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LIME2

Life-cycle Impact assessment Method based on Endpoint modeling

Chapter 1 – Outline of LIME2

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Life-cycle Impact assessment Method based on Endpoint modeling

Outline of LIME2

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Outline of LIME2

1.1 Characteristics of LIME2

1.1.1 Issues in LIME1

LIME was developed as an LCIA method that reflects environmental and social conditions in Japan. Since the publication of this method, many domestic companies have used LIME for the environmental assessment of their products and businesses. LIME has been used not only for LCA but also for environmental accounting, environmental efficiency, assessment of corporate environmental performance, and other fields.

Although the use of LIME has been spreading in this way, problems to be corrected from various viewpoints have been clarified. Among them, the issues to be solved especially urgently are as follows:

1) It is difficult to use LIME1 directly for internal decision-making.

Although LCIA has so far been able to show assessment results by representative values, LCIA provides no information about the reliability of assessment results. Although assessment results expressed by representative values can be used for external disclosure of the environmental performance of products, it cannot be said that they are sufficient information for in-house important decision-making on plans and process changes.

2) weightomg factors of LIME1 does not reflect the Japanese people’s views on the environment.

In LIME1, the base data for the calculation of weighting factors were obtained from the results of interview surveys conducted with about 400 people. However, because the sampling was limited to the Kanto Region, such as Tokyo, the obtained factors could not be said to reflect all of Japan’s representative views on the environment. Therefore, it was necessary to obtain weighting factors that could be used for general purposes in Japan.

3) Measures against sick house syndrome and noise could not be assessed appropriately.

The number of people who suffer sick house syndrome is estimated to be more than one million. The environmental standards for noise are not fulfilled at about 30% of the target points, and more than 10,000 complaints have been filed every year. To solve such serious environmental problems, products have been vigorously developed for measures against sick house syndrome and noise. However, if their impact is not assessed during LIME, it is impossible to clarify the products’ effect of reducing the environmental impact.

1.1.2 Development objectives of LIME2

LIME2 was developed to solve the above-described issues. Research and development was carried out in the second-term LCA National project (the Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization (NETO), 2003 to March 2007). Four committees were established for this project (see Figure 1.1-1), LIME2 was developed by the Impact Assessment Study Group, which concretely discussed the following matters:

1) Analysis of the uncertainty and sensibility of damage factors and integration factors

2) Development of weighting factors that reflect the Japanese people's views on the environment

3) Development of environmental impact assessment methods for indoor air contamination and noise

Below, the outline of each issue is explained.

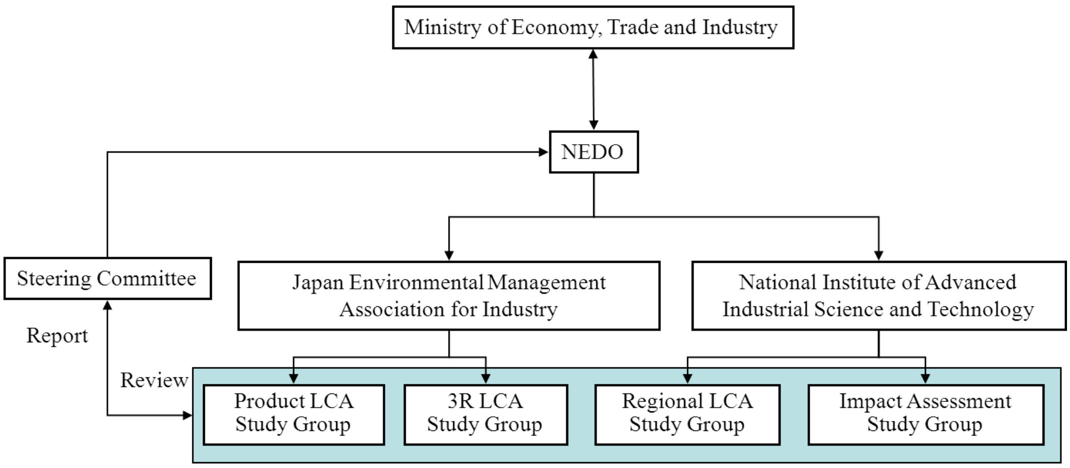


Figure 1.1-1: Structure of organizations for the second-term LCA Project

(1) Analysis of the uncertainty and sensibility of damage factors and integration factors

The list of factors for impact assessment obtained through the development of LIME only contains representative values. It contains no information about the degree of reliability of those factors. If the LCIA method can be used, including information about uncertainty, it is possible to know the reliability of the conclusion based on the LCA result. Therefore, the factors will become important referential information when the practitioner makes a decision.

In addition, ISO14044 demands the reflection of the result of uncertainty analysis when sensibility and integrity for life cycle interpretation are inspected. There have so far been an extremely small number of cases where analysis was made with consideration for the uncertainty of the LCIA method in the LCA case studies.

With regard to LCA research, since the 1990s discussions have been held about uncertainty analysis, including life cycle inventory (LCI). After attention was paid to damage factors, which introduced many parameters and models, and integration factors, discussions about uncertainty in particular have become vigorous. On the other hand, even if the number of parameters or models is large, because only a few of them have especially important influence on the reliability of calculation results, it can be expected that adequately reliable factors will be provided if the accuracy of such parameters and models can be improved.

Therefore, in LIME2, analysis and assessment will be conducted about the uncertainty about main damage factors and integration factors. Figure 1.1-2 shows the procedure in this research. First, probability distribution is set for the models and parameters used for the calculation of damage factors, and then uncertainty analysis of the damage factors is conducted through simulation by the use of the models and parameters. Moreover, sensibility analysis is conducted to pick out the parameter that has especially strong impact on the uncertainty of the damage factors. Reexamination is carried out, centering on the parameter. With the reflection of the result, the probability distribution is redefined and uncertainty analysis is conducted again. Such analysis and examination are repeated several times to improve the reliability of the factors effectively. The final purpose is to create a list of damage factors and integration factors, including not only representative values but also such statistical values as standard deviation and variation coefficients.

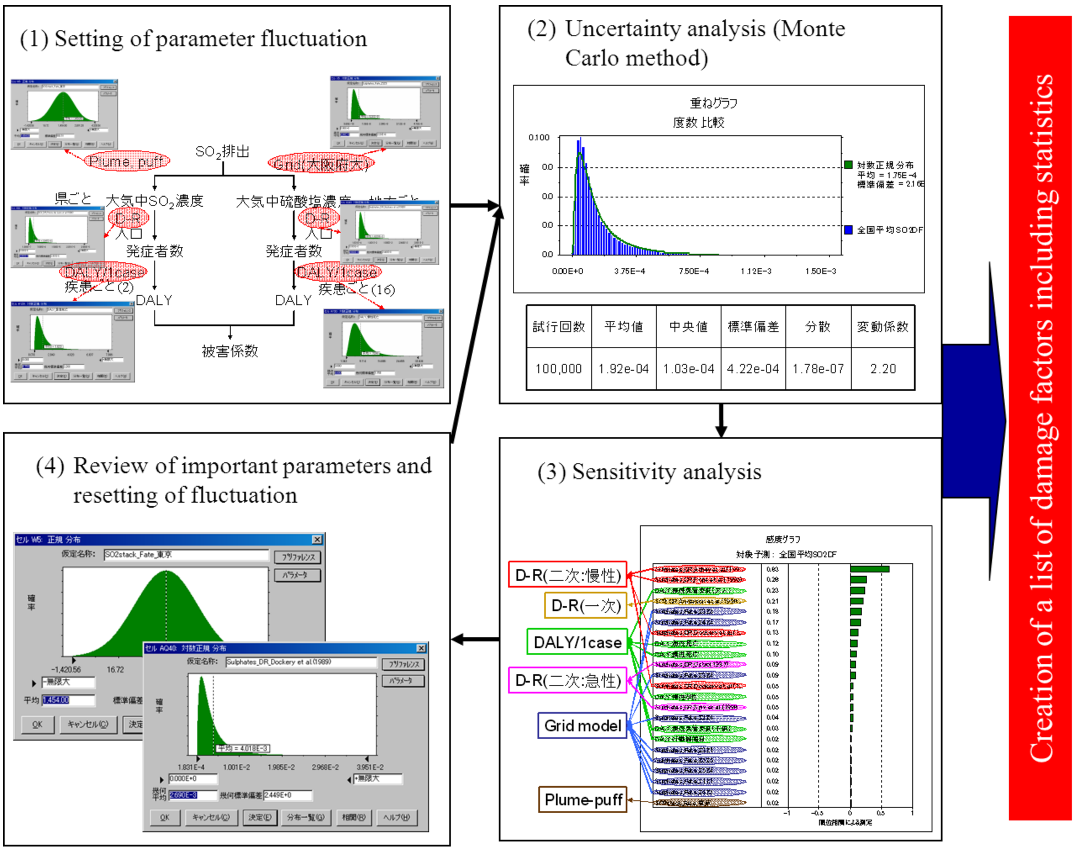


Figure 1.1-2: Procedure for analyzing the uncertainty of damage factors

Figure 1.1-3 shows differences between LIME1 and LIME2 in the method of use of the list of factors and the content of assessment result. In the past, interpretation had to be made only from the LCIA results gained from linear calculation. In the case of LIME 1, no information can be obtained about whether the uncertainty of the result is (a) low or (b) high. In the case of (a), the difference in environmental impact between products is significant and therefore it is possible to obtain a result consistent for the purpose of deciding "which product has lower environmental impact." However, in the case of (b), the uncertainty of the assessment result of both is high, and it is difficult to obtain a result consistent with the purpose from the result of calculation by the use of representative values only. Therefore, it is necessary to carry out reexamination to improve reliability. Information on the reliability of the assessment result can be obtained by the use of LIME2's list of factors, which includes both representative values and statistical values. This leads to the opportunity of reviewing the result of linear calculation, and it can be expected that the "iterative" calculation demanded by international standards can be carried out smoothly.

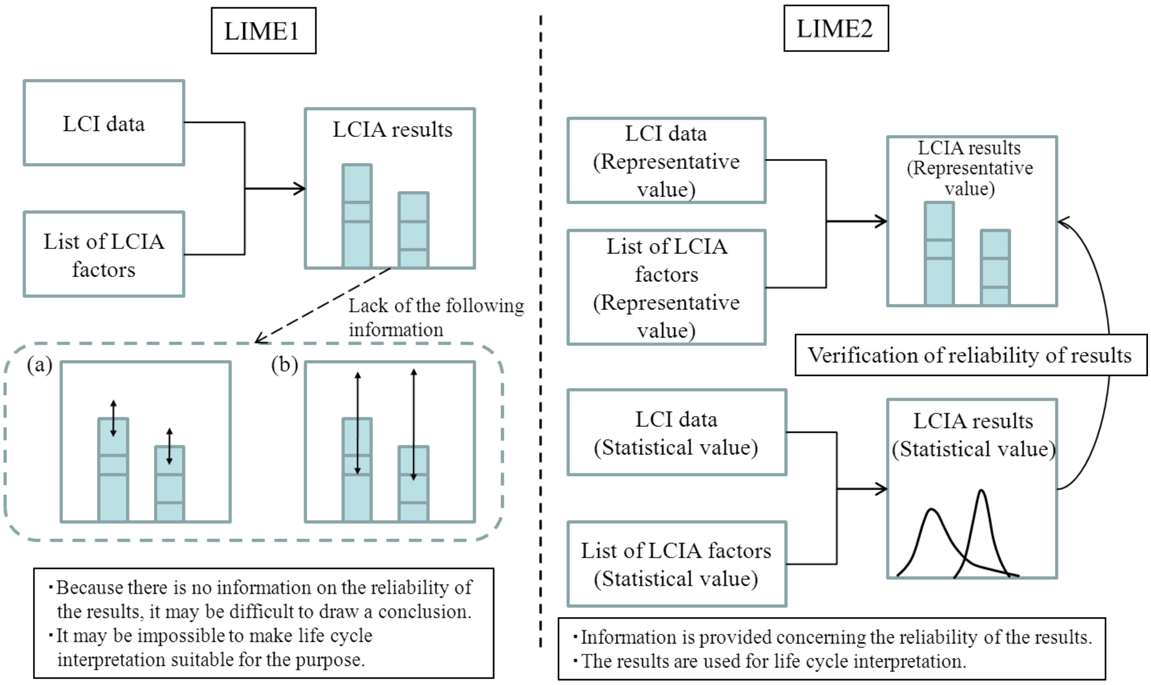


Figure 1.1-3: Differences between LIME1 and LIME2 in the use method and the image of results

When the objects of uncertainty analysis were selected, reference was made to the value of standard – that is, the amount of environmental impact caused by annual economic activities. Figure 1.1-4 shows the value of standard for each impact category in LIME2. The objects of the analysis were the following impact categories where the amount of potential damage was larger compared with each object of protection:

1) Human health: urban area air pollution, global warming, indoor air pollution
2) Social assets: global warming, resources consumption, waste
3) Primary production: resources consumption, land use
4) Biodiversity: resources consumption, land use

In this document, the significance of uncertainty analysis and the details of the analysis method are explained in Section 1.3, the uncertainty analysis of damage factors and the results are explained in each section of Chapter II, and the uncertainty analysis of integration factors and the results are explained in Chapter III.

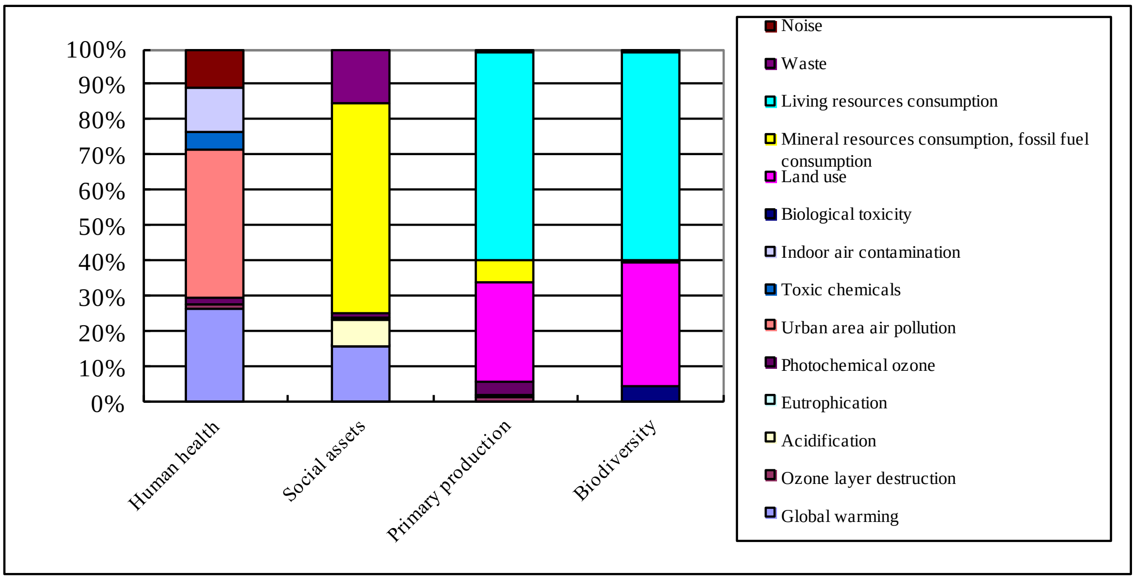


Figure 1.1-4: Breakdown of standard values for each impact category
Uncertainty analysis was conducted for the impact categories whose contribution is large: urban area air pollution, global warming, resource consumption, and land use.

(2) Development of weighting factors that reflect the people's views on the environment

In LIME1, research on conjoint analysis, this has been drawing attention in the fields of market research and environmental economics, was conducted integration of LCIA. As a result, it became possible to obtain statistically significant analysis results and to find the possibility to widely use the LCIA integration factors obtained by the method. To obtain integration factors that can withstand the wide use of various products, it is essential to secure social consensus and representativeness. At present, however, because, due to the limitations of research cost and others, the results of interview surveys in specific areas, such as Tokyo, are used as basic information for the calculation of integration factors, it cannot be said that the integration factors necessarily fulfill the above-described requirements.

Therefore, in LIME2, discussions were carried out to develop weighting factors, increasing social consensus based on nationwide random sampling. Figure 1.1-5 shows an outline of the procedure. First, households are selected randomly on a nationwide scale. At the same time, a questionnaire is prepared for a questionnaire survey. After the contents of the questionnaire and the survey method are revised through several pretests, the survey is carried out. The answers to the questionnaire are statistically analyzed to find estimate values and statistical values. These results are used for calculating integration factors.

Figure 1.1-6 shows a comparison between the characteristics of the weighting factors in LIME2 and those in LIME1. Because an interview survey was carried out on a nationwide scale in LIME2, it can be said that the weighting factors analyzed based on the results reflect the views on the environment all over Japan. Therefore, if a domestic product is analyzed, LIME2's integration factors can be used for general purposes. Moreover, the use of random parameter logit model enabled quantitative expression of difference among individuals in environmental ideas. This made it possible also to analyze the sensibility of assessment results caused by differences among people in environmental ideas.

The survey method, the calculation method, and the results will be explained in Chapter III.

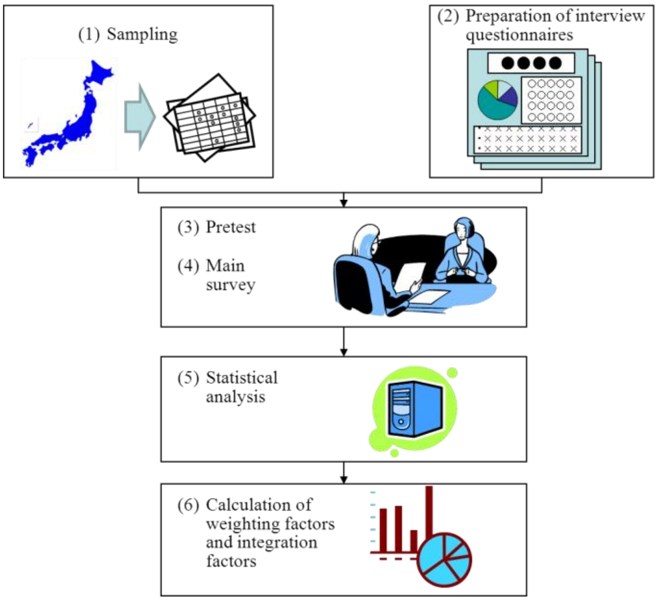


Figure 1.1-5: Procedure for calculating weighting factors and integration factors based on conjoint analysis

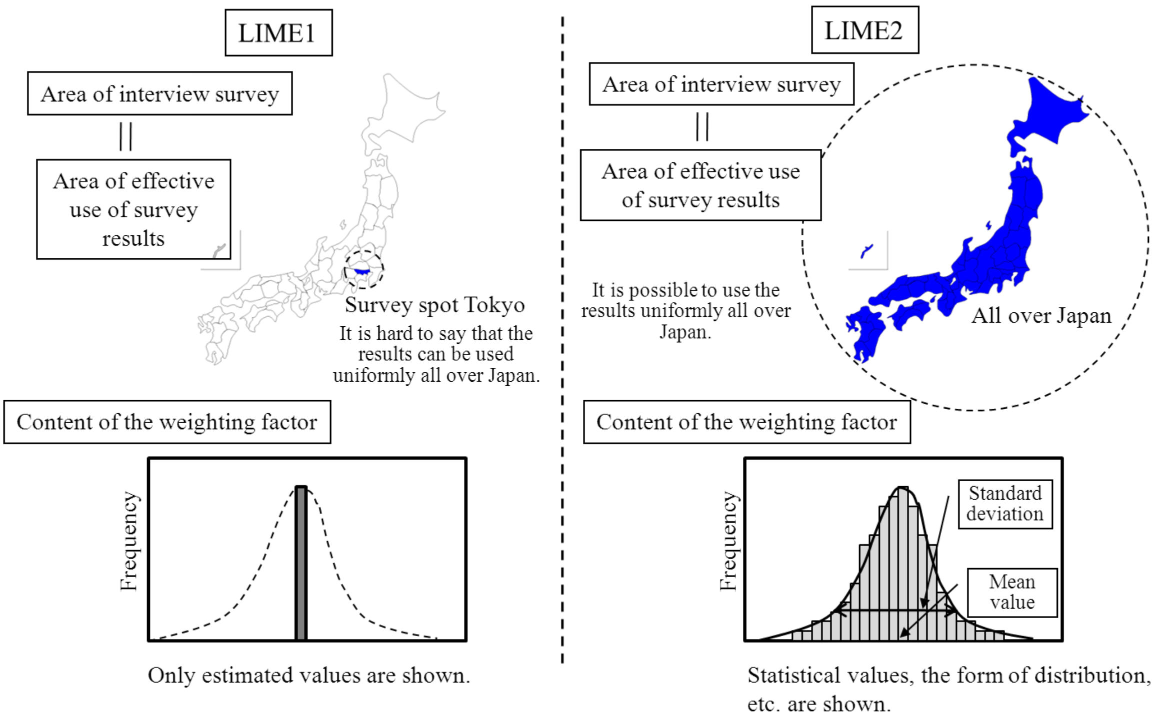


Figure 1.1-6: Difference between LIME1 and LIME2 in the characteristics of the weighting factor

(3) Development of methods for environmental impact assessment of indoor air pollution and noise

LIME1 covered 11 impact categories, such as global warming. When impact categories were selected, consideration was given to the potentiality of environmental impact on four types of area of protection. However, of the environmental issues not assessed during LIME1, priority was given to noise and indoor air pollution concerning the development of new assessment methods, because of the following reasons:

1) Indoor air contamination: Because people spend most of their life indoors, they receive high impact if a toxic substance is emitted indoors. If the amount of emission is the same, the amount of exposure is incomparably larger in the case of indoor emission than in the case of outdoor emission. In Japan, the number of people suffering sick house syndrome has already exceeded one million. According to the World Health Organization (WHO), indoor air pollution contributes much greater to the world's health loss than does air pollution. This situation is seen also in developed countries. Under this situation, manufacturers of construction materials and adhesives are actively developing products that contribute to the reduction of emission of volatile organic compounds (VOC). This demanded the provision of methods that can assess the effect of such products.

