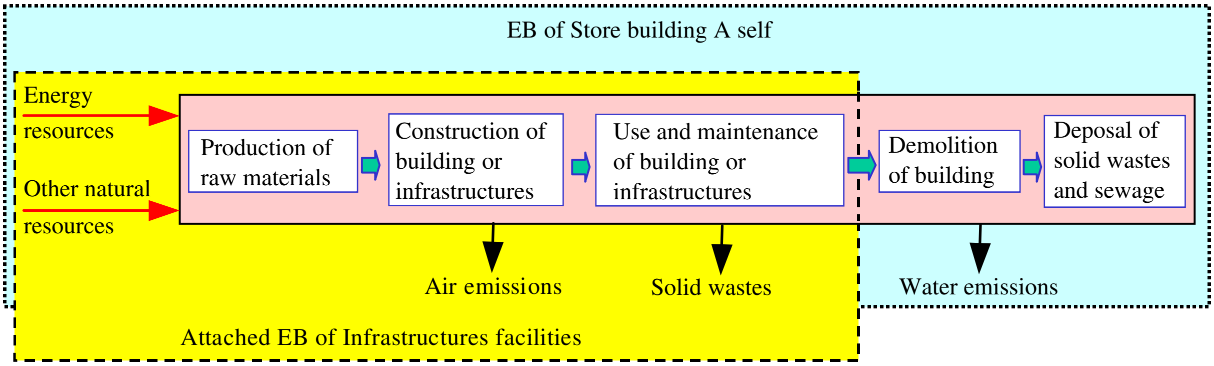

Fig. 3. Life cycle inventory system boundary of store building A.

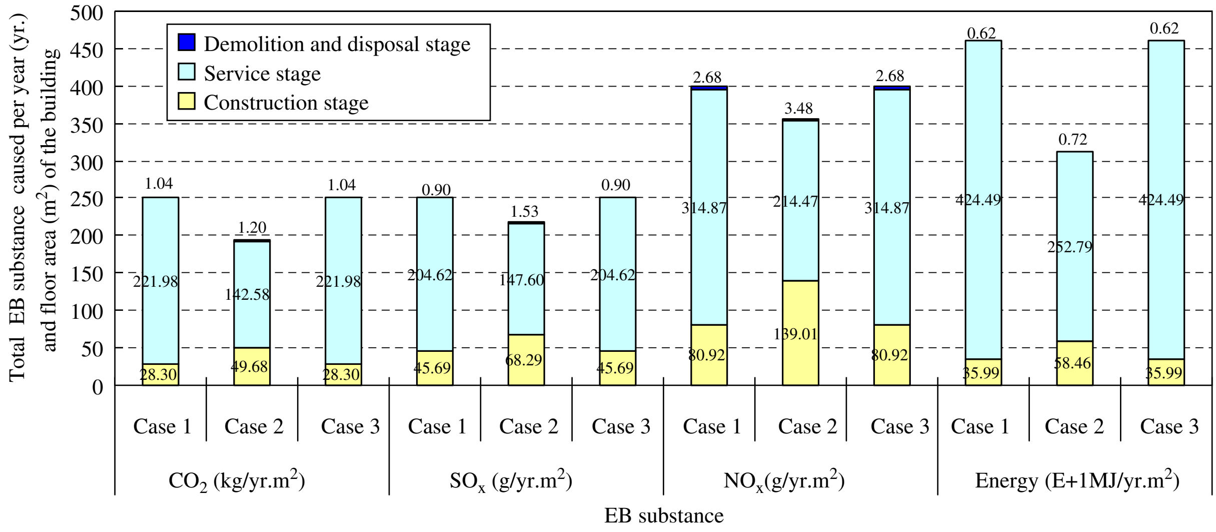

Fig. 4. Total energy input and pollutant releases during life cycle of store building A.