2)Noise: Because Japan's rate of achievement of environmental standards is about 70%, about 30% of the people are exposed to noise pollution. According to research in Europe, health impact by traffic noise is considered equivalent to health impact by the exposure to the emission of a particle matter (PM). Although environmental measures against automobiles are often discussed in terms of air pollution, global warming, and resource consumption, measures against sensory nuisance also have been traditionally carried out. In this context, tires and other products with low noise were developed, and the reduction of noise impact was required to be discussed rationally in relation to other impact categories.

Figures 1.1-7 and 1.1-8 show the procedures for calculating damage factors concerning indoor air pollution and noise, respectively. The procedure concerning indoor air pollution covered not only formaldehyde, to which the greatest importance is placed as substances causing sick house syndrome, but also NO_x, SO_2, and PM, all of which are generated through heating, cooking, etc. The procedure concerning noise covered passenger cars and large vehicles for business use, and assessment was conducted with distinction between day and night. During both procedures, the emission of substances or the occurrence of noise was related with changes in the contaminant or noise level, the amount of exposure, the risk of disease, and loss of life expectancy through fate analysis, exposure analysis, impact analysis and damage analysis. In the case of indoor air pollution, impact on nerves and mind was assessed. In the case of noise, health impact causing sleep disorder and conversation disorder was assessed. The results were expressed in DALY (for details, see 1.3.4 (1)). This makes it possible to compare the impact of noise and urban areas air pollution in the LCIA of the traffic system and to integrate indoor air pollution with other impact categories and assess them in the LCIA of products that prevent sick house syndrome. In addition, the damage factors were applied to the weighting factors for the calculation of integration factors.

In this document, Sections 2.9 and 2.13 show the details of the characterization factors for each impact category, the policy for developing damage factors, the assessment procedure, and the results.

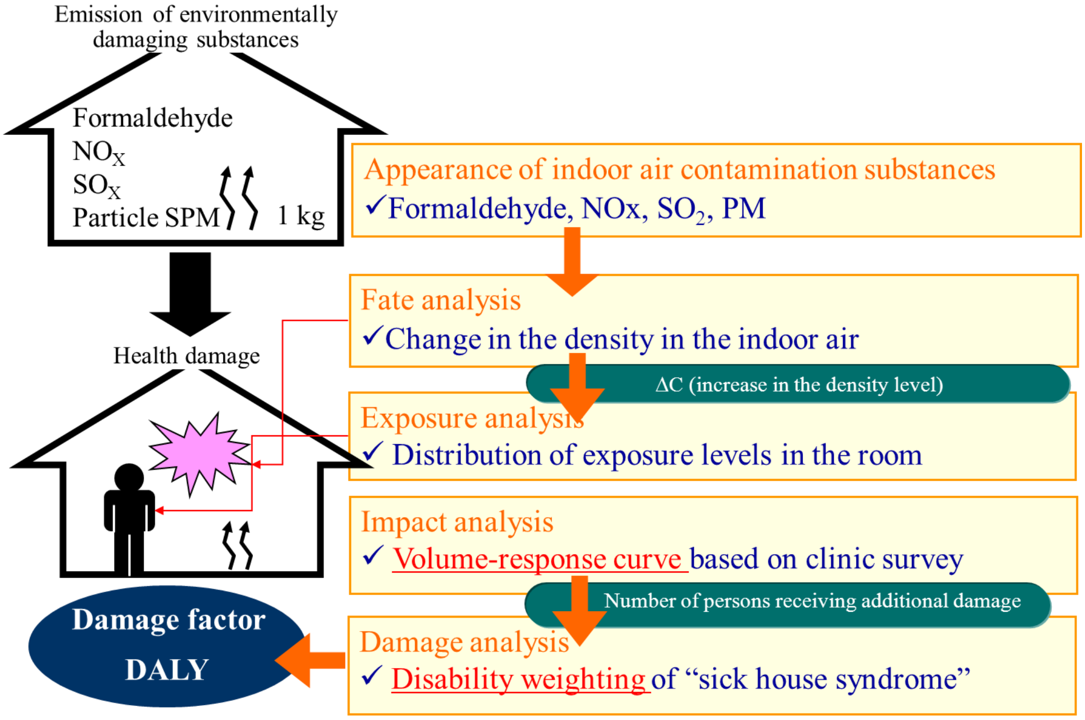


Figure 1.1-7: Procedure for developing a method for assessment of indoor air contamination
Density change and exposure assessment are carried out under indoor conditions.
In this example, health impact is assessed, and the result is expressed in loss of life expectancy.

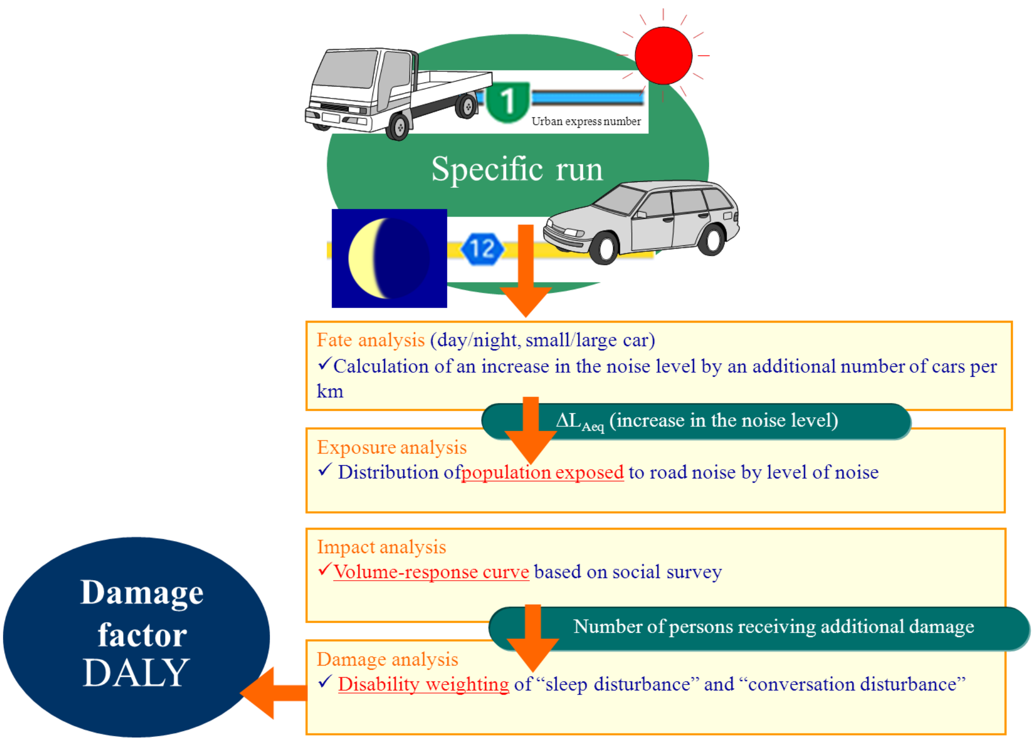


Figure 1.1.8: Procedure for developing the method for assessment of car noise
After noise is divided according to whether day or night and car size, fate analysis, exposure analysis, damage analysis, and impact analysis are conducted.
In this figure, health impact is assessed, and the result is expressed as loss of life expectancy.

1.1.3 Common points and different points between LIME1 and LIME2

After the above-described development and revision, the development of LIME2 was completed. Figure 1.1-9 shows the concept of LIME2. While LIME 2 has inherited the structure of LIME1 and adopted three steps – characterization, damage assessment, and integration – the number of items of impact categories and category endpoints was increased. Like LIME1, the final purpose of the development of LIME2 was to create a list of factors for impact assessment. Table 1.1-1 shows the image of LIME2, compared with the list of factors in LIME1.

In LIME2, data necessary for simulation were disclosed, such as median values, average values, standard deviation, variation coefficients, and distribution forms. The use of them makes it possible for practitioners to obtain information on the reliability of LCIA results. Although it is possible to use this method for linear calculation as before, in this case, it is advisable to use median values.[*1]

The list of factors in LIME2 was improved as follows:

1) Reliability: Uncertainty was improved by the full use of uncertainty analysis and sensitivity analysis.
2) Representativeness: Integration factors representative of the people's environmental ideas were gained.
3) Comprehensiveness: It became possible to assess environmental impact more widely.

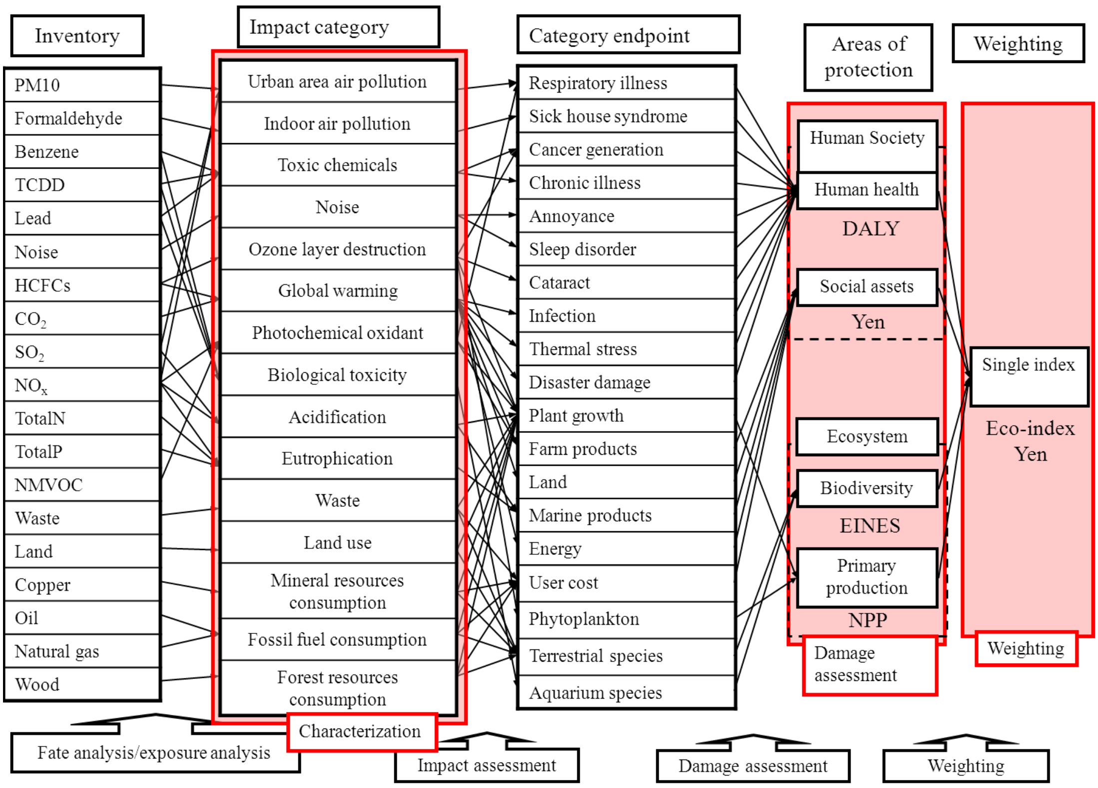


Figure 1.1-9: Concept map of LIME2
It is possible to obtain results of assessment of environmental impact concerning characterization, damage assessment, and weighting.

[*1] In addition to median values, average values may be used for LCIA. According to the results of uncertainty analysis, the distribution of assessment results often widens at the right corner (similar to lognormal distribution). Therefore, in the case of the factors of LIME2, median values are often larger than average values. Because no simulation was carried out and representative values (supposed mode values) were used as the parameters for all assessment in LIME1, the results in LIME2 are thought to be close to median values.

Table 1.1-1: List of factors for LIME2 (urban area air pollution: average in Japan)

(a) LIME1

Related area of protection		Human health
Chemicals		DALY/kg
NOx	Point source	1.46E-05
	Radiation source	2.03E-05
SO_2	-	1.05E-04
PM2.5	Point source	4.16E-04
	Radiation source	1.88E-03
PM10	Point source	2.53E-04
	Radiation source	1.14E-03

(b) LIME2

Related area of protection		Human health						
Type of statistical value		Median (Represen-tative value)	Mean value	Standard deviation	Variation coefficient	10 percentile	90 percentile	Form of distribution
Chemicals		DALY/kg	DALY/kg	DALY/kg	-	DALY/kg	DALY/kg	-
NOx	Point source	1.20E-5	2.75E-5	1.07E-4	3.88	2.70E-6	5.15E-5	Log-normal distribution
	Radiation source	2.13E-5	1.18E-4	1.12E-3	9.47	4.81E-6	1.55E-4	Log-normal distribution
SO_2		1.49E-4	2.64E-4	4.91E-4	1.86	2.19E-5	5.76E-4	Log-normal distribution
PM 2.5	Point source	1.93E-4	5.77E-4	2.46E-3	4.26	4.00E-5	1.12E-3	Log-normal distribution
	Radiation Source	1.33E-3	6.18E-3	2.06E-2	3.33	1.92E-4	1.43E-2	Log-normal distribution
PM 10	Point source	2.38E-5	4.94E-5	1.56E-4	3.15	6.99E-6	9.98E-5	Log-normal distribution
	Radiation source	8.70E-5	2.06E-4	6.98E-4	3.39	2.05E-5	4.21E-4	Log-normal distribution

In LIME1, representative values for regional averages and national averages are calculated. In LIME2, representative values and statistics for prefectures, regional averages, and national averages are calculated.

Table 1.1-2 summarizes the characteristics of LIME1 and LIME2. Although the object of protection and the damage indexes are the same as before, changes were made in the number of impact category items, the types of data disclosed in the list of factors, the method of using the data, and the image of LCIA results. In addition, note that because the parameters and models used for assessment were changed from time to time, changes were made in the representative values in the list of factors. For details of these changes, see the respective sections of Chapters II and III.

Table 1.1-2: Characteristics of LIME1 and LIME2

	LIME1	LIME2	Remarks
Area of protection	4 items	4 items	No change
Damage indexes	4 types for each area of protection	4 types for each area of protection	No change
Integration indexes	3 types: 1 economic index and 2 non-dimensional indexes	Economic index	Based on conjoint analysis; no AHP
Impact categories	11 categories	15 categories	Noise and indoor air contamination were newly developed; resource consumption was divided into fossil fuels, mineral resources, and forest resources consumption.
Survey for calculation of weighting factors	Group interview survey in the Tokyo area	Individual interview survey on a nationwide scale	Japanese people’s environmental ideas were reflected.

Number of target substances	About 1,000 substances	About 1,000 substances	A small increase because of an increase in the number of impact categories
Data shown in the list of factors	Representative value	Representative value + statistic	Identification of standard deviation and form of distribution
Calculation method using the list of factors	Linear calculation	Linear calculation, simulation (Monte Carlo method)	Suitable for uncertainty analysis of LCA
Image of calculation results	Bar graph	Bar graph, frequency distribution	Measurement of risk of conclusion; support for internal decision-making

1.2 Framework of LIME

1.2.1 Theme oriented method and damage oriented method

During the period between the second half of the 1990s and 2000, attention began to be paid to the development of methods for assessing the amount of potential damage at endpoints. As a result, LCA methods, including integration, were roughly divided into theme oriented method, which were proposed traditionally, and damage oriented method, whereby endpoint-type assessment results serve as the base of weighting. This section explains the outline and characteristics of the damage oriented LCIA methods, compared with theme oriented methods.

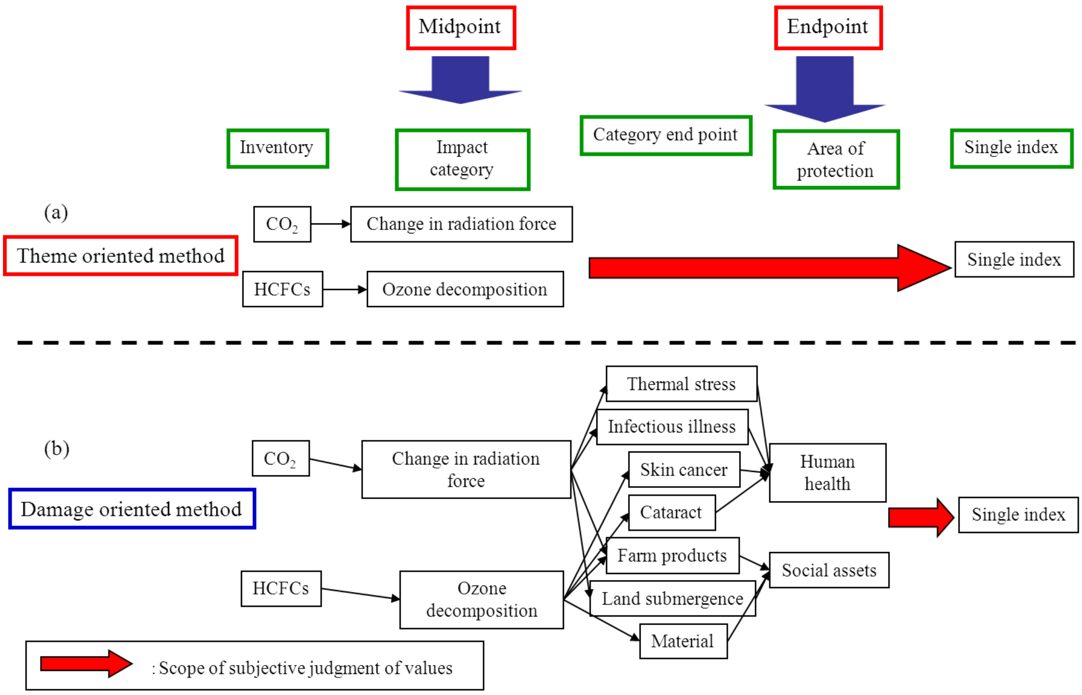


Figure 1.2-1: Comparison in approach between theme oriented method and damage oriented method

The theme oriented method (a) compares and integrates results at the midpoint level, while the damage oriented method (b) compares and integrates calculation results at the endpoint level.

Figure 1.2-1 shows the frameworks of a model based on midpoint modeling and a model based on endpoint modeling. Under the former method (Figure 1.2-1 (a)), integration is conducted by applying importance between impact categories to the result of LCIA characterization (such as contribution to an increase in radiation forcing and the emission amount of protons) as a weighting factor. Many methods for this approach were proposed from the first half to the second half of the 1990s (for example, Goedkoop 1995, Hauschild et al. 1998, Nagata et al. 1995, Itsubo 2000, Natsuno et al. 1999, Yasui 1998). The general LCIA procedure specified in ISO 14044 is based on these research results.

However, a method based on theme oriented method has the following problems:

1) Too many comparison items: If the number of items to be weighted is large, it is difficult to make appropriate judgment of value. Because a decrease in the number of items reduces the trouble of weighting items, the decrease is an important requirement for developing a weighting factor with higher social consensus. Under a method based on theme oriented method, more than ten impact categories are directly compared. Because simultaneous comparison of these items is a great trouble to respondents, accurate reflection of their ideas is difficult.

2) Lack of concreteness: Many results of characterization, which serve as a precondition for integration under a method based on midpoint modeling, indicate environmental changes, such as the power to decompose ozone in the stratosphere and an increase in radiation forcing. When a respondent who conducts weighting considers the significance of an environmental problem, it is essential to have information about what receives damage from the environmental problem to what degree – for example, how many people will suffer skin cancer due to ozone layer destruction and how many people will suffer asthma due to air pollution. However, because such information cannot be obtained from the result of characterization, the respondent has to weight environmental issues with extremely limited information. It cannot be said that the weighting factor obtained through such a process faithfully indicates the respondent’s sense of value about the environment.

3) Lack of transparency: The form of impact caused through an impact category varies. For example, ozone layer destruction gives damage not only to health, such as skin cancer and cataract, but also to forests, farm products, petrochemical products, and plant plankton. Depending on to what extent the impact of ozone layer destruction should be taken into consideration, even the same respondent may change the weighting of ozone layer destruction. However, under many methods based on midpoint modeling, weighting factors are calculated without such consideration. Because this makes the range of the object of weighting unclear, the transparency of the assessment method may become insufficient.

Even if the same inventory is applied, the result of integration may greatly differ depending on the LCIA method used for the integration. If the transparency of the integration method is insufficient, it will be difficult to discuss why the result differed.

4) Difficulty in the reflection of the result in each research field: Impact (amount of damage) that occurs through an environment problem is actively assessed by various fields, such as epidemiology and toxicology. Under a method based on value judgment is applied to all the matters ranging from environmental changes (such as the power to

resolve ozone) to serious environmental problems without reflecting important suggestions provided by knowledge of natural science.

5) Difficulty in the continuation of renewal: Because no perfect impact assessment method exists at present (perhaps in the future also), method developers are required to continue consideration to improve the accuracy and reliability of methods. However, because the transparency of theme oriented method is low, it is difficult to find methodological problems and future issues and therefore the direction of development of method research is difficult to establish.

A damage oriented method is an approach whereby weighting is carried out by comparison among endpoints into which environmental impacts are put together based on the result of assessment as to what receives damage due to an environmental problem to what degree (for example, how many people suffer heat stroke or cataract) (see Figure 1.2-1 (b)). Many of the main LCIA methods developed recently (Eco-indicator 99, environmental priority strategies (EPS), ExternE, LIME) are based on damage oriented method. In relation with the above-described problems in the theme oriented methods, the damage oriented methods have the following advantages:

1) The aggregation of environmental impacts into endpoints makes it possible to decrease the number of items to be weighted to three or four. This contributes to ease burden for respondents who weight items.

2) Damage assessment at the stage preceding weighting is based on academic knowledge. If a method based on endpoint modeling is adopted, it will be possible to clearly distinguish the stages where respondents' value judgment can be avoided (characterization, damage assessment) with the stages where assessment is made by the social science analysis method (stages from damage assessment to single index).

3) It is possible to provide a medium for information that is easy for respondents to understand. While the result of a method based on midpoint modeling is the result of characterization (in the case of global warming, for example, the amount equivalent to CO_2 focusing on radiation forcing), the result of a method based on endpoint modeling is the result of damage assessment (in the case of human health, loss of life expectancy (number of years)), which expresses the object of environmental impact more directly. If respondents' burden of weighting is eased, it can be expected that the statistical significance of the weighting factor will be improved accordingly.

4) Because the assessment range of category end points can be clarified, it can be said that transparency is high. If the result differs among the methods used for LCIA, it is possible to analyze the causes of the difference (for example, difference in the model for assessment of malaria due to warming, and whether the benefits from warming are taken into account).

5) If the transparency of methodology is high, it will be possible to clarify the research issue to be solved first during method development through accumulation of case studies (for example, improvement in the accuracy of the fate analysis model of chemical substances). This will become an important requirement for continuous improvement of LCIA methods.

In addition, damage oriented methods have not only methodological advantages but also advantages from the practical aspect of LCA, as follows:

6) Damage assessment can be conducted as a step of LCIA. Damage assessment makes it possible to logically compare and aggregate forms of damage belonging to different impact categories, such as thermal stress due to warming and skin cancer due to ozone layer destruction, by putting together diversified forms of damage into the object of protection and using loss of life expectancy and other indexes.

7) Presentation of damage assessment results as a new step between characterization and integration increases practitioners' opportunities of selecting assessment steps and facilitates the interpretation of integration results.

8) If a practitioner has its own weighting, it is possible to estimate integration that reflects it.

Table 1.2-1 summarizes the differences between the characteristics of methods based on midpoint modeling and the characteristics of methods based on endpoint modeling. In this way, methods based on endpoint modeling are expected not only to suggest the direction of the solution of problems in theme oriented methods but also to provide information that is easier for practitioners to use.

Against the above-described backgrounds, a method based on endpoint modeling was adopted for the basic framework of LIME. However, the adoption of a method based on endpoint modeling does not mean rejection of characterization (assessment at the midpoint level). As described above, characterization is essential for LCA, relatively reliable, and very useful for supplementing the results of damage assessment and integration.

Table 1.2-1: Comparison between theme oriented method and damage oriented method in the characteristics of the integration method

	Theme oriented method	Damage oriented method
Number of comparison items	Large (10 items or more)	Small (5 items or less)
Transparency	Low (It is unclear what types of damage occurring through environmental problems should be assessed)	High (It is clear what types of damage should be assessed)
Scope of judgment of values	Wide (academic knowledge on epidemiology, toxicology, etc. is not included in assessment)	Only between endpoint and single index
Quantitative indication method for the object of comparison	Different from actual environmental impact (ex. amount equivalent to emission of CO_2)	Amount of damage at endpoint (ex. loss of life expectancy)
Existence of damage assessment	Not included	Assessment results can be regarded as a step of LCIA.

1.2.2 History of LIME development

Even if the amount of environmental burden is the same, environmental impact differs according to the weather, topography, population, and vegetation distribution at the point of emission. Therefore, to make LIME a method for appropriately assessing environmental impact in Japan, it was necessary to settle the following issues:

1) Development of characterization methodology and factors that reflect the environmental conditions in Japan

2) Development of damage assessment methodology and factors that reflect the environmental conditions in Japan

3) Development of iweighting methodology and factors that reflect the Japanese people’s environmental ideas

4) Establishment of an environment assessment method that enables systematic implementation of characterization, damage assessment, and integration under an assessment scheme

In the LCA Project (official title: Development of Assessment Technology of Life Cycle Environmental impacts of Products and so forth 1998 - 2003, Development of Technology to Assess and Verify Life Cycle CO_2 Emissions 2003 – 2006: Ministry of Economy, Trade and Industry, New Energy and Industrial Technology Development Organization (NEDO), Japan Environmental Management Association for Industry), a technical committee consisting of LCIA experts and environmental science experts, was established and developed LIME as an LCIA method for settling the issues 1) to 4) above.

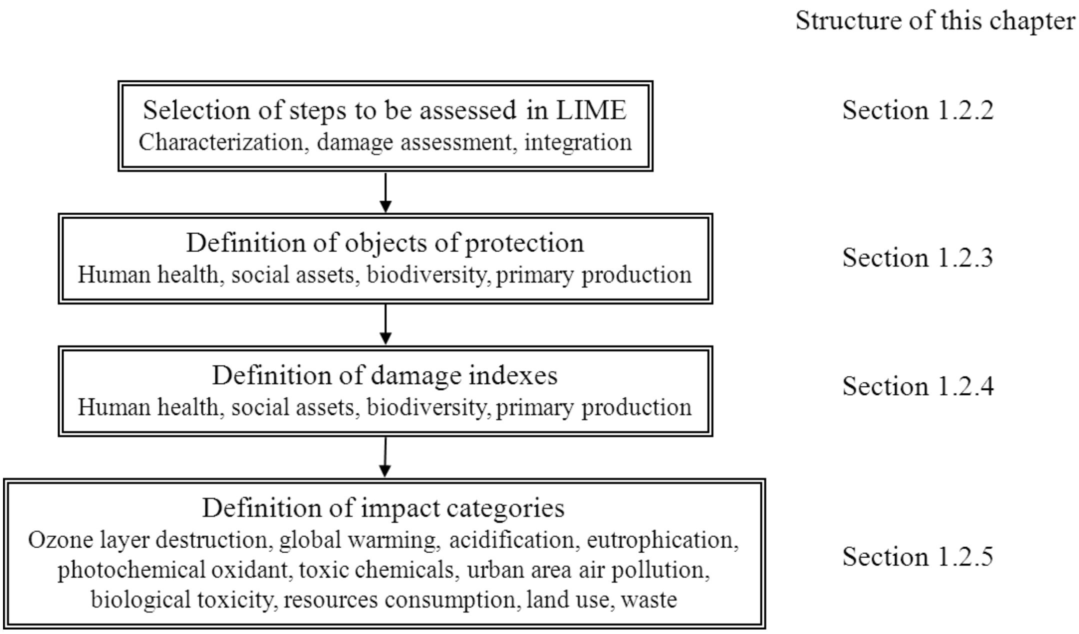


Figure 1.2-2: Relation between the procedure for creating the framework of LIME and the structure of this chapter

Figure 1.2-2 shows the flow of the examination procedure for creating the framework of LIME, together with the structure of this section. With regard to the procedure, the steps of LCIA covered by LIME were defined and then the items to be assessed in each step were established. Moreover, indexes expressed as results of LCIA were defined for each item.

As seen in the framework shown in Figure 1.1-9, this method has been designed to carry out LCIA that reflects the environmental conditions and ideas in Japan in three steps – characterization, damage assessment, and integration. Top priority is given to dealing with issues 1) to 4) above. However, these three steps have both advantages and disadvantages. Table 1.2-2 summarizes the characteristics of each step.

Table 1.2-2: Characteristics of characterization, damage assessment, and integration

	Advantages	Disadvantages
Characteri-zation	• Uncertainty is relatively small. • Subjective judgment of value is not included. • It is often used by Traditional LCIA. • It is specified as an essential element of ISO.	• The number of evaluation result items is large. • A trade-off relationship may arise between impact categories. • Because it does not measure actual environmental impact (damage) (for example, the degree of contribution of an increase in radiation force), it is difficult to understand the meaning of calculation results.
Damage assessment	• Knowledge of natural science is fully used. • The number of assessment results is minimized, excluding subjectivity and preference as much as possible. • Because assessment results are the amount of damage at the endpoint, it is relatively easy to understand the meaning of calculation results. • It is used as a precondition for integration and for verifying integration results.	• It is a domain where LCIA research is immature. • Uncertainty is generally high, compared with characterization. • It is not defined as a step of ISO.
Integration	• It is possible to obtain a single index. • Applicability to other environmental assessment tools (such as environmental accounting and environmental efficiency) is high. • No trade-off relationship arises. • It is excellent as an environmental communication tool.	• Because it is based on subjective judgment of value and social preference, the reproducibility of results may not be realized, depending on the method. • Many methods have not verified the social representativeness of weighting. • ISO considers it an optional element.

As the International Organization for Standardization (ISO) regards characterization as an essential element for LCA, characterization is conducted for LCA of almost all case studies. Because the characterization factors used for assessment are based on knowledge of natural science, the reliability of assessment results is thought to be higher than the reliability of the other steps. Meanwhile, because the results of assessment by characterization can be obtained for each impact category, the items of assessment results number more than ten. Therefore, if two or more products are assessed by comparison, a trade-off relation is highly likely to be found. In addition, a characterization factor is generally a relative value (the amount of impact of a standard substance, such as CO_2, on a specific impact category is defined as 1). Because assessment by the use of the characterization factor is not assessment of actual environmental impact, it is difficult to compare it rationally with other environmental impacts based solely on the result of the assessment.

On the other hand, because integration makes it possible to obtain an integrated single index after comparison of various environmental impacts, no trade-off relation is found. Because of this, integration is very useful when there is a trade-off relation between assessment items at a preceding stage, such as damage assessment. In addition, because a single index makes it easy to interpret assessment results, it is useful as a communication tool. Moreover, integration step can be applied beyond the framework of LCA, such as environmental efficiency and environmental accounting. On the other hand, because individuals' and society's judgment of value and preference enter into the weighting of environmental impacts, the introduction of assessment by integration has been criticized so far.

Damage assessment stands at the middle between characterization and integration, because it makes the most use of knowledge of natural science and focuses on the amount of damage to common endpoints. Since the results of assessment are put together into endpoints, the number of result items can be reduced to about five (four in the case of LIME). Moreover, because assessment is based on knowledge of natural science, it is possible to avoid individuals' judgment of value to the greatest possible extent. In addition, the results of damage assessment as the stage preceding integration are extremely useful for logically explaining the results of integration. On the other hand, the level of research on damage assessment methods is still under development, and the number of internationally agreed items is small. Therefore, a lot of data and models are utilized in the connection with inventory through damage. In addition, because data necessary for damage assessment are insufficient in some categories, the uncertainty of damage assessment may be relatively high.

Which step to emphasize among the three steps of LCIA depends on the practitioner's purpose. In addition, to facilitate the interpretation of LCIA results, comparing the results of all the steps is more useful than using only one of the steps. Therefore, it was decided that the purpose of the development of LIME should be to carry out, under an integrated system, assessment that can deal with all the LCIA steps shown in Figure 1.1-9. The fruit of method development is the following group of lists for LCIA assessment:

1) List of characterization factors

Global warming, ozone layer destruction, acidification, eutrophication, photochemical oxidant, urban area air pollution, toxic chemicals (chronic toxicity, carcinogenesis), biological toxicity (terrestrial animals, aquatic organisms), land use, indoor air contamination, noise, waste, mineral resources consumption, fossil fuel consumption, biological resources consumption (15 impact categories in total)

2) List of damage factors
Human health, social assets, primary production, biodiversity (4 items in total)

3) List of integration factors
External cost, non-dimension (2 types in total)

Roughly, there are two ways of using these lists. One of them is linear calculation by the use of representative values; the other is simulation by the use of statistical values.

LCIA by the use of representative values can be easily conducted by extracting inventory data and corresponding environmental assessment factors from the lists.

Characterization: $$CI^{Impact} = \sum_{X} \left(CF^{Impact}(X) \times Inv(X) \right) \quad (1.2\text{-}1)$$

Damage assessment: $$DI(Safe) = \sum_{Impact} \sum_{X} DF^{Impact}(Safe, X) \cdot Inv(X) \quad (1.2\text{-}2)$$

Integration: $$SI = \sum_{Impact} \sum_{X} IF^{Impact}(X) \cdot Inv(X) \quad (1.2\text{-}3)$$

X, *Impact*, and *Safe* stand for inventory item, impact category, and the area of protection, respectively. CI^{Impact}, DI ($Safe$), and SI stand for the calculation result of characterization (impact category index), damage assessment (damage index), and integration (single index), respectively. CF^{Impact} (X), DI^{Impact} ($Safe$, X), and IF^{Impact} (X) stand for characterization factor, damage factor, and integration factor, respectively.

Simulation of LCIA by the use of statistical values is carried out by randomly extracting parameters from formulas 1.2-1 and 1.2-3 under a certain probability distribution and carrying out calculation by the use of them several times. Calculation can be carried out easily by the use of statistical analysis software, such as Crystal Ball or Analytica, or LCA software for statistical analysis. Although this document shows statistical values of the lists of LCIA factors (standard deviation, form of distribution, etc.), it is necessary to prepare statistical values of inventory data for calculation beforehand.

Because the assessment of environmental impact by the use of LIME can be conducted if data on environmental burden exist, LIME can be used also for purposes other than LCA. LIME is expected to be used for various purposes, such as cost-benefit analysis, life cycle cost-benefit analysis (LCCBA), assessment of environment conservation effect for environmental accounting, assessment of comprehensive cost integrated with external cost, and assessment of environmental efficiency and factors.

1.2.3 Definition of areas of protection

There are two types of approaches to create the framework of an LCIA method and the scope of assessment: the bottom-up approach and the top-down approach (Figure 1.2-3). The bottom-up approach first selects substances to be assessed and then picks out impact categories closely related to these environmental burdens and endpoints. The top-down method first defines what should be assessed among the endpoints that constitute the natural environment and then pick out impact categories and environmentally damaging substances that can give some damage to them.

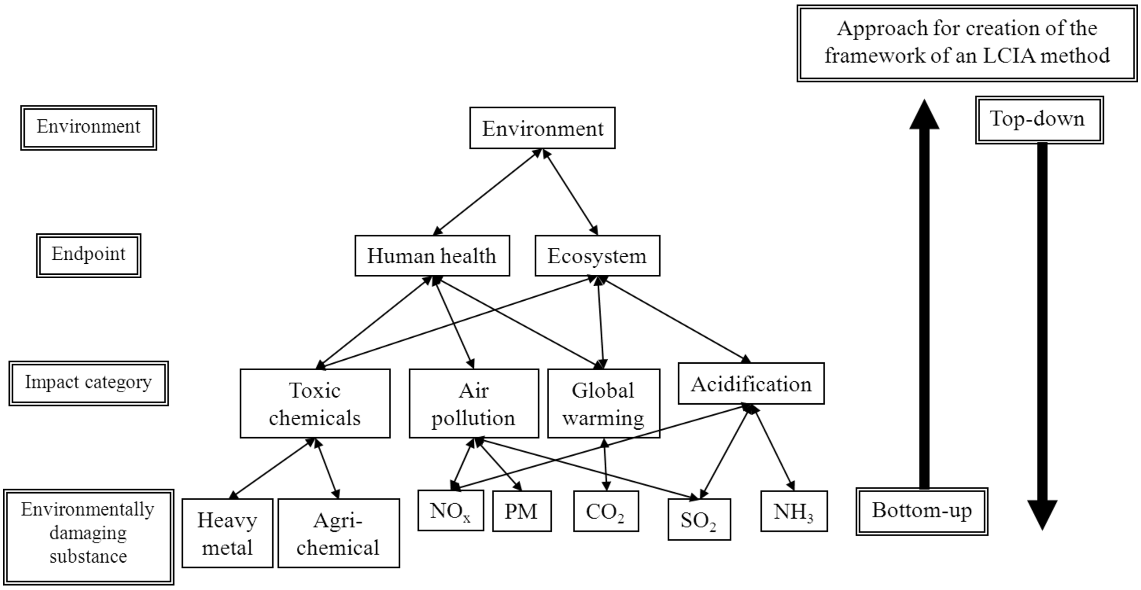


Figure 1.2-3: Approach for creation of the framework of an LICA method
Bottom-up approach and top-down approach

If an LCIA method is developed mainly to cover all the substances that are thought to be important for a specific product, the bottom-up approach is adopted. However, the bottom-up approach cannot clarify how the “environment” is grasped as the object of assessment. Because many LCIA methods have already been developed and proposed, clarifying how assessment methods grasp the “environment” and for which component of the environment the quantification of impact is carried out is extremely important information for the selection of an LCIA method suitable for the practitioner’s purpose. When LIME was developed, priority was given to the clarification of the concept of the assessment method, and the top-down approach was adopted. Because the explanatory documents for the other proposed LCIA methods based on endpoint modeling (Eco-indicator 99, EPS) also describe the objects of protection at the beginning, the top-down approach has been adopted also for these methods.

To make the framework of LIME with top-down perspective, discussions were first held to define areas of protection. Because many of the proposed lists of areas of protection were prepared by LCIA method developers or panels of persons concerned, the grounds for the final judgment often lacked sufficient clarity. To improve the objectivity of standards for selecting areas of protection, LIME began with research on theoretical backgrounds in other research fields and consideration of the results.

In the field of environmental ethics, many various ideas and assertions were already proposed concerning post-anthropocentrism. Discussions have been held from various angles as to how the human beings are required to think and act as members of the living organism in the Earth. Therefore, when areas of protection were defined in LIME, it was decided that main environmental ideas in the field of environmental ethics should first be researched and analyzed and then discussions should be held based on the results to select objects of protection.

Because some proposed ideas in the field of environmental ethics (see Column 1.2-1) conflict with each other, it is difficult to define areas of protection that satisfy all the ideas. However, efforts were made to secure the objectivity of concepts of methods by seeing to it that these ideas on environmental ethics are reflected as much as possible and by clarifying the relation between LIME's list of areas of protection and the ideas on environmental ethics.

Column 1.2-1

Discussions from the viewpoint of environmental ethics

Environmental ethics originated with the romanticism developed in the early 19th century. Rousseau was a pioneer in recognizing the value of nature, and Goethe's and Wordsworth's poems expressed ideas about environmental ethics. Although romantic ideas tended to be emotionally engaging, they developed into environmental ethics beyond anthropocentrism.

Today's environmental ethics started with Leopold's "The Land Ethic" (Leopold 1949). Leopold collectively called water, soil, plants, and animals "land" and advocated the importance of protection of the safety and view of the whole land. Leopold's idea is characterized not by individualism, under which rights are granted to each living thing, but by ethical consideration of the interests of biotic communities. Although Callicott has succeeded to such holistic environmental ethics, there is criticism that no consideration is given to individuals who are sacrificed for the interests of the whole.

From 1960 to the 1970s, responding to the emergence of environmental problems, many ideas about environmental ethics that advocated the importance of giving the ecosystem rights equivalent to the human rights, such as Carson's "Silent Spring," were proposed. The ideas proposed during this period can be roughly divided into animal liberation theory, natural objects' standing, and deep ecology.
Stone discussed "trees' standing" in 1974 (Stone 1974) and Singer demanded the abolition of "speciesism" in his "Animal Liberation" (Singer 1975). Moreover, Naess advocated 'biocentric equality" in his "Deep Ecology" (Naess 1973), asserting that all living things have the right for "self-fulfillment." These are regarded as assertions that rights equivalent to human rights should be granted to all the living things other than the human beings.

These ideas concern the relation between human beings and nature. Brisk discussions were held also about ethics for relationships in human society.

In Hardin's "Tragedy of the Commons" (Hardin 1968), he logically explained that if a reasonable person in a common puts sheep out to pasture, other persons will follow him, with the result that the situation will get out of control and their environment will collapse. He also asserted that the maintenance of the environment requires the restriction of individuals' freedom. In addition, Hardin's "Living on a Lifeboat" (Hardin 1974) compared countries to people on a lifeboat to explain whether rich countries should give assistance to poor countries. He concluded that rich countries should not give assistant to poor countries, because the lifeboat itself will sink. While "lifeboat ethics" compares countries to people on a lifeboat, "spaceship ethics" (for example, Boulding 1996, Fuller 1966) compare the whole Earth to a spaceship. Because the environment of the Earth functions as the system for maintaining the spaceship, ignorance of a specific poor country affects the whole system of the spaceship. Using this "spaceship ethics," Frechette refuted "lifeboat ethics" by asserting that if developed countries help developing countries, this will affect developed countries and then the whole Earth (Frechette 1981).

Moreover, in his "Intergenerational Ethics," Frechette asserted that the current generation should not adopt policies for promoting mass consumption of exhaustible resources or requesting the future generation to purify polluted environments. In addition, in his "Environmental Justice," he demanded the prevention of occurrence of an environmental gap between North and South, because relatively inferior people also have the right to enjoy a good environment.

According to Kato (1991), the above-mentioned environmental ethics contain the following three assertions:
Nature's right to exist: Not only human beings but also species of living things have the right to exist.
Intergenerational ethics: The current generation must not force worsened environments on the future generations.
Earth totalitarianism: The Earth is a closed system whose components are interrelated with each other.

Referring to these three assertions, Kito (1996) classified the above-mentioned ideas on environmental ethics into 1) humankind-nature relationship, 2) interhuman relationship, and 3) individual-whole relationship, as shown in Table 1.2-A.

Table 1.2-A: Classification of ideas on environmental ethics (according to Kito)

Humankind-nature relationship	Interhuman relationship	Individual-whole relationship
Land ethic Animal liberation Trees' standing Deep ecology	Intergenerational ethics Environmental justice	Totalitarian environmental ethics Tragedy of common land Lifeboat ethics Spaceship ethics

As shown in Table 1.2-A, many environmental ideas classified as 1) human-nature relationship (land ethic, animal liberation, deep ecology, and trees' standing) advocate post-anthropocentrism and biocentric equality, and 3) the environmental ideas classified as individual-whole relationship (spaceship ethics, totalitarian environmental ethics) assert that the global ecosystem is a system and should be treated as a component of an essential system. These ideas on environmental ethics suggest the importance of discussions about not only human beings as an area of protection but also avoidance of environmental impact on the ecosystem. It can be said that the minimum requirement for making the concept of LCIA methods consistent with these environmental ideas is to make the environmental impact on both human beings and the ecosystem (living things other than human beings) reflected in the assessment.