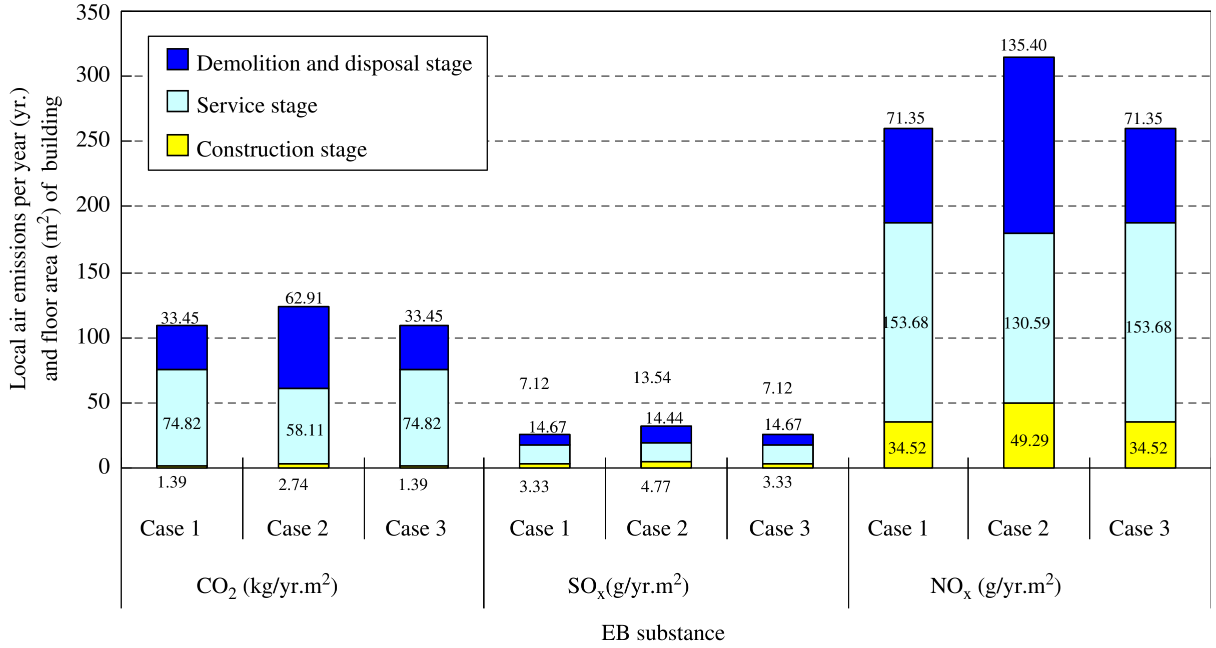

Fig. 5. Local air emission during life cycle of store building A.

All the energy input and air emissions on a global scale resulting from the life cycle of the infrastructure facilities supporting store building A are shown in Fig. 6. The input and output in the service stage are greater than those in the construction stage, and this trend is the same as that of the building. Since the construction of parking lots on the ground is increased, the EB in the construction stage in Case 2 is greater than that in Case 1. In Case 3, the length of the newly constructed road decreases, so the EB from the road construction is greatly reduced. However, the EBs in the service stage are the same for the three cases because the traffic and vehicle traveling distances are not changed.

The local proportion of air emissions due to material production and transport, operation of construction machines, and car traveling are shown in Fig. 7. The local air emissions in the service stage are obviously greater than those in the construction stage, and do not vary among the three cases because the traffic and vehicle traveling distances are the same. In Case 3, because the newly constructed road is shorter, the local air emissions are smaller than those in the other two cases. However, in the construction stage, operation of