It can be assumed that "human beings" and "the ecosystem" are defined as items to be protected by LIME. With regard to "human beings," however, it is necessary to clarify whether only the life of each individual should be protected or whether quality of life (QOL), social infrastructure for life, and products also should be included. In addition, because the ecosystem includes not only plants and animals but also decomposers, such as microbes, and inorganic environments, such as the air and water, the meaning may differ depending on the range of objects. Moreover, when an LCIA method is developed for Japan, it is necessary to show views as to whether environmental impact in other countries should be taken into consideration, whether differences in the point of occurrence of impact should be weighted, and whether the ecosystem for future generations should be taken into consideration. The clarification of the components and ranges of the human beings and the ecosystem is a requirement for quantifying environmental impact during LCIA. Therefore, the components of "human beings" and "the ecosystem" were defined based on past ideas on environmental ethics, and their geographical and temporal ranges were discussed.

If, as advocated by Kato, nature's right to exist covers human beings, the lives of human beings should be included in the objects of respect as a component of nature. The ideas on environmental ethics belonging to Table 1.2-A 2) interhuman relationships, advocate equality in human society, asserting that human health and affluence should not be damaged by environmental impact anywhere or anytime. "Intergenerational ethics" and "environmental justice," which are included in the category, advocate the rights of future generations and the abolition of discrimination in environmental conditions among developing countries. It is interpreted that they include not only the life of mankind but also living affluence. In other words, it can be thought that continuous and fair allocation of the supports of human society, such as farm products and resources, is consistent with these assertions. Therefore, the elements to be protected should include valuables, such as mineral resources, fossil fuels, agricultural resources, and aquatic resources.

The ecosystem was considered as follows. According to biocentrism, which centers on Singer's animal liberation and Stone's trees' standing, it is desirable to include animals and plants in the areas of assessment by LCIA as components of the ecosystem. Moreover, according to the spaceship ethics, because decomposers, such as soil organisms, and microbes, such as plankton, play an important role in circulating the global environmental system, they should be included in the objects of assessment as components to be protected. The "biocentrism" of deep ecology has adopted the principle of diversity and symbiosis, and biodiversity can be interpreted as an important element of the ecosystem. When species of living things are selected as objects of assessment, one of the issues may be whether to treat higher animals and plants equally. From the viewpoint of avoiding the principle of species discrimination, no consideration will be given to the importance among species of living things.

Based on these discussions, the areas of protection under LIME were determined. Under LIME, the items representative of the right of existence of "human beings" and "the ecosystem" are "human health" and "biodiversity," respectively. "Human health" includes not only life but also QOL. This is because intergenerational fairness and environmental justice are interpreted as advocating the granting of the right for health in a wider sense, including QOL, also to future generations and developing countries. The item representative of the existence right of the ecosystem is biodiversity, because a totalitarian idea that gives priority to the continuous existence of species rather than that of individual organisms has been adopted.

Moreover, "social assets" and "primary production" are regarded as items to be protected, because they are necessary for "human beings" and "the ecosystem" to assert the right of self-realization as living organisms. Social assets include not only mineral resources and fossil fuels but also farm products, forest resources, and aquatic resources. In addition to intergenerational fairness, social assets are essential elements for lessening regional and temporal environmental impact gaps under "environmental justice." Primary production includes microbes, such as plankton, and plants, such as grassland and forests. All living things that cannot photosynthesize depend on plants for the production of energy. Plants continuously supply oxygen and food essential for almost all living things. The definition of primary production as an object of protection means that plant production is recognized as important.

Table 1.2-3 shows the objects of protection under LIME and the relations among them. By the use of ideas on environmental ethics, the four items shown in the table ("human health," "social assets," "biodiversity," and "primary production") were defined as the areas of protection. However, this expresses the ideas as one of the LCIA methods, but is not concerned with whether they are true or false. The following are issues and problems concerning the areas of protection under LIME.

Table 1.2-3: Positioning of objects of protection defined in LIME

Broader concept of area of protection / Classification standard of area of protection	Human society	Ecosystem
Item interpreted as expression of each broader concept's right to exist	Human health	Biodiversity
Item essential for maintenance of each broader concept	Social assets	Primary production

After human society and the ecosystem were defined as broader concepts of the objects of protection, they were divided into those representing the objects' right to exist and those essential for supporting their maintenance. These four items have been defined as the objects of protection in LIME.

1) If "the ecosystem" consists of "biodiversity" and "primary production," it can be interpreted that importance is placed on consideration for species or plant production as a whole rather than individual organisms. In this respect, the concept of LIME may focus on the totalitarianism of land ethic, etc. rather than trees' standing. However, a decrease in the number of individual organisms leads to an increase in the risk of extinction and a reduction in primary production. Actually, a method for assessing change in the risk of extinction due to a decrease in the number of individual organisms has been adopted for the impact assessment by LIME, and changes in the number of individual organisms have been reflected in the impact assessment.

2) Although it was planned that impact on future generations would be examined from the viewpoint of intergenerational fairness, there is no clear standard about to what extent the future should be considered.

3) Generally, “the ecosystem” includes not only living things but also environmental media, such as water, air, and soil, and landscape. However, the pollution of environmental media is treated as a matter to be measured intermediately in LIME, and environmental media are not included in the areas of protection. In this sense, LIME is a concept relatively close to biocentrism.

4) The results of damage assessment by LIME expresses that environmental impact is larger when an unspecific number of people receive a large amount of damage than when a specific number of people receive a small amount of damage. In principle, there is no regional or chronological discrimination. This indicates that there is a stronger tendency toward totalitarianism than toward individualism. In addition, such a way of understanding is adopted by many LCIA methods.

5) It can be thought that the establishment and weighting of the four items to be protected are relatively consistent with the “spaceship ethics,” which places importance on the balance of the components, thinking of the whole Earth as a system. This may be inconsistent with assertions based on the lifeboat ethics.

6) To increase the objectivity of the definition of areas of protection, LIME adopted theories of environmental ethics. However, because method developers make final judgment about the definition of areas of protection, their ideas cannot be completely eliminated. However, a panel of experts held discussions as described above so that objectivity could be secured to the extent possible.

In this way, there are some problems n the definition of areas of protection. However, according to the results of analysis of weighting factors conducted after the interview survey, all the four items included in the objects of protection specified by LIME were statistically significant (see Chapter III). This indicates that people think of all the four items as valuable, and it can be proven that assessment of these impacts is important.

Table 1.2-4 is a list of objects of protection proposed so far. Points of similarity and points of difference can be summarized as follows:

[Points of similarity]

- Items concerning human health are defined as independent areas of protection.
- Items concerning biodiversity are included in the objects of protection as qualitative elements of the ecosystem.
- Mineral resources and fossil fuels are included in the objects of protection or the elements of the objects of protection.

[Points of difference]

- Whether to include plant growth in the areas of protection differs among methods.
- The methods differ in whether to include farm products, aquatic resources, forest resources, and others regarded as valuable in human society in the areas of protection.
- Some methods treat mineral resources and fossil fuels as independent areas of protection, while other methods define their broader concept (such as social assets) as the areas of protection and treat mineral resources, etc. as components of the concept.

Table 1.2-4: Lists of objects of protection proposed so far and damage indexe

	EPS ver. 2000	Eco-indicator '99	LIME	SETAC
Human life	Human health Death: YOLL, serious illness・illness・serious discomfort・discomfort: Case	Human health DALY (death, illness)	Human health DALY (death, illness)	Human health
	Nonliving resources kg (each type of resource)	Resources MJ; Surplus energy (each type of resource)	Social assets Yen (resources, farm products, marine products)	Natural resources Artificial environment
Soundness of ecosystem	Biodiversity NEX (Normalized Extinction of Species)	Quality of ecosystem PDF (Potentially Disappeared Fraction)	Biodiversity Number of extinct species (expected number)	Natural environment
	Ecological productivity (farm products, marine products, meat, water: kg, cation: H^+)	-	Primary production NPP (Net Primary Productivity)	Life maintaining function
	Quantitative assessment of damage assessment and integration			No indication

Eco-indicator 99 mentioned the three items in Table 1.2-4 as the items recognized as the most serious environmental problems in Europe, referring to EEA (1996). Eco-indicator 99 deals with impacts in Europe and assumes that farm products' impact on artificial environments will not become serious. EPS does not show special discussions about the selection of areas of protection. However, it regards mineral resources and fossil fuels as components of "abiotic resources," while it includes farm products, fishery resources, and wood in the objects of assessment as areas of protection called "ecological productivity," together with cation, water, etc. In addition, although EPS has selected "landscape" as an object of protection, there is no integration factor that includes the impact on the item. Therefore, in reality, the impact on landscape is not measured. The Society of Environmental Toxicology and Chemistry (SETAC) regards forests and other plant production as a "life-support function," but includes the resources produced through human beings' encouragement to the natural environment, such as farm products and aquatic resources, in another object of protection called "man-made environment."

In this way, the selection of areas of protection still differs among the previous research cases. It can be said that the selection of areas of protection are materialization of what components of the natural environment should be protected by the LCIA methods. Therefore, the clarification of the concepts and theories that serve as backgrounds to the establishment of areas of protection is important for securing objectivity. In addition, because differences in the range of areas of protection among the LCIA methods greatly influence integration results, the differences require attention.

1.2.4 Definition of damage indexes

(1) Human health

Indexes of damage to human health are widely used for medical economy and insurance statistics in order to grasp the current situation of health loss and make decisions about medical activities. Recently, the use of such indexes has begun in the field of environmental assessment.

The following are standards that express human health:

1) Number of people (such as the number of victims and the number of deaths)
2) Time (such as duration of disability)
3) Degree of reduction in QOL due to disability

It is desirable to include all the standards appropriately. The following indexes include all of them:

1) YOLL (Years of Life Lost)
2) QALY (Quality Adjusted Life Year)
3) DALY (Disability Adjusted Life Year)

Figure 1.2-4 shows the images of these indexes. A sheet in the figure is a life balance sheet that indicates the health condition over one's entire life. The horizontal line of the sheet indicates age and the vertical line indicates QOL. If an age is entirely expressed by a light shade (QOL=1), this indicates healthy. If an age is partially expressed by a dark shade, QOL decreases due to a certain disability (QOL<1). If QOL is 0, this indicates death. In this case, asthma occurs in the 10s, an accident occurs in the 20s, cataract occurs during the 40s and the 50s, pneumonia occurs in the 60s, and cancer occurs during the 70s and the 80s, which causes death.

1) Because YOLL basically includes the loss of life expectancy due to early death, early death due to cancer is counted in this case.

YOLL due to cancer = 85 – 81 = 4 (years) (1.2-4)
(When it is assumed that the person could live until 85 years old if he did not suffer cancer)

YOLL does not count any disability or disease that does not lead to death. Therefore, if the emission of CHC increases the number of persons who suffer cataract, this is not counted by YOLL unless they die. As indexes that avoid this problem, 2) QALY and 3) DALY have been drawing attention. They are characterized by being able to integrate death and disability by measuring loss of health due to disability as loss of life expectancy. Both measure loss of health due to disability by multiplying a reduction in QOL due to disability by the period over which the disability continues. In the case of Figure 1.2-4, loss of QALY due to cataract can be calculated as follows:

Loss of QALY due to cataract = 0.15 (Loss of QOL) × 10 (years) = 1.5 (years) (1.2-5)

For the purpose of risk assessment and insurance statistics, an index that expresses the integrated death and disability as loss of life expectancy is called "QALY." QOL and the period of disability used for the calculation of QALY differ among individuals, and the average QOL and period of disability differ among countries and regions. Because of this, when QALY is assessed, the assessor selects an area for the assessment, independently carries out analytical research, and calculates QOL and other parameters concerning each disability. Consequently, universal QALY that can be used all over the world has not been obtained for every disease or cause of death.

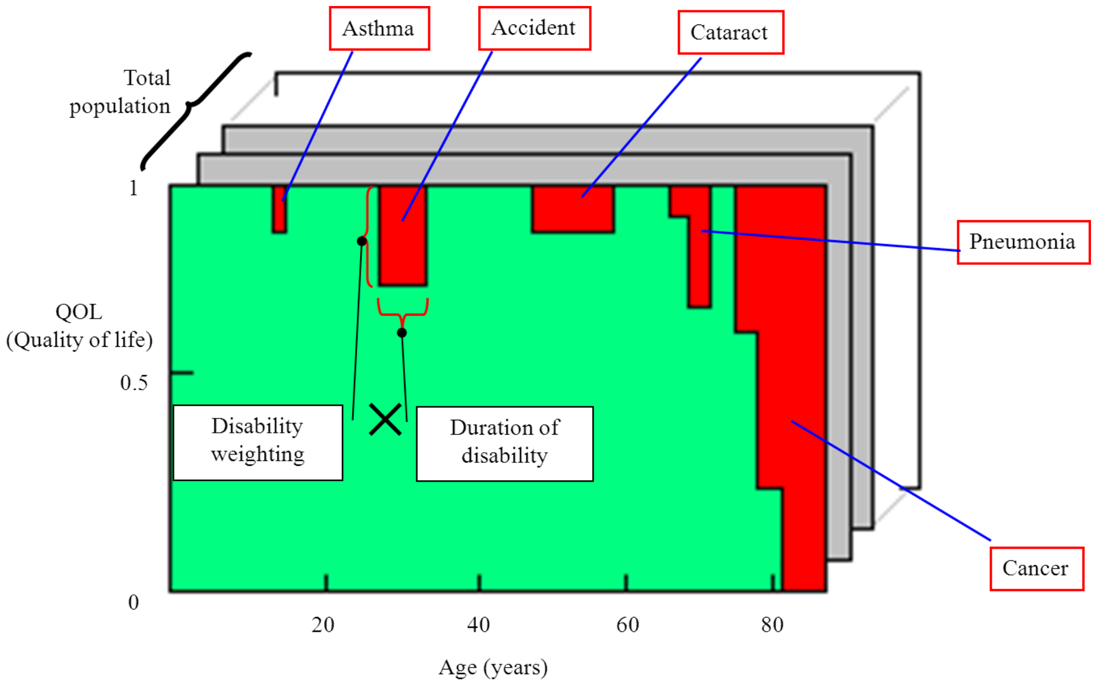


Figure 1.2-4: Image of indexes that indicate damage to human health
The loss of life expectancy due to a specific disease, etc. is indicated by the parts in red (product of a decrease in QOL and the period of disability).

On the other hand, DALY was developed to assess the situation of health loss in the world quantitatively, including health loss in developing countries. DALY is a health index that Murray et al. of Harvard University (1994, 1996) developed together with WHO during research on the Global Burden of Disease (GBD) at the request of the World Bank. Figure 1.2-5 compares the annual DALY in the world (2000) with the annual DALY in Japan (1995). Although the situation of health loss varies in the world, including infectious diseases, perinatal diseases, and acquired immune deficiency syndrome (AIDS), diseases peculiar to developed countries, such as cancer and cerebrovascular diseases, rank high in Japan. In this way, the situation of health loss greatly differs among regions and countries, and each country uses such an index to select diseases to be deal with first.

DALY is defined as follows and is used for the calculation of loss of life expectancy in the world:

$$DALY = YLL + YLD$$

$$\int_{x=a}^{x=a+L} Cx \exp(-\beta x) \exp\{-r(x-a)\} \, dx + \int_{x=a}^{x=a+L_a} DCx \exp(-\beta x) \exp\{-r(x-a)\} \, dx \tag{1.2-6}$$

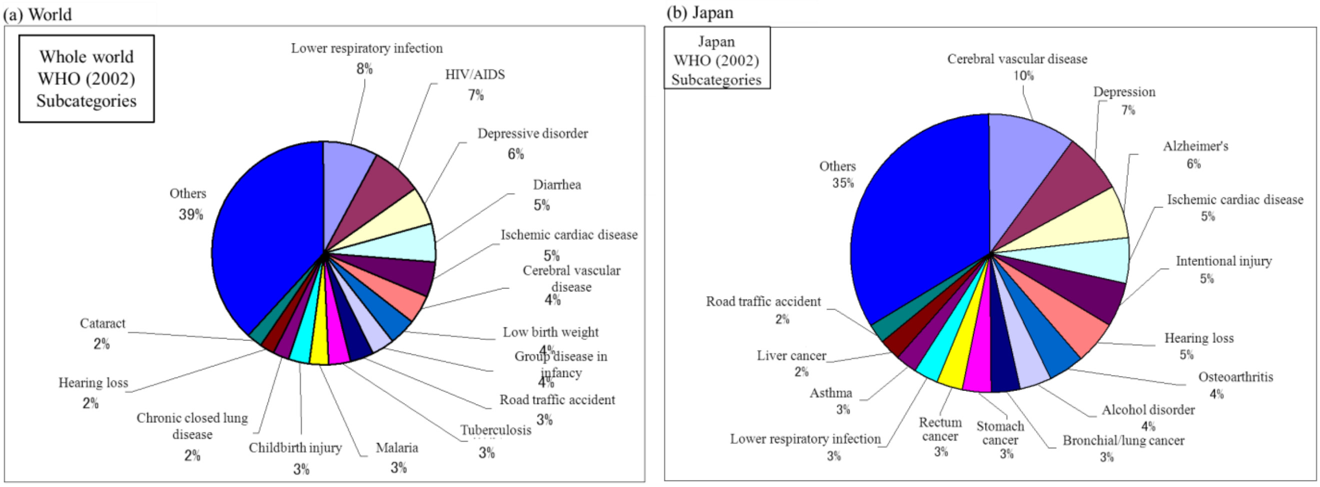


Figure 1.2-5: Current situation of health loss in the World and in Japan

YLL refers to years of life loss due to early death, YLD refers to years lost due to disability, and DALY is the total of the two. a is the age of occurrence of disability or death, L is the difference between life expectancy and the age of death, and La is the duration of disability. C and β are fixed numbers of 0.1658 and 0.04 respectively. This formula can be obtained by integrating the product of the following three items over time:

1) Weighting of disability (D)

2) Social value of the age of disability or death (weighting by age) ($Cx \exp(-\beta x)$)

3) Time discounting ($\exp\{(-r)(x-a)\}$)

1) Weighting of disability was introduced to compare and integrate it with respect to the number of years lost due to death, by including a decrease in QOL as described above. D = 0 in the case of health, while D = 1 in the case of death. D is set between 0 and 1, depending on the seriousness of disability due to each disease. The Delphi method was adopted for the setting. First, a panel of experts classified disabilities into seven classes, referring to specific standards (Table 1.2-5). The standards for classification reflect four basic elements for human life (entertainment, education, reproduction, and work). Whether one or more of them are partially or wholly damaged is the criterion for classifying various disabilities. For example, diseases that wholly damage almost all of the elements (paralysis of the extremities, serious dementia) are classified into Class 7, which represents the most serious condition. After all the diseases covered by DALY are classified into these classes, each disease is weighted.

2) Weighting by age (Figure 1.2-6) reflects difference in value between a year when physical strength is high and a year when it becomes lower. If the function is differentiated with respect to x, the differential function becomes $C(1-\beta x)\exp(-\beta x)$ and has its maximum value when $x = 1/\beta$. Murray et al. set β at 0.04 so that the annual value will become the maximum at the age of 25.

Table 1.2-5: Criteria and basic classification of disability weighting

(90 categories, 250 subcategories)

Class	Weighting	Examples of health condition
1	0.00-0.02	White spots on the face, low height (less than 2SD)
2	0.02-0.12	Watery diarrhea, serious sore throat, serious anemia
3	0.12-0.24	Fixing of plaster cast due to radial bone fracture, sterility, erection failure, rheumatoid arthritis
4	0.24-0.36	Lower limb amputation (under knees), complete hearing loss
5	0.36-0.50	Rectovaginal tumor, slight mental retardation
6	0.50-0.70	Depressive disorder, complete sight loss, paraplegia
7	0.70-1.00	Active mental disorder, dementia, serious migraine, limb paralysis

Healthy: 0; death: 1

Four standards for determining weighting: amusement, education, reproduction, employment

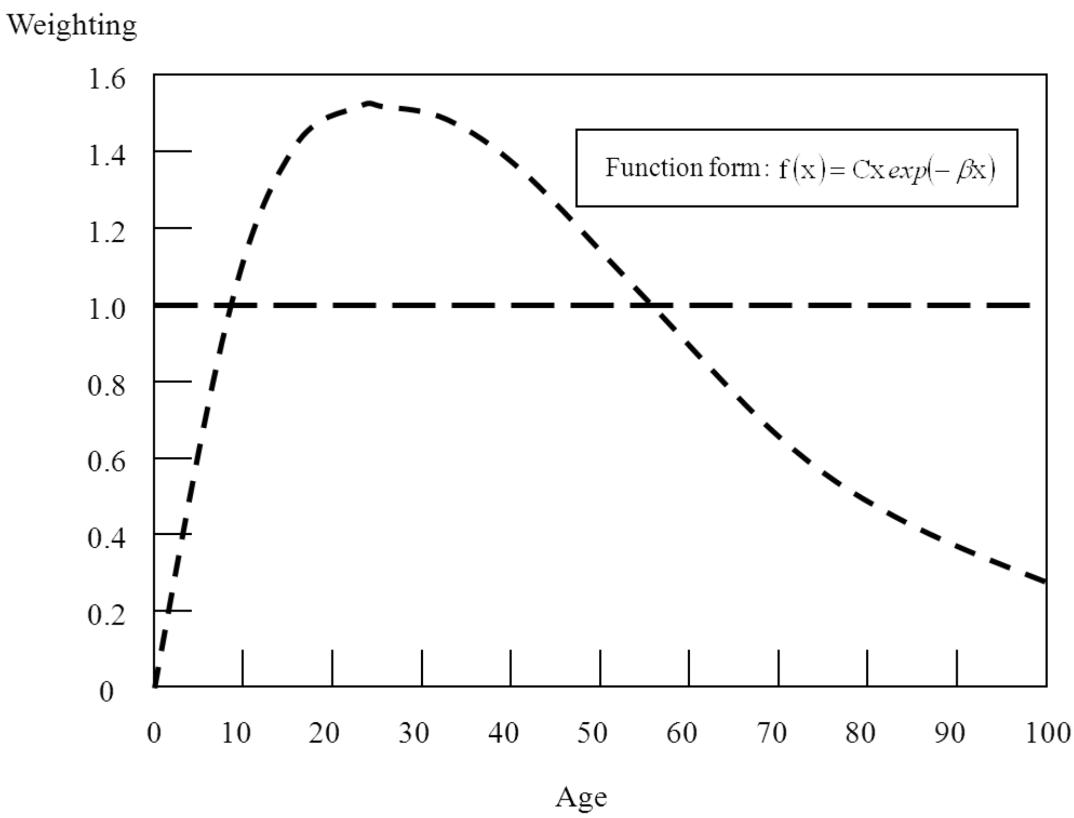


Figure 1.2-6: Age weighting function

3) Time discounting is consideration of difference in the value that may differ depending on the time of occurrence of the same event. For example, there is difference between receiving one million yen now and receiving the same amount 50 years in the future. The amount can be used during the 50 years if it is received now, while whether the money can be actually used is unknown if it is received 50 years in the future. Therefore, it is usually thought that the value of money is higher when the money is received now. In contrast, if the same damage occurs, it is better to receive it as late as possible. In the field of economics, time discounting is a concept in common use. Murray et al. adopted time discounting also for DALY, uniformly applying $r = 0.03$; that is, an annual rate of 3%. Figure 1.2-7 shows the relation between time and value if the discount rate is 3%. In this case, when 20 years pass, the value will become almost half. Therefore, the value of yearly loss 20 years after is equivalent to the value of half-year loss at present.

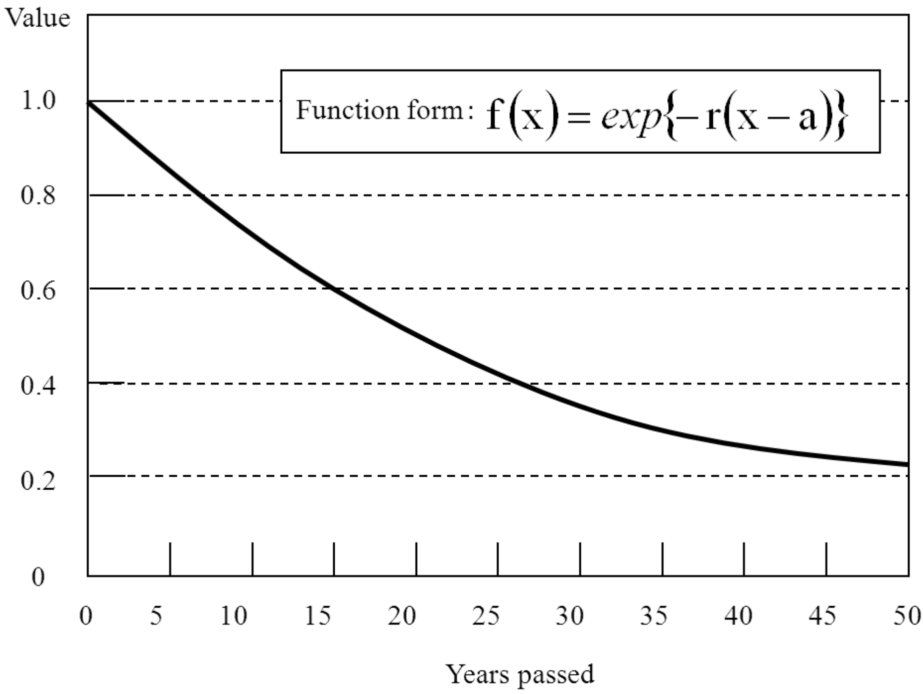


Figure 1.2-7: Discounting function (when the discounting rate r = 0.03)

DALY was adopted for LIME as the index of health damage, for the following reasons:

1) Because the health impact in the whole world has already been qualified, DALY is suitable for assessing global environmental impacts, such as global warming and ozone layer destruction.

2) DALY has been authorized internationally. For example, WHO uses it for its Health Report.

3) DALY is often used for LCIA. DALY enables direct comparison of the results of assessment in this research with the results of assessment by other LCIA methods and facilitates comparison of methods.

However, when the concept of DALY was examined in light of LIME not as insurance statistics but as an LCIA method, the necessity for inheriting all the characteristics of

DALY like the weighting of age seemed low. Therefore, discussion was held about whether to adopt the components of DALY.

The strongest characteristic of DALY as an index of health is the weighting of ages. There is much criticism of the highest value of life being assigned to the age of 25. Because of this, when health damage is assessed under LCIA, it seems almost unnecessary to apply the weighting of ages. Therefore, the weighting of ages was not adopted for LIME. Although time discounting was usually used for economic analysis, an agreement has still not been reached in the field of health science concerning the application of similar discounting to life expectancy. With regard to time discounting, there are two issues: whether to adopt it and how much time should be discounted if time discounting is applied. With regard to the latter issue in particular, it is difficult to find reasonable grounds. For the purpose of this method, it was decided that time discounting should not be taken into consideration at present, awaiting discussions in the field of insurance statistics, etc. Table 1.2-6 summarizes how to consider the components of DALY for the purpose of LIME, comparing it with WHO and Eco-indicator 99. Although Eco-indicator 99 includes the weighting of ages in the individualism established as one of the environmental ideas, LIME and Eco-indicator 99 have taken similar measures concerning the other matters.

Table 1.2-6: Comparison of treatment of parameters that constitute DALY

	WHO, Murray (1996)	Eco-indicator ’99	LIME
Disability weighting	Adopted	Adopted	Adopted
Age weighting	Adopted	Partially adopted (Individualism only)	Not adopted
Time discounting	Adopted (yearly rate of 3%)	Not adopted	Not adopted

In this way, because the original DALY was revised in LIME, it would be rather appropriate to say that QALY is used as the index of health damage. However, although other LCIA researches (for example, Hofstetter (1998), Goedkoop et al. (1999)) have not adopted the weighting of ages and time discounting, the index of health damage is called DALY. Therefore, in the field of LCA, it is becoming common to call loss of life expectancy, including disability, DALY. Following this trend, it was decided that the index of health damage should be called DALY for the purpose of LIME.

Under LIME, damage factors to human health are expressed by DALY/kg concerning all the target substances (For the method for calculating damage factors and the list, see Chapter II and Annex 1.2, respectively). The index of damage can be derived by multiplying inventory data *Inv* (*X*) by the corresponding damage factor DF^{Impact} (*HumanHealth, X*). As a result, *DI (HumanHealth)* is expressed by DALY – that is, the number of years.

$$DI(HumanHealth) = \sum_{Impact} \sum_{X} \left\{ DF^{Impact}(HumanHealth, X) \cdot Inv(X) \right\} \tag{1.2-7}$$

(2) Social assets

The number of agreements about the environmental impact on social assets is smaller than that on agreements about the environmental impact on human health (see Column 1.2-2). In addition to methodology, the coverage and assessment indexes have not been discussed fully. However, because pioneer LCIA methods also assess the items related to social assets, it is expected that methods covering the items will be developed in the future.

Under LIME, social assets are regarded as an essential element that supports the mental and physical health of human beings and social soundness from the aspect of resources. This is a response to the following: because the growth of plants (primary production) supplies oxygen and is the starting point of food webs, it is considered to be one of the areas of protection as an essential element for maintaining the ecosystem. This is because Japan greatly depends on importation concerning not only energy resources and mineral resources but also forest resources and food and does not possess sufficient resources for life. Because of this, under LIME, “social assets” were included in the areas of protection as a broader concept that covers fossil fuels, mineral resources, forest resources, aquatic resources, and agricultural resources as its components.

Column 1.2-2

Components of social assets

Table 1.2-B compares main LCIA methods’ ways of understanding social assets. EPS (Steen 1999) divides social assets into “ecosystem production capacity” and “abiotic resources.” The former is related to living elements, while the latter is related to nonliving elements. Although ExternE (EC 1998) has no definition of areas of protection, the impacts that occur mainly when environmentally damaging substances are emitted (output) are assessed. Eco-indicator 99 (Goedkoop et al. 1999) defines “resources (mineral resources, fossil fuels)” as the area of protection. Contrary to ExternE, Eco-indicator 99 takes into consideration the consumption of exhaustible resources, but excludes the impact on the depletion of assets caused by emission of pollutants such as fishery and forestry.

If social assets are examined at the element level (Table 1.2-B), all the methods that cover nonliving resources include fossil fuels and mineral resources, but they differ in the treatment of water resources and materials. Although developed countries are highly interested in the exhaustion of minerals and fossil fuels, a shortage of water in developing countries is severe at the global level. Eco-indicator 99 covers Europe, LIME covers Japan, and EPS deals with the world. Difference in the range of objects of assessment among the methods may be caused by difference in the target areas.

Although all the methods that assess living resources include forest resources, aquatic resources, and farm products, EPS also takes into consideration the impact on meat and cation (buffer capacity against acidification of soil). It seems necessary to verify the comprehensiveness of the components of social assets (whether the impact of environmental pollution on meat, etc. is small enough to ignore, compared with other elements).

Table 1.2-B: Concept of social assets in main LCIA methods

		EPS ver.2000	Eco-indicator'99	ExternE	LIME
Area of protection related to social assets		Ecological productivity Nonliving resources	Resources	No definition	Social assets
Assessment area		Global	Europe	Europe	Japan (in the case of mining of resources, impact at spots of mining is assessed)
Nonliving		Fossil fuels	Fossil fuels	-	Fossil fuels
		Mineral resources	Mineral resources	-	Mineral resources
		Cation	-	-	
		Water	-	-	
		-	-	Materials	
Living		Forest resources	-	Forest resources	Forest resources
		Aquatic resources	-	Aquatic resources	Aquatic resources
		Farm products	-	Farm products	Farm products
		Meat	-		

Many of the LCIA methods developed mainly by developed countries have so far targeted nonliving resources, in order to restrict the consumption of fossil fuels and mineral resources and increase resource productivity. However, there are suggestions that, if a valuable resource degrades due to an environmental impact, an economic assessment method, such as ExternE or EPS, should assess the depletion of the resource as a socioeconomic impact, regardless of whether or not its market exists (see Column 1.2-3).

The index for assessing the amount of damage to social assets differs depending on the components of the social assets. Table 1.2-7 summarizes the damage indexes for items related to social assets and how to assess the indexes. If, like Eco-indicator 99, an LCIA method covers fossil fuels only or mineral resources and other nonliving substances, it can express damage in physical amount, such as energy amount.

If forest resources, farm products, and other living resources are also assessed comprehensively, the degree of damage to them is often expressed by economic indexes. However, the assessment methods differ according to what LCIA method is used and what is assessed. For example, transaction prices are applied for farm products, forest resources, and aquatic resources, for which markets exist. With regard to resources for which markets do not exist or are hard to find (water, cation), the willingness to pay (WTP) calculated by the contingent valuation method (CVM) is often used. With regard to resources for which markets exist, but it is difficult to use market prices as they are, because of the relation with future generations (fossil fuels, mineral resources), the manner of treating them differs among methods. Assuming that an alternative resource will be used after the exhaustion of each resource, EPS adopts the (integration) result of impact assessment in the case of production of alternative resources as the integration factor. On the other hand, LIME adopts the user cost method. The user cost method calculates the amount of money that the current generation should save in order to make the profit that the future generation will gain through the procurement of the resource in question equivalent to the profit received by the current generation (for details, see Section 2.10). Because the result is expressed in amount of money, it is possible to examine the relation with the impact on the other elements (forest resources, living resources, and farm products).

Table 1.2-7: Damage indexes of social assets and methods of calculating the amount of damage to each component in main LCIA methods

Method	EPS ver. 2000	Eco-indicator ’99	ExternE	LIME
Damage index / Component	Amount of money	Energy	Amount of money	Amount of money
Fossil fuel	Integration of alternative resources	Excessive energy	-	User cost
Mineral resources	Integration of alternative resources	Excessive energy	-	User cost
Cation	WTP	-	-	-
Water	WTP	-	WTP	-
Material	-	-	Maintenance cost	-
Forest resources	Price	-	Price, WTP	Price
Aquatic resources	Price (lump-sum)	-	Price, WTP	Price
Farm products	Price (lump-sum)	-	Price	Price

In this way, the simultaneous use of several assessment methods, such as price, willingness to pay, and user cost, enables comprehensive assessment, but the following issues seem to remain:

1) Is it possible to simply add up results derived by different methods?

2) To calculate a value lost in society, it is better to add up losses in consumer surplus and total surplus (total of consumer surplus and producer surplus). The amount of damage can be calculated by multiplying the amount of valuables lost due to environmental changes (for example, the amount of aquatic resources) by their economic values. This amount of damage differs from the reduction in consumer

surplus. At present, however, it is impossible to measure changes in surplus concerning all farm products, forests, etc.

3) Although the user cost method is excellent in that it can comprehensively assess nonliving resources, it is necessary to set a discount rate. LCIA usually does not discount the impact on future generations, which is often treated in the same way as the impact on the current generation. If assessment results gained from methods that differ in treating the impact on the future are added up, it is necessary to make some adjustment.

Under LIME, attention was paid to the following impact categories that influence social assets: global warming, ozone layer destruction, acidification, eutrophication, photochemical oxidant, wastes, mineral resources consumption, and fossil fuels consumption. Table 1.2-8 shows the relation between the impact categories and the components of social assets. For reference, the table also shows relations with other LCIA methods.

Table 1.2-8: Relation between components of social assets and impact categories

ICA method / Impact category	EPS	ExternE	LIME
Glo bal warming	Farm products	Farm products	Farm products
	Wood	-	Forest
	-	Land	Land submergence
	-	-	Energy resources
	-	Water resources	(Impact of water shortage on farm products)
Ozone layer destruction	(Interrelated with warming)	-	Forest (conifer forest)
Acidification	Fish/meat	Fish	Aquatic resources (salmon/trout)
	-	Forest	Forest resources
	-	Farm products	-
	-	Material	-
	Cation	-	-
Eutrophication	Fish/meat	-	Aquatic resources
	Wood	-	
Photochemical oxidant	Wood	Forest	Forest
	Farm products	Farm products	Farm products
Waste	-	-	Disposal site
Fossil fuel consumption	Fossil fuel	-	Fossil fuel
Mineral resources consumption	Mineral resources	-	Mineral resources

Under LIME, the impact of acidification on farm products and the impact of eutrophication on forests, etc. were not assessed. This is because, as shown below, these impacts do not seem serious at present in Japan.

1) Generally, farm products are highly acid-resistant. Nouchi (1996) asserts that rainfall has almost no impact on the growth or yield of farm products unless the pH of rainfall decreases to the 2.0 level. Because the current rainfall in Japan is at a level of pH 4 to 5, it is thought that acid rain does not directly damage agriculture. Many experiments on the impact of acid deposition on farm products show that the usual level of acid rain causes no reduction in yield (Banwart et al. 1990, NAPAP 1987, Hosono et al. 1994).

2) The impact of eutrophication on the terrestrial ecosystem is one of the items to which great importance is attached in Europe. According to GEO-2000 (UNEP 2001), the whole of North Europe is saturated with nitrogen at present. The number of research cases about whether nitrogen saturation has occurred is increasing also in Japan. As described in Yo et al. (1999), Kato et al. (1999), Baba et al. (1998), Yo et al. (2001), Hayashi et al. (2001), and Ohrui (1997), many experts have the opinion that the forests in Japan are sound, although the density of nitrate nitrogen is generally or seasonally high in soil and soil solution. Moreover, because nitrogen burden brings about a positive effect at the beginning, it is necessary to discuss how to formulize the relation with the negative effect of nitrogen saturation.

Although LIME includes not only mineral resources and fossil fuels but also living resources consumption in “resources consumption,” the economic value of forest ecosystem services greatly differs among assessors and it cannot be applied to LCIA due to insufficient discussions. Therefore, it is not included in the objects of assessment (however, damage to primary production and biodiversity due to the use of living resources is included in the objects of assessment. See Section 2.10).

Moreover, in LIME2, the loss of social assets due to landfill of waste was newly included in the objects of assessment. This is because waste disposal sites have scarcity in Japan, whose land is narrow. As in the case of mineral resources and fossil fuels, the user cost method was adopted as the assessment method.

Under LIME, damage factors to social assets are expressed in Yen/kg concerning all the target substances (for the calculation method and list of damage factors, see Chapter II and Annex 1.2 respectively). Damage assessment can be conducted through multiplication by the damage factor DF^{Impact} (*SocialAssets*, *X*), which corresponds to inventory data *Inv* (*X*). As a result, *DI* (*Social Assets*) is expressed in Yen.

$$DI(SocialAssets) = \sum_{Impact} \sum_{X} DF^{Impact}(SocialAssets, X) \cdot Inv(X) \tag{1.2-8}$$

(3) Biodiversity

Because human activities have been giving great damage to the natural environment, the conservation of biodiversity has become essential for guaranteeing the right of living with the blessings of nature to not only the current generation but also future generations. Biodiversity is a word coined during the second half of the 1980s. Biodiversity is defined as the concept that the diversity of life brought about on the Earth between the birth of life and the evolution of living things, ranging from hereditary diversity to landscape diversity, has compositional, structural, and functional strata (see Figure 1.2-8) (Washitani 1996).

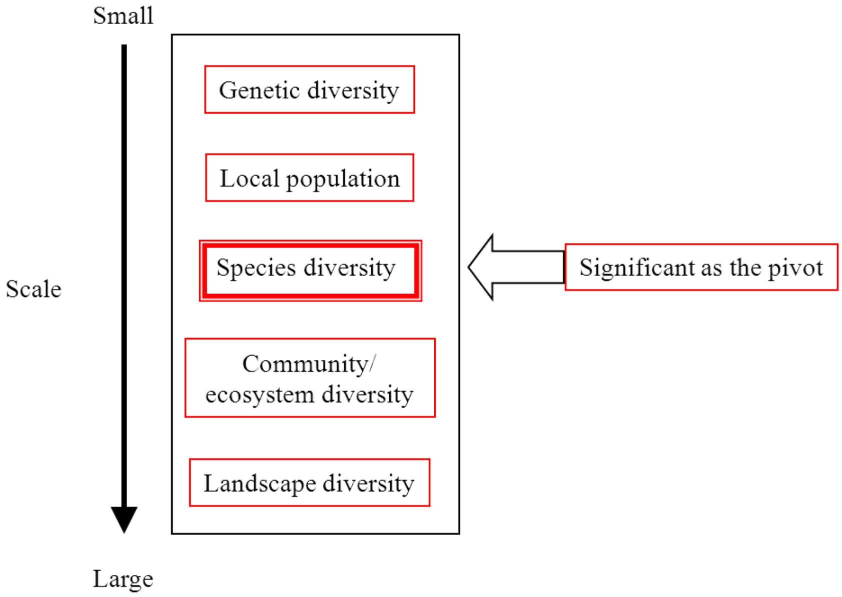


Figure 1.2-8: Layered structure of biodiversity (Washitani (1996))

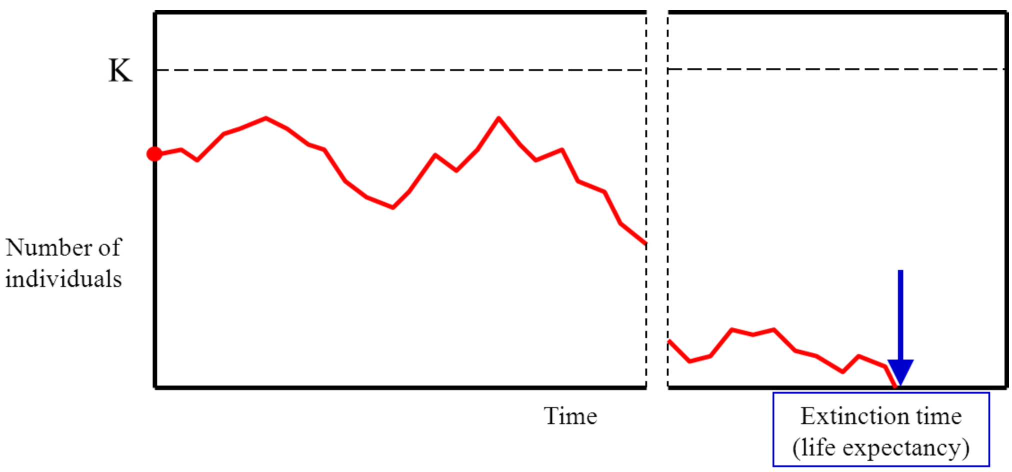
Because it was difficult to express the impact of all these strata on the ecosystem, when a damage index is selected for LIME, it was necessary to select representative elements of biodiversity from among the strata. The following are the processes up to the selection of a damage index for LIME:

The Endangered Species Act in the US and the Washington Convention on International Trade in Endangered Species of Wild Fauna and Flora specify the living things to be protected concerning each species. In addition, the Red Data Book (RDB) of the International Union for Conservation of Nature (IUCN) specifies the living things in danger of extinction and their degree of risk of extension. Then the Environment Agency published RDB in accordance with IUCN's RDB, describing the current situation of the endangered species in Japan. Ecologists have expressed the view that the stratum of "species and population" is the "pivot" of biodiversity. This is because the stratum is the base for the stratum of "community and ecosystem" at a larger-scale level through interrelation among living things, while it influences the properties of the stratum of "gene" at a smaller-scale level through the movement of gametes within a population and between populations.

Moreover, RDB and other data necessary for quantitatively assessing the impact on biodiversity exist at the level divided by species. Usually, the assessment of the ecosystem by LCIA focuses on species.

In this way, from every aspect, such as domestic and foreign trends in biodiversity, current ecological views, and the feasibility of development of assessment methods, it was decided that LIME should focus on changes in "species" as the element representative of biodiversity. In addition, because RDB and other activities for protecting species aim to prevent the extinction of species, LIME picked up the risk of extinction of species as the index that most directly expresses the damage received by biodiversity.