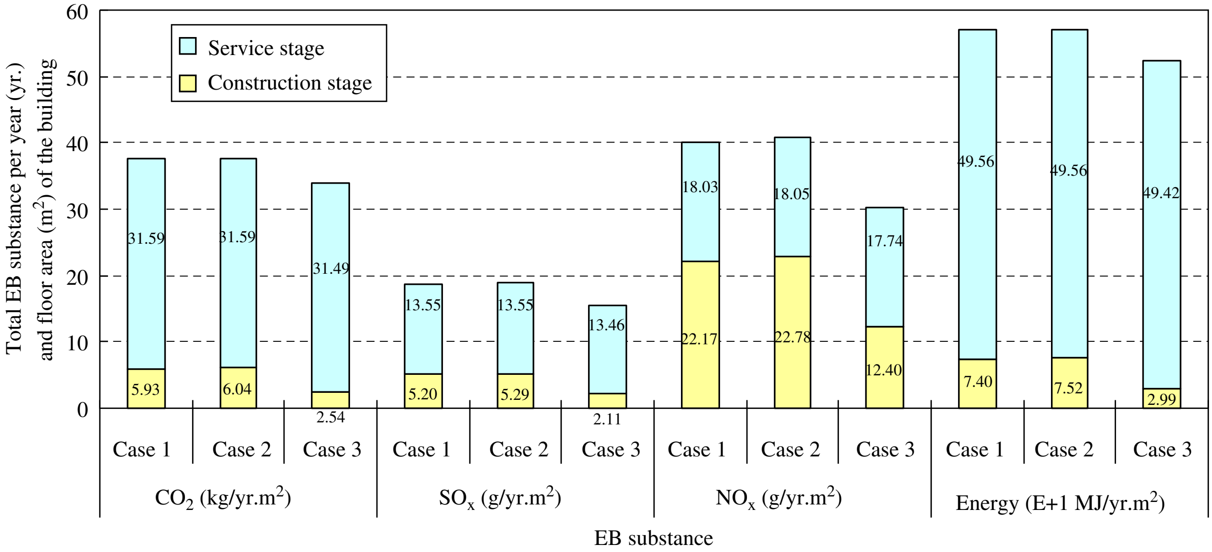

Fig. 6. Total energy input and pollutant releases in life cycle of infrastructure facilities.

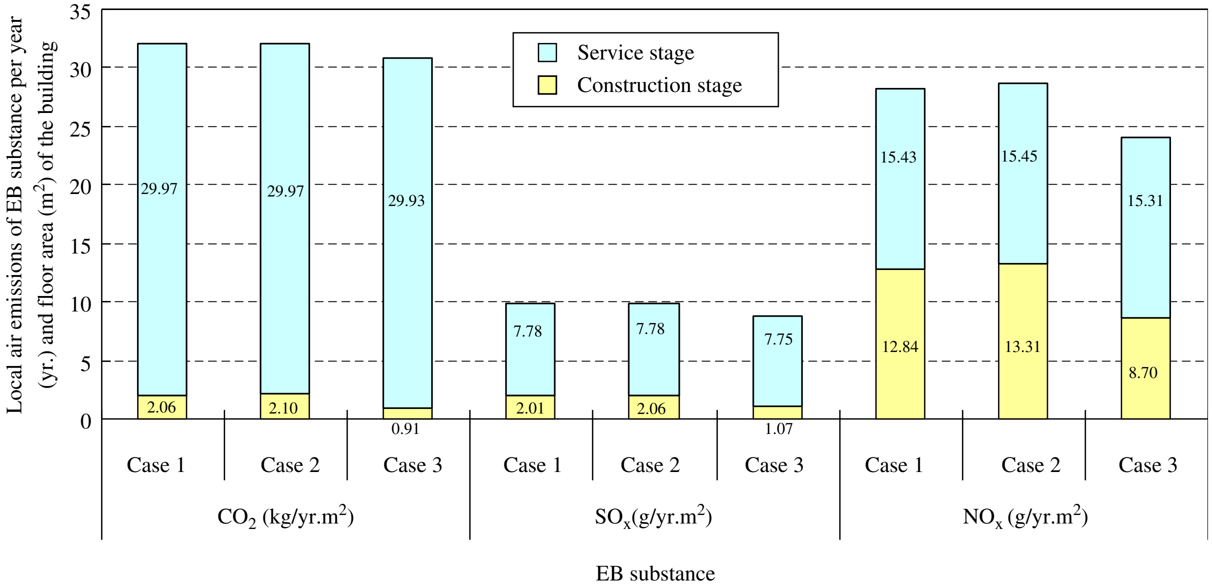

Fig. 7. Local air emissions in life cycle of infrastructure facilities supporting store building A.

construction machines and production of concrete and macadam results in large local NO_x emissions in all three cases.