Figure 1.2-9 shows an image of secular changes in the population of a species. The population of a species is thought to move between 0 and the maximum permissible level (*K* in Figure 1.2-9). This is because, as the population becomes closer to a certain level (*K*), food and other resources become insufficient and the competition among individuals becomes fiercer, with the result that the number of individuals will be limited. After the population changes within a certain range, receiving influences from various limitation factors, it becomes 0; that is, the extinction of the species. The time between the present and the extinction is called the "extinction time" hereinafter. This extinction is regarded as the life expectancy of the species. The reciprocal of the extinction time is used as the risk of extinction. That is, if the extinction time is 100 years, the risk of extinction per single year is 1/100, the reciprocal.



Extinction time = f (K, r, v)

Figure 1.2-9: Relation of temporal changes in the number of individuals of a species and the extinction of the species

K: environmental capacity, number of existing individuals
r: intrinsic rate of natural increase, decreasing rate
v: sensitivity to environmental changes

In the field of conservation ecology, detailed examination has been promoted concerning methods for assessment of risks of extinction in the ecosystem and collection of data about the risks. For this purpose, the extinction time is usually calculated based on the results of simulation by the Monte Carlo method, etc. Therefore, the extinction time gained from simulation is an expected value. To derive a damage factor for biodiversity, it is effective to use regression research results based on such calculation of the extinction time.

As the damage index for biodiversity, LIME adopted the Expected Increase in Number of Extinct Species (EINES) gained from the expected value of the increased risk of extinction of species due to environmental burden.

EINES is calculated as follows:

$$EINES = \sum_s \Delta R_s = \sum_s \left(\frac{1}{T_{a,s}} - \frac{1}{T_{b,s}} \right) \tag{1.2-9}$$

ΔRs refers to a change in the risk of extinction of the species *s* due to environmental burden, and $T_{b,s}$ and $T_{a,s}$ refer to the extinction time before and after occurrence of environmental burden, respectively.

After the calculation of a change in the extinction time due to occurrence of environment burden concerning each species, EINES is calculated by adding up the changes.

As shown in Formula 1.2-9, the calculation of EINES requires the assessment of the extinction time of the species before and after occurrence of environmental burden. Lande (1993) mentions the following three parameters that influence the extinction time (Figure 1.2-9):

1) Intrinsic natural increase rate: increase rate when a type of population displays its maximum biotic potential under the most favorable environment

2) Carrying capacity: maximum population that can be maintained stably in the habitat

3) Sensibility to environmental changes: changes in the population due to environmental changes, such as changes in temperature and precipitation

In LIME, attention was paid to “land use,” “mineral resources consumption,” “fossil fuel consumption,” “living resources consumption,” “waste,” and “biological toxicity” as impact categories related to the extinction of species. Damage factors were developed by relating these environmental burdens with the above-described three parameters related to extinction time.

In the case of the assessment of the impact of land use, the plant population decreases in a site where land is physically rearranged.[*2] A damage factor was calculated by relating this change in the population to the change in carrying capacity explained in 2) above. In addition, the mining of resources and the landfill of waste also are accompanied by land rearrangement. Therefore, the impact of these acts on the ecosystem was included in the impact categories “mineral resources consumption,” “fossil fuel consumption,” biotic resources consumption,” and “waste.”

In the case of impact assessment by a toxic substance, changes in sensitivity were calculated in relation to changes in 1) intrinsic natural increasing and 3) environmental changes due to exposure to the toxic substance, and assessment was made on the

[*2] The impact of land use can be roughly divided into the impact of land rearrangement and the impact of land maintenance. For the purpose of the impact on biodiversity, only the former was assessed. This is because it was assumed that the population of a species, one of the parameters used for the assessment of extinction time, greatly changes when land is physically rearranged, but does not change by land maintenance. Because (artificial) land maintenance influences plant growth more than that under natural conditions, the impact of land maintenance is assessed in relation to damage to “primary production.”

assumption that changes in sensitivity would lead to a reduction in the extinction time. Table 1.2-9 summarizes the relation between assessment of damage to biodiversity and conservation ecology.

Because a damage factor is a change in EINES due to an environmental burden, the use of it for LCIA requires the calculation the damage index *DI (Biodiversity)* through sum of products of the damage factor DF^{Impact} *(Biodiversity, X)* and the corresponding inventory *Inv (X)*. The unit of damage factor is EINES. However, because LIME gives consideration to several impact categories as factors for changes in the risk of extinction of species (Table 1.2-9), there are two units of the inventory *Inv (X)*: weight (kg) (in the case of emission of chemical substance, waste landfill, and resources consumption) and area of land transformation (m2). Note that, accordingly, there are two units of damage factor – EINES/kg and EINES/ m^2.

$$DI(Biodiversity) = \sum_{Impact} \sum_{X} DF^{Impact}(Biodiversity,\ X) \cdot Inv(X) \tag{1.2-10}$$

Details of the methodology of calculating damage factors were explained in Sections 2.7 and 2.9.

Table 1.2-9: Summary of damage assessment of biodiversity in LIME

Impact category	Biological toxicity	Land use	Resource consumption	Waste
Elements of ecosystem influenced by environmental burden	Intrinsic rate of natural increase Sensitivity to environmental changes	Number of individuals	Number of individuals	Number of individuals
Species	Aquatic organisms (fishes, Crustacean, algae)	Vascular plants (weakest against land readjustment)	Vascular plants	Vascular plants
Base data	Toxicity data Red Data Book	Red Data Book Environmental assessment report	Environmental assessment report (sites of resources mining) Damage factor for land adjustment	Environmental assessment report (construction of landfill sites) Damage factor for land adjustment
Theory/regression equation used for estimation of amount of damage	Lande (1998), Tanaka (2000) (2001), Lande & Orzack (1988)	Matsuda (2003)	Matsuda (2003)	Matsuda (2003)
Unit of damage factor	EINES/kg	EINES/m^2	EINES/kg	EINES/kg

Column 1.2-3

Biodiversity damage assessment by LCIA methods

The biodiversity damage assessment methods proposed during LCIA researches can be mainly divided into the following:

1) Assessment of the impact caused by the exposure of a toxic substance, such as a chemical substance (example: biological toxicity)

2) Assessment of the impact on the ecosystem caused by a change in an environmental medium due to the emission or deposition of a acidifying substance (examples: acidification, eutrophication)

3) Assessment of the impact on the ecosystem caused by a physical change in a habitat (examples: land use, resource mining, waste landfill)

At present, the extinction of species is mostly caused by artificial factors. Among them, the destruction of habitats, overhunting, environmental pollution, and the invasion of introduced species are regarded as main factors (Matsuda 2000). In the above case, 1) and 2) concern environmental pollution, and 3) concerns the destruction of habitats. Although hunting and the invasion of introduced species is problematic from the viewpoint of the conservation of the ecosystem, because LCIA is conducted concerning the life cycle of products, etc., the necessity for considering them is relatively low.

Table 1.2-C summarizes the LCIA methods proposed so far concerning biodiversity. PAF and PDF have been adopted as damage indexes by Eco-indicator 99. NEX and EINES have been adopted as damage indexes by EPS and LIME, respectively. According to the table, although all of them indicate impact on biodiversity, they differ in many points, such as the meaning conveyed by each damage index, the scope of assessment, and the assessment method.

PAF refers to the ratio of species “receiving impact,” while PDF refers to the ratio of species “disappearing” from a specific area. This is because of the difference in the characteristics of the basic data used for the calculation of each damage factor. PAF uses a threshold of occurrence of impact due to the exposure of a toxic substance. PAF can be calculated from the ratio of species that exist in an environment where the density of pollutants exceeds the threshold.

The calculation of PDF is based on the ratio of species that can exist in a grid with a side of 250 meters (POO). After the calculation of POO, the disappearing ratio is calculated by deducting POO from 1. PDF is excellent in that it can assess the amount of damage caused by acidification and eutrophication in addition to the impact of land use and reflect the geographical characteristics of the target area. Eco-indicator 99 assesses damage by integrating PAF and PDF through the conversion of the former into the latter. Goedkoop et al. (1999) pointed out that it is difficult to carry out this conversion reasonably and the uncertainty is high.

Table 1.2-C: Comparison of damage indexes concerning biodiversity

Damage index	PAF (Potentially Affected Fraction of species)	PDF (Potentially Disappeared Fraction)	NEX (Normalized EXtinction of species)	EINES (Expected Increase in Number of Extinct Species)
Adopted method	Eco-indicator ‘99	Eco-indicator ‘99	EPS ver.2000	LIME
Meaning of index	Ratio of influenced species	Ratio of extinct species	Degree of annual contribution to extinction of species	Expected number of extinct species
Unit of damage index	Non-dimensional	PDF (non-dimensional) × area × time	Non-dimensional	Number of extinct species (total of extinction risks)
Related impact category	Biological toxicity	Land use, acidification/ eutrophication	Warming, acidification, eutrophication, biological toxicity, land use	Biological toxicity, land use, resources mining, waste landfill
Method of calculating damage factor	Marginal	Marginal	Average	Marginal
Strong points	・Toxicity data are reflected in damage assessment. ・The number of assessed substances is large.	・Because assessment results at the mesh level are accumulated, it is easy to reflect the characteristics of the target area. ・It is possible to take into consideration the impact of acidification and eutrophication.	・The index is highly comprehensive. ・It is relatively easy to calculate the damage factor.	・It is relatively easy to understand the meaning of the index. ・The index is based on conservation ecology. ・The index is consistent with the data of the Red Data Book.
Problems/issues	・It is difficult to integrate it with PDF rationally. ・It is difficult to understand the relation between the ratio of influenced species and the diversity of species.	・The validity of extrapolation of the result in Holland to the whole of Europe is uncertain. ・It is difficult to recognize the result of multiplying PDF by time and area as an impact on diversity.	・The validity of extrapolation of the result in Sweden to the whole of Europe is uncertain. ・Actual impact is not included in the ratio to the whole impact.	・Because of future forecast, it is difficult to verify the results. ・No consideration is given to the weighting of species.

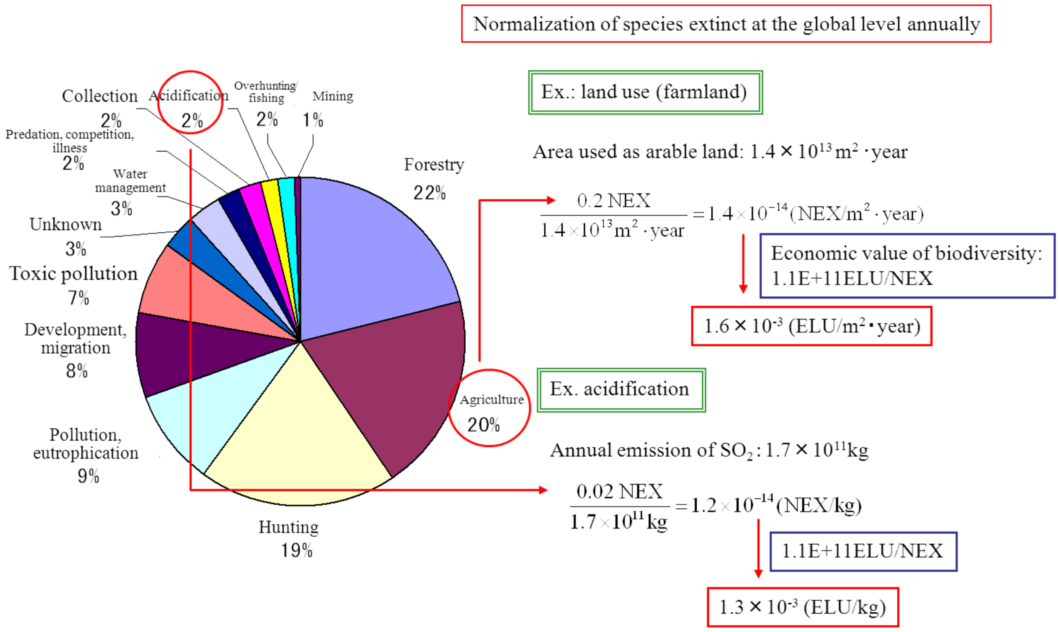


Figure 1.2-A: Calculation method of NEX (prepared by the author based on Steen 2000)
ELU: Integration index of EPS

Figure 1.2-A shows an image of a method for calculating NEX. The damage factor is calculated by dividing the annual amount of potential damage received by the ecosystem by factor and dividing the composition ratio by the annual environmental burden of the substance contributing the factor or the land use (average type). The integration factor can be calculated by multiplying the damage factor by the annual cost spent for the conservation of the ecosystem. This calculation is carried out on the assumption that the total annual cost spent for the conservation of the ecosystem is equivalent to the willingness to pay for the annual potential damage to the ecosystem. One of the advantages of this method is that it can cover various impact categories, such as agriculture, toxic chemical substances, eutrophication, and acidification. On the other hand, because the target area of the base information is Sweden, the method is carried out on the assumption that the method spreads all over the world without the validation of this assumption.

ENIES to be adopted by LIME can be obtained by adding up the risk of extinction calculated for each species. Its advantages are that the meaning of the result and the form of expression are easy to understand because the number of extinct species is directly calculated and that it is possible to compare and integrate different channels, such as the exposure of a toxic substance and land rearrangement. In addition, impact of waste and resource mining is included in assessment with consideration for the characteristics of the environmental problems in Japan. On the other hand, because the calculation of the risk of extinction is a prediction for the future, problems may arise in the future about how to verify assessment results and how to consider importance among the living species covered by the calculation of the risk of extinction.

In this way, biodiversity damage assessment methods under LCIA differ in various aspects and are still under development. Further research and development and international discussions will be required in the future.

(4) Primary production

Living things' vital activities require energy, most of which originates from sunlight. However, sunlight is not used directly. Plants use sunlight (light energy) for synthesizing CO_2 and water into organic substances. This photosynthesis generates oxygen and serves as the basis for a source of energy. In other words, plants are an existence that creates accumulative chemical energy (organic substances) from transient radiant energy (sunlight). Therefore, plants are also called producers.

Plants play various roles in the ecosystem. The most important roles for the continued existence of the ecosystem are the following two:

1) The role as the starting point of the food chain
2) The role of supplying oxygen through photosynthesis

Figure 1.2-10 shows the relation among the constituents of the ecosystem – producers, consumers, and decomposers. Because plants are living things that can create nutrition by themselves (producers), they occupy the most basic position in the food chain. Heterotrophic organisms (consumers), which cannot create nutrition by themselves, depend on autotrophic organisms for the source of nutrition. Plants are eaten by herbivorous animals, primary consumers, which are then eaten by carnivorous animals, secondary consumers. Decomposers carry out activities at every stage of the food chain, decomposing organic substances in living things' carcasses and wastes into inorganic substances so that producers can use them again, and living by the use of energy that is generated during the decomposition. Plants function as the starting point of such a cycle in the biosphere.

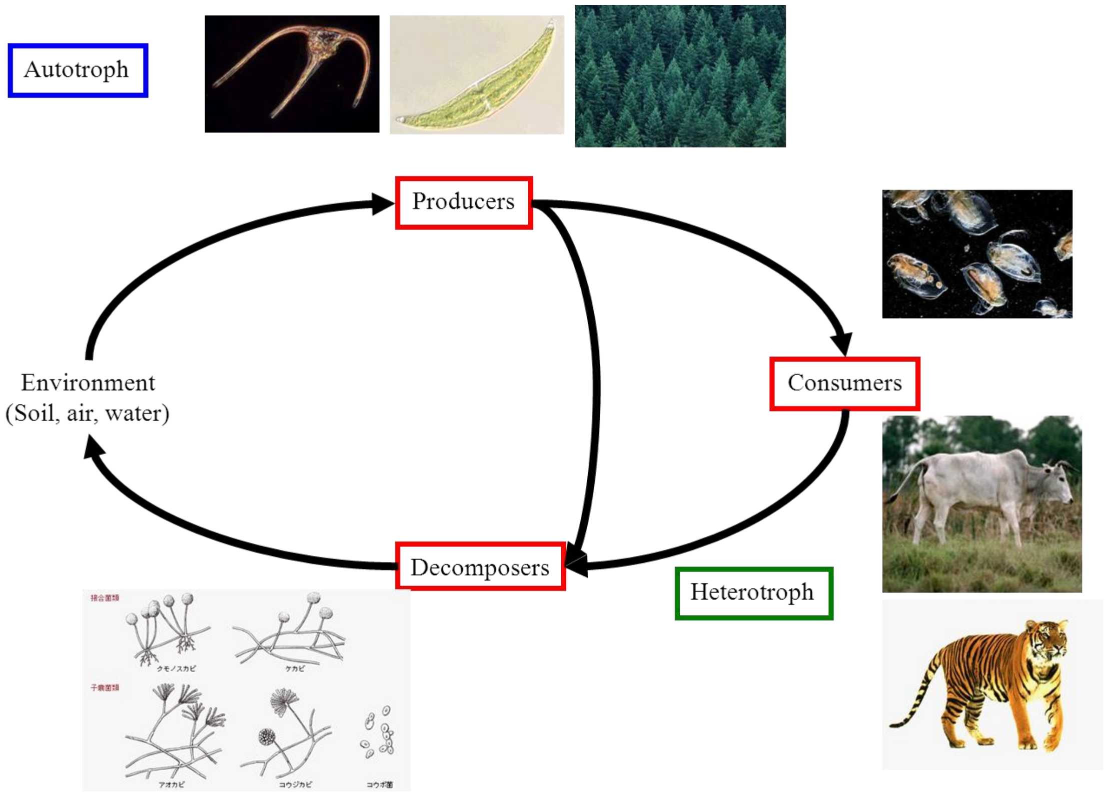


Figure 1.2-10: Environmental and biological cycling in the ecosystem

Figure 1.2-11 shows the relation between oxygen partial pressure and the track of biological evolution so far (Wada 2002). In this way, biological evolution correlates with oxygen partial pressure. That is, microbes completed the oxygen respiration system when the oxygen partial pressure in the atmosphere increased to 1/100 the pressure at present, and the ozone layer appeared and the landing of living things began when the pressure increased to 1/10 the present pressure. After oxygen was accumulated sufficiently, various higher animals prospered and biodiversity was brought about, centering on interactions among living things. In this way, the history of the development of the biosphere can be explained as the history of changes in the oxygen partial pressure in the atmosphere. Oxygen is supplied through plants' photosynthesis.

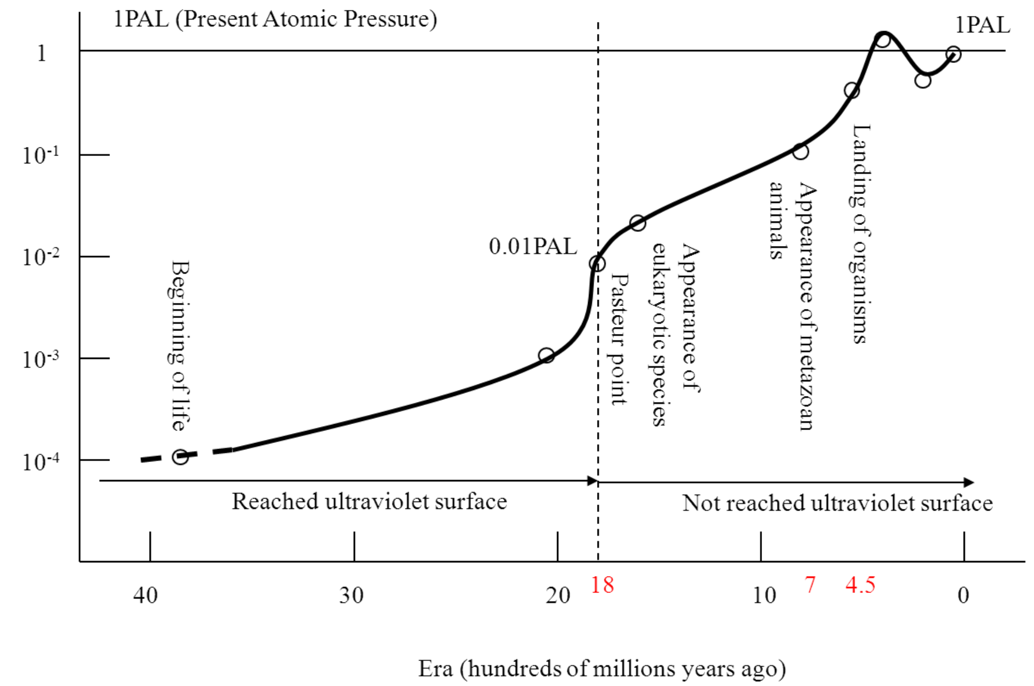


Figure 1.2-11: Relation of oxygen partial pressure and development of creatures (Wada 2002)

Plants' creation of organic substances through photosynthesis is called primary production. This is distinguished from heterotrophic organisms' production, which is called secondary production. The total amount of organic substances' production is called gross production, most of which is consumed by the respiration of plants themselves. The remaining production becomes organic substances that constitute plants, which is called net production. A part of net production flows into the food chain that starts with herbivorous animals that eat plants as the source of energy (consumers) or into microbes that decompose organic substances into inorganic substances (decomposers). Therefore, plants' primary production is recognized as the important base for the energy flow of the ecosystem.

The following are prospective damage indexes for assessing the impact on primary production:

1) Gross primary production (GPP)
2) Net primary production (NPP)
3) Volume of Plant biomass

Figure 1.2-12 shows the relations among them. GPP and NPP are expressed in production per hour – that is, production rate. Both are usually expressed in dry matter production per unit land area per year (example: t ha^{-1} yr^{-1}). On the other hand, plant biomass is expressed in gross dry matter production per unit land area at a certain point of time (example: t ha^{-1}). This is equivalent to net production less predation and litter integrated by the length of life of vegetation.

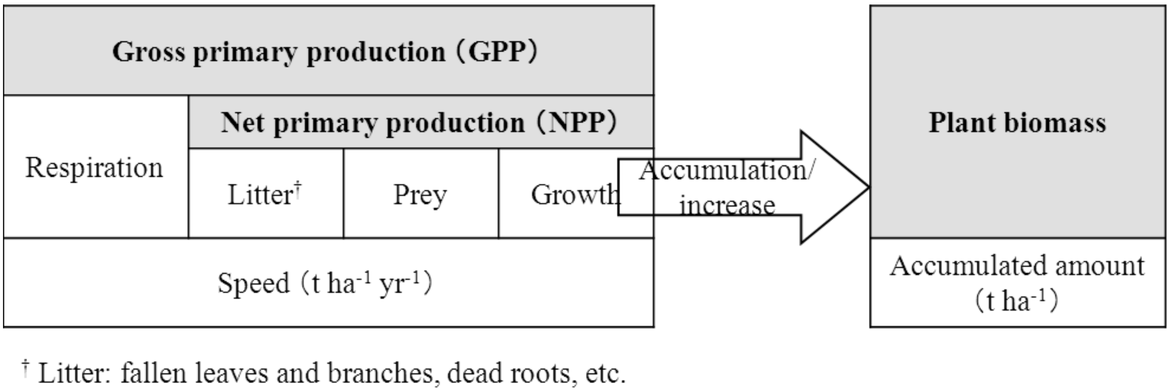


Figure 1.2-12: Relations among gross primary production, net primary production, and plant biomass concerning plant production

In LIME, a damage index for primary production was selected from the viewpoint of the above-described roles of plants as producers (starting point of the food chain and the supply of oxygen).

If the three indexes – GPP, NPP, and plant biomass – are compared in light of the supply of food to consumers, plant biomass seems to be the most suitable for the supply from the viewpoint of securing a certain volume of plants. However, from the viewpoint of continuous supply of a certain cumulative volume of plants, the requirement will not be fulfilled only by a large cumulative volume. It is necessary to grow at a speed higher than a certain level. NPP seems the most suitable as the index that fulfills this requirement.

If the three indexes are compared from the viewpoint of supply of oxygen, because oxygen is created by production activities through photosynthesis, plant biomass cannot deal with this. In addition, because GPP includes the respiration of plants themselves, it includes oxygen consumption. Therefore, from this aspect also, NPP seemed to be the most suitable because it indicates production activities excluding the respiration.

Therefore, it was decided that NPP should be used as the damage index for the primary production in LIME. In addition, the objects of assessment are producers (which supply oxygen and serve as the base for the food chain) – concretely, terrestrial plants and aquatic phytoplankton.

The damage factor is the unit amount of change in NPP caused by an environmental burden. When the factor is used for LCIA, the damage index *DI* (*PrimaryProduction*) is calculated by adding up the products of the damage factor DF^{Impact} (*PrimaryProduction, X*) and corresponding inventory *Inv* (*X*). The unit for the damage index *DI* (*PrimaryProduction*) is dry weight (dry – kg).

$$DI(PrimaryProduction) = \sum_{Impact} \sum_{X} DF^{Impact}(PrimaryProduction, X) \cdot Inv(X) \tag{1.2-11}$$

The impact categories that influence the primary production vary, including "ozone layer destruction," "acidification," "photochemical oxidant," "waste," "land use (maintenance and rearrangement)," "mineral resources consumption," "fossil fuel consumption," and "living resources consumption." Table 1-2-10 summarizes the relation between the impact categories related to primary production and the impact categories where the amount of damage is assessed in LIME. As shown in the table, it was decided that the impact of "global warming" and "eutrophication" on primary production should not be included under this method. The causes for the impact of global warming on primary production include not only changes in weather conditions and the submergence of land but also the fertilizer effect caused by an increase in the density of CO_2 (which works as a benefit). With regard to eutrophication, the flow of nutrition sources, such as nitrogen and phosphorus, into oligotrophic lakes improves environmental conditions. In LIME, impact assessment is carried out concerning not only damage but also benefits in principle (for example, a decrease in cold stress due to global warming, a decrease in energy consumption for cooling, and land rearrangement from an urban area to a forest are included as benefits). However, the fertilizer effect of CO_2 and the flow of nutrition into oligotrophic lakes were excluded from the objects of assessment, because the uncertainty of the assessment of these benefits is high and because their inclusion will greatly influence the final results. It was decided to wait and see the progress in each research field in the future.

Table 1.2-10: Damage assessment of primary production in LIME

Impact category	Existence of object of damage assessment and reason	Element of object of assessment
Ozone layer destruction	○	Phytoplankton
Global warming	× (The result greatly differs depending on the effect of fertilization.)	-
Acidification	○	Terrestrial vegetation
Eutrophication	× (It is difficult to assess positive and negative impacts on plant production comprehensively.)	-
Photochemical oxidant	○	Terrestrial vegetation
Waste	○ (Land readjustment by waste landfill)	Terrestrial vegetation (excluding marine landfill)
Land use	○ (Physical readjustment and maintenance of land)	Terrestrial vegetation
Mineral resources consumption	○ (Impact of mining of resources)	Terrestrial vegetation

Fossil fuel consumption	○ (Impact of mining of resources)	Terrestrial vegetation
Biofuel consumption	○ (Impact of deforestation)	Terrestrial vegetation

Table 1.2-11: Defined objects of protection and adopted damage indexes for LIME

Abject of protection	Damage index	Dimension	Elements
Human health	DALY	Year	Death, non-fatal disability and illness
Social assets	Yen	Yen	Farm products, aquatic resources, forest resources, mineral resources, fossil fuels
Biodiversity	EINES	(Expected) number of extinct species	Extinction of species (Vascular plants, aquatic organisms (fishes, crustacean, algae))
Primary production	NPP	kg-DW	Terrestrial plants, marine plankton

As the conclusion of this section, Table 1.2-11 shows the elements included in each area of protection and the damage indexes adopted for LIME. In LIME, damage factors were developed, giving priority to the impact categories and endpoints points where these areas of protection were regarded as highly likely to receive serious damage with the worsening of environmental problems.

1.2.5 Impact categories and category endpoints

Section 1.2.3 explained the definition of the areas of protection, adopting a top-down approach to natural environments. With regard to the selection of impact categories also, priority was given to the impact categories likely to have a strong impact on the areas of protection from a top-down viewpoint. However, because LCIA recognizes impact categories as the objects in the step of characterization, the definition of impact categories is restricted in relation to the development of methods for the characterization model. In addition, one of the points to consider when defining impact categories is that many impact categories are generally assumed to be environmental problems. As a result, under this method, impact categories were defined mainly by the use of a top-down approach and with consideration for bottom-up requirements. Table 1.2-12 shows the results and the grounds for selection. In LIME2, “indoor air pollution” and “noise” were added as new impact categories. This enabled appropriate assessment of construction materials containing adhesives and paints with lower emission of VOC and car parts that can effectively reduce noise.

The framework of LIME has been completed after a lot of discussions. Figure 1.1-9 shows the concept of LIME2. As shown in the figure, this method defines 15 impact categories and 4 areas of protection (see Section 1.2.3 “Definition of areas of protection”). The assessment of environmental impact by this method consists of the following steps:

Table 1.2-12: Impact categories included in assessment under LIME and grounds for the inclusion

	Impact categories included in assessment	Grounds for including them in assessment
Out-put	Global warming	• It has impact on human health, social assets, biodiversity, and primary production. • It is usually an object of assessment concerning characterization.
	Ozone layer destruction	• It has impact on human health, social assets, and primary production. • It is usually an object of characterization.
	Acidification	• It has impact on social assets and primary production. • It is usually an object of assessment concerning characterization.
	Photochemical oxidant	• It has impact on human health, social assets, and primary production. • It is usually an object of assessment concerning characterization.
	Urban area air pollution	• It has impact on human health. • Because it is possible to create models for characterization and damage assessment at the regional level, it was separated from toxic chemicals.
	Toxic chemicals	• It has impact on human health. • Because it is impossible to create models for characterization and damage assessment at the regional level at present, it was separated from urban area air pollution.
	Indoor air contamination	• It has impact on human health. • Because of difference in exposure efficiency, it was separated from the impact of emission in the general atmosphere, such as toxic chemicals and air pollution.
	Biological toxicity	• It has impact on biodiversity. • It is usually an object of characterization.
	Eutrophication	• It has impact on social assets and biodiversity. • It is usually an object of characterization.
	Noise	• It has impact on human health. • In Japan, it is recognized as an important problem due to a low achievement rate of environmental standards.
	Waste	• At the time of waste landfill, it has impact on social assets, primary production, and biodiversity. • In Japan, it is recognized as a serious problem.
In-put	Mineral resources consumption	• At the time of mining of resources, it has impact on primary production and biodiversity. • Resource consumption depletes social assets. • In Japan and in the world, it is recognized as a serious problem. • It is usually an object of characterization.
	Fossil fuel consumption	• At the time of mining of resources, it has impact on primary production and biodiversity. • Resources consumption depletes social assets. • In Japan and in the world, it is recognized as a serious problem. • It is usually an object of characterization.
	Living resources consumption	• At the time of mining of resources, it has impact on primary production and biodiversity. • In Japan and in the world, it is recognized as a serious problem.
	Land use	• It has impact on biodiversity and primary production. • It is generally known that land adjustment ranks high among the factors for the extinction of species.

1) Analysis of changes in the density of air and water in the environmental medium due to the occurrence of an environmentally damaging substance (fate analysis)

2) Analysis of changes in the amount of exposure to human beings and other receptors due to changes in the density of an environmentally damaging substance in the environmental medium (exposure analysis)

3) Assessment of changes in the amount of potential damage to receptors due to changes in the amount of exposure (impact analysis)

4) Totaling of the amounts of damage to each common areas of protection (such as human health) (damage analysis)

5) Application of weighting among the areas of protection to obtain a single index for environmental impact (integration)

The inclusion of the above-mentioned impact categories means that this method has covered many environmental problems closely related to the four areas of protection. However, some important impact categories could not be included, because the level of research in each field was not sufficiently high to be applied to LCIA methods. The following are impact categories excluded from the assessment by this method.

- Radiation
- Vibration
- Offensive odor
- Nanoparticle
- Water resources consumption
- Heat island phenomena
- Work environment
- Salt pollution

When products that have especially important impact on the above-listed impact categories are assessed, it seems difficult to obtain assessment results according to the purpose. One of the issues to be settled in the future is how the important items excluded from this method should be included in the scope of assessment so that the method can become highly general-purpose (see Chapter IV).

Impact categories can be interrelated with areas of protection by endpoints. Because the assessment of the amount of damage to category endpoints by a damage function greatly depends on background data in emission areas and the theoretical maturity of environmental science, it is extremely difficult to include all category endpoints in an environmental assessment method. Therefore, it was thought that preferential inclusion of important category endpoints is an important approach for obtaining assessment results close to reality. In LIME, before the development and research of a damage function, discussions were made to select category endpoints to be included in the assessment from a screening survey based on the results of prior research. For details of the results, see the respective sections of Chapter II.

Column 1.2-4

Relation between LIME and ISO 14044

In LIME, characterization, damage assessment, and integration constitute the stage of assessment, which is almost consistent with the procedure of ISO 14044. However, there are some differences between the two, as follows:

First, the two differ in the flow of impact assessment.

- LIME: characterization → damage assessment → (normalization) → integration
- ISO 14044: selection of impact categories → classification → characterization → normalization → grouping → weighting → data quality analysis (however, the steps up to characterization are essential elements, while normalization and thereafter are optional elements)

In the step of selection and classification of impact categories, the practitioner using LIME can choose from the list of impact category and that of factors characterization based on the purpose of LCA.

With regard to characterization, although ISO does not specify a concrete list of impact categories, it can be thought that LIME's characterization factors fulfill ISO's requirements.

One of the greatest differences between the two is damage assessment. LIME defines four items, including human health, and quantifies the amount of potential damage to them at the same step. On the other hand, although what is the closest to damage assessment in the ISO procedure is grouping, the purpose of the grouping is not qualification or the comparison and integration of impact categories but the classification of impact categories into several groups under some criteria and the priority ranking of the groups. In addition, ISO has no concrete provision about groups. Although ISO 14047, a collection of impact assessment cases, includes cases that express the amount of damage from health impact and the amount of damage to the ecosystem, these are included as cases about characterization.

With regard to LIME2, which has two types of integration factors (see Annex 2), in Ver. 2, which expresses an integration result as a non-dimensional index, normalization is carried out to render the amount of damage to endpoints non-dimensional. However, in Ver. 1, which calculated social cost, normalization was not carried out. Because the economic value per unit amount of damage (economic value / amount of damage) can be obtained by conjoint analysis, the integration factor (economic value / unit amount of environmental burden) can be obtained by multiplying the value by the damage factor (amount of damage / unit amount of environmental burden), with the result that it becomes unnecessary to render the amount of damage non-dimensional through normalization. As ISO defines normalization as "calculation of a relative ratio by reference to base information on index results of impact categories," normalization seems to refer to rendering the results of characterization of impact categories non-dimensional. On the other hand, the targets of LIME's normalization are not impact categories but the four areas of protection. Therefore, the objects of normalization differ between the two. However, both make the results of the preceding step non-dimensional.

Integration corresponds to weighting in ISO. ISO points out that weighting is based on selection by the sense of values, not on natural science. In LIME2, integration brings two types of results – economic indexes and non-dimensional indexes. With regard to the conclusion of assessment results, a recommendation has been made to carry out sensitivity analysis about whether the use of other integration methods brings the same results.

1.3 List of factors including statistic values

1.3.1 Significance of calculation of statistics

Generally, LCA uses foreground data collected by the practitioner and background data cited from databases and reports. To carry out LCA quickly, it is necessary to enrich the background database. Japan, Switzerland, Italy, the US, and South Korea have already created national databases. In addition, making these databases available to the public has greatly contributed to the popularization of LCA.

Meanwhile, in connection with these activities, the treatment of uncertainty has been pointed out as an important issue. Although some existing inventory databases show upper and lower limits, many of them only describe representative values, and the degree of their reliability is often unknown.

The result of LCA gained from the linear calculation of representative values can be expressed as shown in Figure 1.3-1(a). If several products are compared, it will be concluded that Product 2 is better because environmental impact is low. However, the reliability of the result cannot be judged from this information alone. Although the result of Product 2 is small as a whole, Product 2's environmental burden is larger in Process C. If Product 2's uncertainty in Processes A and B is large, and the amount of environmental burden is underestimated, there is the possibility that the environmental burden of Product 2 may be larger. Because inventory data and impact assessment factors used for LCA have uncertainty, if uncertainty is added to the assessment result (Figure 1.3-1 (b)), the conclusion founded only upon the representative values may be disproved, or draw a clear conclusion may be impossible. In such a case, it is necessary to reexamine processes that greatly influence the uncertainty of the result (Figure 1.3-1 (c)).

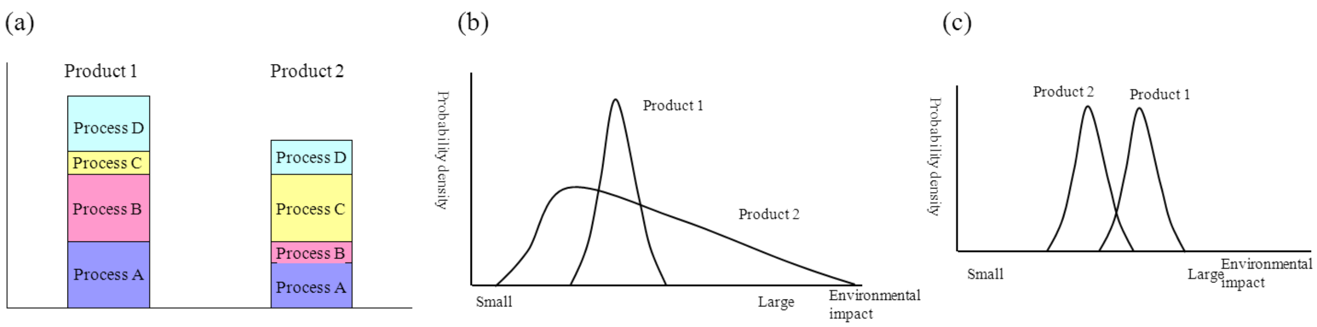


Figure 1.3-1: Image of LCA results

(a) Total of representative values

(b) Frequency distribution of uncertainty of LCA (when the uncertainty of Product 2 is large)

(c) Frequency distribution of uncertainty of LCA (when the uncertainty of both products is small)

If the result of LCA is discussed only by representative values, incorrect decision-making may be overlooked. Information on the reliability of the result of LCA like that shown in Figures 1.3-1(b) and (c) is essential for making decisions without misunderstanding. ISO 14044 demands that information on the quality of data, including the uncertainty of the information, should be written in a report. In addition, ISO highly recommends setting the purpose and the scope of research again in response to the results of life cycle interpretation and iteratively carrying out LCI and LCIA to achieve the purpose. That is, information on the reliability of LCA becomes an important material for judgment about iterative implementation of LCA.

Not only inventory databases but also LCIA methods lack information on the uncertainty of the current LCA infrastructure. Table 1.3-1 shows how to deal with uncertainty by LCIA methods.

Many methods do not include information on uncertainty. Although some methods include it, with the exception of ExternE, they do not specify the calculation method and the grounds. The variability of weighting in particular has not been assessed by any method. Because all calculation methods use approximate formula (see Column 1.3-2), it is impossible to obtain information on statistics and the form of distribution of assessment results from the results of the calculation.

Data on the uncertainty of impact assessment factors are essential for verifying the reliability of LCIA results. Because it is difficult for the LCA practitioner to establish the uncertainty of impact assessment factors, the method developer should provide information.

Table 1.3-1: Treatment of uncertainty by LCIA methods

		CML	TRACI	EDIP	Impact 2002+	ExternE	Eco-indicator ’99	EPS	LIME2
Country of development		Holl-and	US	Den-mark	Switz-erland	Europe	Holland	Sweden	Japan
Scope of assessment		C	C	C	D	I	D, I	I	C, D, I
Disclosed informa-tion on uncer-tainty	Calculation method	×	×	×	×	Approxi-mation formula	Unknown	Approxi-mation formula	Simu-lation
	Uncertainty of data used for analysis	×	×	×	×	○	Unknown	○	○
	Uncertainty of factor	×	×	×	×	Standard deviation	Standard deviation	Standard deviation of amount of damage (no statistic of integration factor)	Statistic, form of distributio n

* C: characterization; D: damage assessment; I: integration

Column 1.3-1

ISO's requirements for the quality of data

ISO 14044 demands description of the quality of the data used for LCA. Concretely, the following items should be described:

- Effective temporal scope: time of acquisition of data, time passed from acquisition of data (example: operation data within five years)
- Effective geographical range: geographical range of collected data (examples: local, state, continental)
- Effective technical range: specific technique or combination of techniques (example: highest-level technique or worst operational condition)
- Precision: range of used data
- Completeness: ratio of used data in the target process
- Representativeness: comprehensiveness of used data from the viewpoint of technical, temporal, and geographical conditions
- Consistency: whether used condition is consistent among multiple objects of assessment
- Reproducibility: whether the same result can be achieved by another practitioner
- Data source
- Uncertainty of information (such as data, model, supposition)
  In the case of comparative assertion supposed to be open to the public, ISO 14044 demands the inclusion of the information in a report and the implementation of uncertainty analysis.

Column 1.3-2

Uncertainty analysis under ExternE

Table 1.3-1 shows how to deal with uncertainty by the existing LCIA methods. Among the methods, ExternE explains the procedure and the result in detail. Table 1.3-A shows the procedure for calculating the uncertainty of the integration factor. A geometric standard deviation (σ_g) is calculated for each of the processes from emission to impact (such as diffusion, transformation, and exposure), and the geometric standard deviation of the integration factor is calculated from the square sum of these logarithms.

$$\left[Ln\left(\sigma_{gz}\right)\right]^2 = \left[Ln\left(\sigma_{gx1}\right)\right]^2 + \left[Ln\left(\sigma_{gx2}\right)\right]^2 + \cdots + \left[Ln\left(\sigma_{gxn}\right)\right]^2$$

In this case, it is thought that processes with a large geometric standard deviation – that is, information on the economic value of the loss of life expectancy ($\sigma_g = 2$) and the toxicity of each substance – have great impact on the uncertainty of the integration factor.

If this method is used, although the procedure for calculating the integration factor can be explained clearly, the following problems will remain:

- Although the geometric standard deviation for each process is often determined by the development, the grounds for this are insufficient.
- The calculation method uses an approximate formula, and it is difficult to verify the reliability of the result.

- Although the standard deviation can be obtained as a result of the calculation, it is impossible to obtain information on other statistic values and the form of distribution.

Table 1.3-A: Procedure for analysis of uncertainty of integration factor by ExternE

		PM		SO_2		NO_x	
		σ_g	$\mathrm{Ln}(\sigma_g)^2$	σ_g	$\mathrm{Ln}(\sigma_g)^2$	σ_g	$\mathrm{Ln}(\sigma_g)^2$
Exposure	Diffusion	1.5	0.164	1.5	0.164	1.5	0.164
	Transformation	1	0.000	1.2	0.033	1.4	0.113
	Amount of emission	1	0.000	1.05	0.002	1.15	0.020
D-R	Relative risk	1.3	0.069	1.3	0.069	1.3	0.069
	Toxicity	1.5	0.164	2	0.480	2	0.480
	YOLL	1.3	0.069	1.3	0.069	1.3	0.069
Economization	YOLL	2	0.480	2	0.480	2	0.480
Total		2.65	0.95	3.13	1.30	3.26	1.40

Among the research efforts for the development of LCIA methods, the development of damage assessment methods has drawn special attention. At the same time, the necessity for uncertainty analysis has been carried out further. While analysis is generally conducted for each impact category in the case of characterization, even the amount of damage of each endpoint is calculated in the case of damage assessment. Because the number of parameters and the number of models further increase in the case of damage assessment, the uncertainty of damage factors also increases (Figure 1.3-2). On the other hand, these comments are only expressed qualitatively and are not verified fully.