3.3. Integrated environmental burden indicator

To compare the environmental impacts of the three cases, integrated impact assessments are conducted using the integrated assessment coefficients of EB substances shown in Table 3. According to the structure of energy consumption in Japan (oil: 49%, coal: 22%, natural gas: 14%, and uranium: 10%), consumption of oil, coal, natural gas, and uranium ore is estimated on the basis of the energy input obtained by the LCI. Moreover, NO_x and SO_x emissions associated with the transport of construction materials and solid wastes during the building's life cycle and in the construction stage of the infrastructure facilities are smaller. Thus, when conducting the impact assessment, NO_x and SO_x emissions are not classified into spot emissions and linear ones, spot-type integrating assessment coefficients of NO_x and SO_x are used. However, when comprehensively assessing the impacts of NO_x emitted from cars traveling in the service stage of roads, a linear type of integrated assessment coefficient is employed.

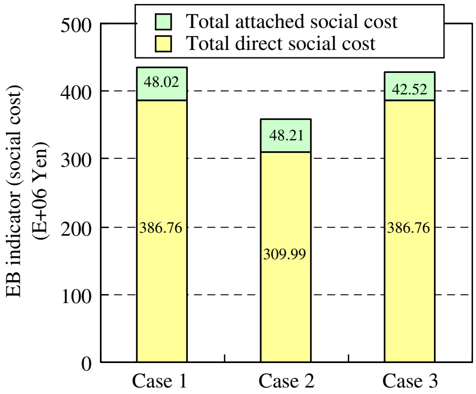

Fig. 8. EB indicator (direct and attached social cost) of store building A.

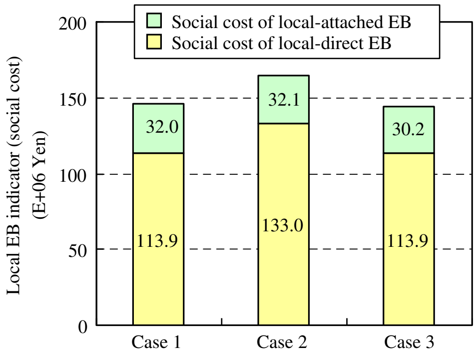

Fig. 9. Local EB indicator (direct and attached social costs) of store building A.

Fig. 8 shows the total EB indicator of store building A expressed in the form of social cost. This indicator is composed of two potions: direct social cost of the building itself and attached social cost caused by the infrastructure facilities. Because of the introduction of a photovoltaic energy system, the total EB indicator of the building greatly decreases (Case 2), and the change of building location causes a decrease in attached social cost (Case 3). The attached social cost accounts for more than 10% of the total, so it is important to reduce the attached EB through adequate building and urban planning.

Fig. 9 indicates the local environmental burden indicator of store building A. Traffic, which is the main factor in local-attached EB, is the same in the three cases. Thus, the social cost caused by the local-attached EB is nearly the same. The use of photovoltaic energy reduces the EB in the building's service stage, but since a lot of local EB is caused in the demolition and disposal stages in demolishing the RC building and crushing waste concrete, the local EB indicator of Case 2 is greater than those of the other two cases. The social cost of the local-attached EB accounts for more than 17% of the total local social cost, so reducing the local-attached EB is obviously important for regional environment preservation.

4. Conclusions

This study proposed a region-type life cycle impact assessment (R-LCIA) approach for buildings, and examined methods of assessing local environmental burden and attached environmental burden of building, as well as suggested an integrated impact assessment method that is an endpoint LCA approach based on social cost account. Moreover, as an example of R-LICA, the environmental burden of a store building was assessed, and the effects of location, structural form, and energy system were discussed.

Operation of construction machines, vehicle traveling, and disposal of wastes are main factors of local environmental burden. Reducing emissions from construction machinery is very important in lightening a building's local environmental burden. The attached environmental burden caused by infrastructures supporting the building is great for large-scale buildings. It is thus necessary to reduce it through adequate building and urban planning. Assessment of the attached EB is useful in selecting a building location and the planning of regional development.

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