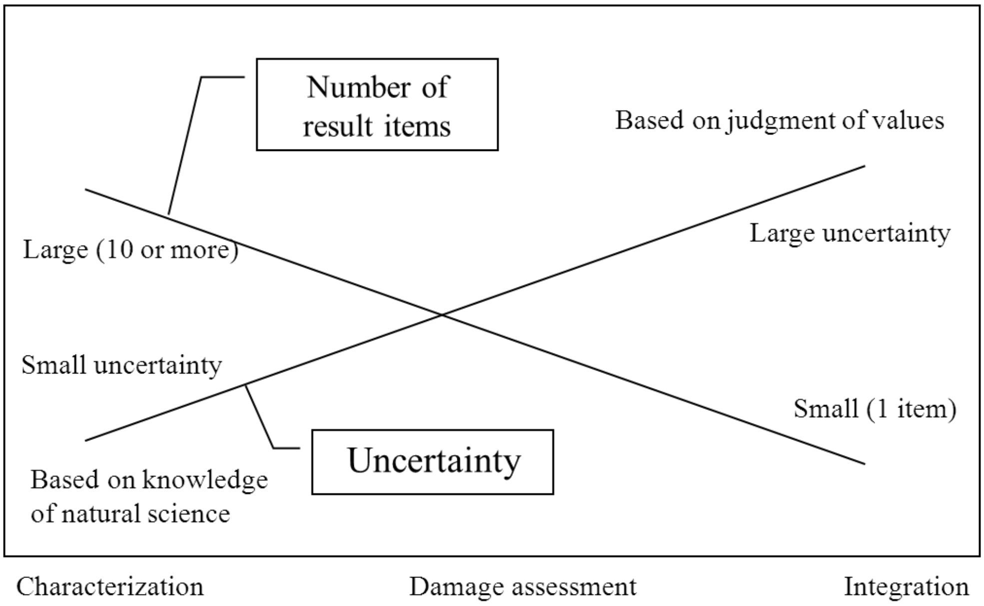


Figure 1.3-2: Relations among environmental impact assessment methods, reliability, and the number of items

Although, as described above, data and methods used for analysis and the precision and reliability of LCA results based on them are essential for decision-making under LCA, it cannot be said that infrastructure has been sufficiently established to fulfill this requirement.

The reasons why uncertainty analysis is not carried out in the current LCA can be summarized as follows:

1) The database on LCI has little data about uncertainty.
2) The impact assessment method has little data about uncertainty.
3) Even if the database has data about uncertainty, there is no tool for carrying out the analysis of the uncertainty of LCA by the use of the data.

With regard to 1), the data about the uncertainty of inventory data, research institutes in Europe and other regions are preparing inventory data, including the probability distribution of LCI. In addition, because data formats in which inventory data are entered have spaces in which information on uncertainty can be entered, the movement to share data on the reliability of LCI is expected to become brisk. With regard to 3), the analysis of the uncertainty of LCA has already been introduced by the latest LCA software (such as Simapro, Gabi), and this problem is expected to be solved with the popularization of such software.

Given the above-described trends, the possibility of carrying out the analysis of the uncertainty of the whole LCA has a restriction – the period until 2) information on the uncertainty of the LCIA method is open to the public. To cope with this, in LIME 2, examination was carried out to calculate the statistics of damage factors and integration factors as one of the main issues.

1.3.2 Types of uncertainty

The uncertainty of LCIA varies. Uncertainty can be roughly classified into the following types:

1) Uncertainty of the model used for impact assessment
2) Uncertainty of the parameters used for impact assessment
3) Variability of each person's environmental idea
4) Geographical and temporal variability

1) refers to the uncertainty of the diffusion model or the regression formula of the risk of extinction of species. In the case of the diffusion model, the uncertainty can be expressed as the difference between the density of air pollutants in the actual environment and the result of calculation of the model under the same conditions.

2) refers to the uncertainty of the parameters used for an impact assessment model, including D-R functions, such as the unit risk of cancer generation, and weather data, such as wind velocity. Because D-R functions of air pollutants are estimated values obtained from the results of epidemiological research and surveys of patients, some errors occur. Reliability can be improved by securing a certain number of samples and a certain period of measure.

3) refers to differences among individuals in weighting used for integration of environmental impacts. Weighting requires the reflection of the population's environmental ideas, and the degree of the unevenness can be analyzed by statistical analysis. The use of the recently developed analysis methods enabled quantitative expression.

Although the above-described three categories should be taken into consideration when the uncertainty of impact assessment methods is measured, 4) requires prior discussions as to whether to include it in the analysis of "uncertainty."

For example, in the case of a resource mining, there are not one but several places in the world where the resource can be collected. Suppose that, with regard to damage functions, the mean value at each mine is adopted for the surface transformed area when one ton of iron ore is mined. If the mean value can be calculated after the acquisition of information on all the mines, no error will arise in the estimation of the mean value.

However, if this is applied to the result of inventory analysis, because the iron ore described in the inventory was mined at one or more mines in the world, the surface transformed area rates of the mines are generally different from the world's mean value, and it can be thought that an error will occur in the result of the assessment of the land use area. On the other hand, if inventory data include information on not only iron ore consumption but also the mines where the iron ore was mined, such an error will not arise in principle. Therefore, with regard to impact assessment factors, if there is no error in the estimation of the population's mean value, it can be thought that there is no uncertainty.

With regard to geographical and temporal variability, an error in the result of impact assessment cannot be reduced without geographical and temporal details of inventory data. However, it was decided that geographical and temporal variability should also be included in the objects of uncertainty analysis so that the maximum uncertainty can be calculated when assessment factors are applied to inventory data aggregated geographically and temporally.

1.3.3 Method to conduct uncertainty analysis

If a variable value is included in the model, or if uncertainty exists in the model itself, the result of calculation has uncertainty. Although there are various methods to analyze the uncertainty of the result, the Monte Carlo method was adopted this time.

The advantages of uncertainty analysis by the Monte Carlo method are not only that it can measure the uncertainty of the assessment result but also that it can conduct sensitivity analysis as an approach for effective improvement of the uncertainty of the objects of assessment. Sensitivity analysis examines the interrelation between each variable and the calculation result. The overall sensitivity of the prediction result for a certain variable receives the impact of the following two factors:

1) Sensitivity of the dependent variable for the variable
2) Uncertainty of the variable

Even if the uncertainty of a variable is low, the variable has a great impact on the uncertainty of the final result if its impact on the overall assessment is great. In contrast, if the uncertainty of a variable is great, but has not a great impact on the final result, the sensitivity to the final result is small. Because sensitivity analysis can identify the variable that has the greatest impact on the prediction result, it is possible to take measures for effectively improving the accuracy of the factors for LCIA. In addition, it is also possible to identify the variables that have no impact on the prediction result and exclude them from the objects of examination for the improvement of accuracy. These processes make it possible to make the factors for LCIA more closely reflect the reality and make them more accurate.

In LIME2, uncertainty analysis and sensitivity analysis based on the Monte Carlo method were conducted concerning the damage and integration factors for about 200 types of environmentally damaging substances related to urban area air pollution, resource consumption, global warming, acidification, land use, and waste. Important impact categories were picked out beforehand based on the result of the calculation of the normalization value (potential amount of environmental impact that occurs through the yearly economic activities in Japan) (see Chapter III).

The following is the procedure for uncertainty analysis:

1) Arrangement of the procedure for calculating damage factors: clarification of the processes from inventory and the calculation of the amount of damage at the endpoint, and arrangement of the characteristics of the models and parameters used until the calculation of damage factors

2) Identification of variables and establishment of probability distribution: identification of parameters and models important for the calculation of the amount of damage

3) Uncertainty analysis: iterative calculation based on the Monte Carlo method – the number of times of calculation should be fixed so that the fluctuation of statistical values will almost disappear.

4) Sensitivity analysis: among the set variables, picking up the variables that have a great impact on the uncertainty of the final result

5) Reexamination and recalculation of important parameters: reexamination of the variables that have a great impact on the final result, renewal of their probability distribution, and conduct of simulation again

6) Calculation of a representative value and statistics: implementation of the procedure from 1) to 5) several times to obtain the final result of damage factors

The next section shows actual cases where uncertainty analysis was carried out under the procedure described above.

Column 1.3-3

Monte Carlo method

The Monte Carlo method (Monte Carlo simulation) is a method for simulating models by repeating the allocation of randomly produced values among uncertain variables. The name comes from Monte Carlo, a city in Monaco famous for its casinos. This is because random movement exists in game probability.

For example, when a die is cast, the die will show a number, 1, 2, 3, 4, 5, or 6. However, it is impossible to guess the number without fail. This principle is applicable to a variable that has a clear range but cannot be fixed at a certain value (for example, the amount of exposure for the amount of emission of a toxic substance).

With regard to each variable, a value that can exist in the range of the variable is defined by the use of probability distribution. What type of distribution to select depends on the circumstances of the variable. In general, normal distribution, triangular distribution, uniform distribution, and logarithmic normal distribution are used frequently. During simulation, a value to be used for each variable is selected randomly according to the defined probability distribution, and calculation is repeated by the use of the selected value. The number of times of calculation depends on the object and purpose of analysis. Usually, calculation is conducted between several thousand times and hundreds of thousands of times.

The results of the calculation are expressed in a graph by the use of statistics, such as mean values and standard deviation, and frequency distribution. As the number of times of calculation increases, the form of the graph becomes smoother. Monte Carlo simulation requires the occurrence of random numbers and more than a certain number of times of calculation. At present, this problem has begun to be solved by the use of high-speed computers.

1.3.4 Development of a list of factors including statistics

This section describes the procedures from uncertainty analysis to the calculation of factors, taking damage factors in urban area air pollution as an example. For details of the calculation method and parameters of damage assessment, see Section 2.4.

(1) Flow of calculation of the damage factor and setting of uncertainty of parameters

Figure 1.3-3 shows the flow from the occurrence of an environmental burden to the calculation of the amount of damage concerning urban area air pollution. Emitted PM2.5 diffuses in the air. People inhale or are exposed to a portion of it. The risk of causing illness changes with an increase in the amount of exposure. This change contributes to the expected number of persons who suffer illness – that is, a change in the loss of life expectancy. After these processes are modeled and integrated, the amount of emission and the amount of change in the loss of life expectancy are calculated by type of illness. The total of the calculated damage functions is the damage factor.

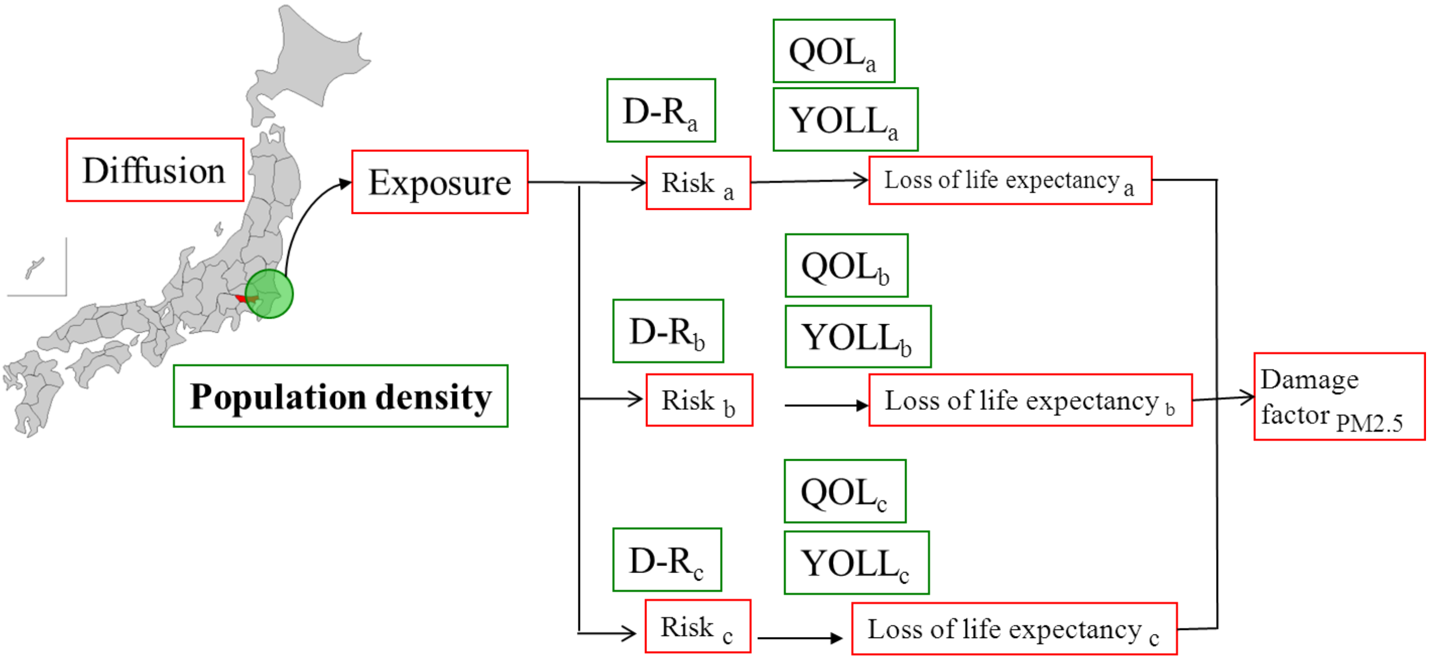


Figure 1.3-3: Flow of calculation of the damage factor (human health) of urban area air pollution (PM2.5)

Calculate a change in the loss of life expectancy due to emission by type of illness and total the changes to derive the damage factor. The uncertainty of the parameters (such as D-R, QOL, and YOLL) and models (such as exposure analysis) used for the assessment is determined based on existing documents.

(2) Setting of the range of variables

Next, the range of models and parameters to be used until the calculation of the damage factor is defined. This is summarized in Table 1.3-2. Fate analysis determines the degree of the range by comparison between actual measured values and analyzed calculation results. A change in the death rate due to exposure to PM is calculated from the existing results of epidemiological research. An increase in the loss of life expectancy per case of chronic death is calculated based on statistical materials issued by WHO. No range was defined for the parameters considered highly reliable, such as population density.

(3) Implementation of uncertainty analysis

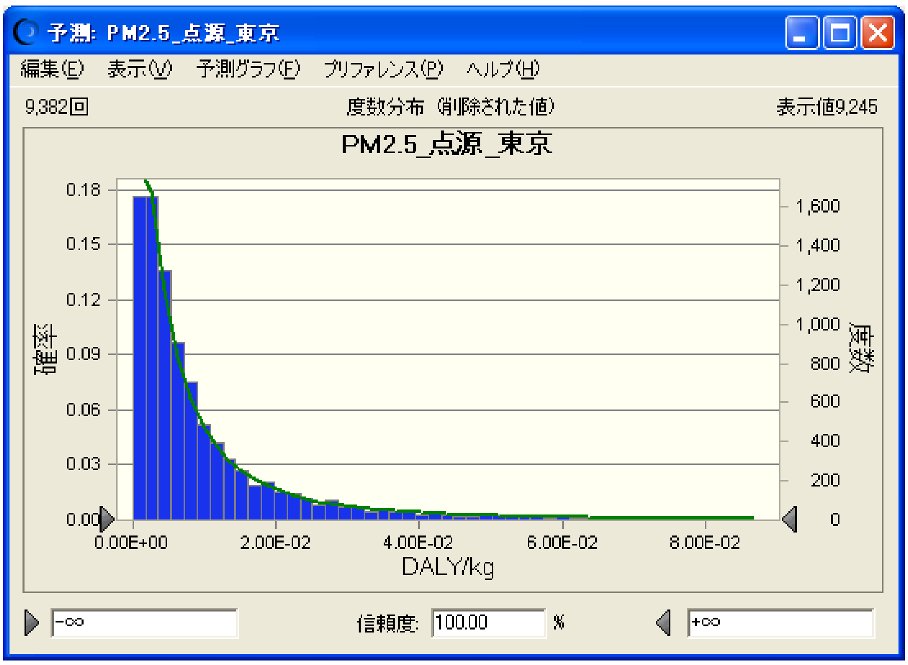
Uncertainty analysis is carried out by the Monte Carlo method. The result is expressed in frequency distribution as shown in Figure 1.3-4. In this case, because the variation coefficient[*3] exceeds 2, the uncertainty is thought to be relatively high.

[*3] The variation coefficient is standard deviation divided by the mean value. The larger the mean value, the larger the value of standard deviation. The variation coefficient is used for examining the relative seriousness of an error.

Table 1.3-2: Types of variables used for assessment of impact of chronic death due to exposure to PM2.5 and an example of the range of variables

Type of variable	Unit	Statistics		Form of distribution
		Mean value	Standard deviation	
Result of fate analysis (Tokyo)	$((ug/m^3)/(kg/yr))*m^2$	1.5E+3	9.6E+2	Normal distribution
Death rate of persons aged 30 and over	$Risk_{baseline}/yr$	1.14E-2	-	On the assumption that there is no distribution
Increase in the death rate by an increase of 1 unit of pollutant density	$(Risk/Risk_{baseline})/(\mu g/m^3)$	6.43E-3	4	Log-normal distribution
Population density of persons aged 30 and over	$Person/m^2$	3.59E-3	-	On the assumption that there is no distribution
Loss of life expectancy per case of chronic death	DALY/person	6.6	1.7	Log-normal distribution

Multiplication of them enables the calculation of an estimated loss of life expectancy due to chronic death when 1 kg of PM2.5 is emitted.



Mean value	Median	Standard deviation	Variation coefficient
1.22E-02	5.55E-03	2.70E-02	2.22

Figure 1.3-4: Result of uncertainty analysis of damage factor(PM2.5 (Tokyo)) (before reexamination)

(4) Implementation of sensitivity analysis

Next, sensitivity analysis is carried out to calculate variables that have an important impact on the uncertainty of the damage factor. Table 1.3-3 shows the result. If the rank correlation coefficient is larger, the interrelation between the variable and the damage factor becomes higher and receives higher priority for reexamination. In the case of PM2.5 (Tokyo), it was found that the D-R function of chronic death is highly interrelated with the damage factor. Therefore, if the reliability of this data becomes higher, the damage factor can be improved with a higher probability.

(5) Reexamination and recalculation of important parameters

As a result of reexamination of epidemiological research on chronic death due to exposure to PM, the results of the epidemiological research that Pope published in 2002 were adopted. The results were obtained from a follow-up survey of 500,000 people and were thought to be more representative and reliable than the survey results from 1995. In addition, the data also describe the reliability of the data, the result of which was also used. Table 1.3-4 shows a comparison between the data before and after the reexamination.

(6) Calculation of representative values and statistics

The new D-R function obtained by the reexamination was inputted to carry out uncertainty analysis by the Monte Carlo method. Figure 1.3-5 shows the results. Because the above-described analysis results (Figure 1.3-4) found that the variation coefficient was small and that the rank correlation coefficient of the D-R function of chronic death decreased, the improvement of the reliability could be confirmed from a change in the variable. To improve the accuracy of the damage factor further in the future, the fate analysis model must be improved.

After these processes were repeated, the definite value of the damage factor was obtained. The results were disclosed as a list of factors, including representative values and statistics.

Table 1.3-3: Result of sensitivity analysis of damage factor (PM2.5 Tokyo)

Type of variable	Rank correlation coefficient
D-R (chronic death, adult)	**0.43**
Fate model	0.35
D-R coefficient (chronic bronchitis, adult)	0.24
DALY (chronic death)	0.15
D-R coefficient (chronic death)	0.28
DALY (chronic bronchitis)	0.10

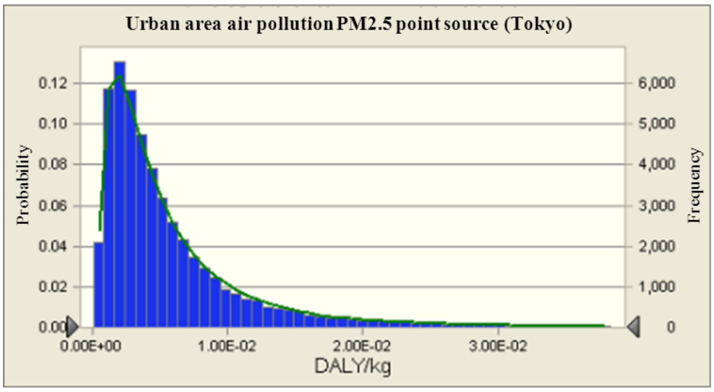
・The table shows variables whose rank correlation coefficient is 0.1 or more.
・The higher the rank correlation coefficient of a variable, the higher the correlation with the damage factor and the higher the priority of reexamination.

Table 1.3-4: Result of reexamination of D-R coefficient (chronic death)

The unit of the mean values: $(Risk/Risk_{baseline})/(\mu g/m^3)$

	Before reexamination			After reexamination		
Substance	Mean value (Pope1995)	Form of distribution (Hofstetter 1998)	Geometric standard deviation (Hofstetter1998)	Mean value (Pope 2002)	Form of distribution (Pope 2002)	Standard deviation (Pope 2002)
SO_4^{2-}	6.43E-3	Log-normal	4	7.69E-3	Normal	1.04E-3
PM2.5	6.43E-3	Log-normal	4	5.93E-3	Normal	1.99E-3
PM10	3.86E-3	Log-normal	4	1.00E-3	Normal	5.80E-4
O_3	-	-	-	3.40E-4	Normal	9.60E-5

(a)



Mean value	Median	Standard deviation	Variation coefficient
6.65E-03	3.96E-03	1.13E-02	1.70

(b)

Type of variable	Rank correlation coefficient
Fate model	0.64
D-R coefficient (chronic bronchitis, adult)	0.47
DALY (chronic death)	0.29
D-R coefficient (chronic death)	0.28
DALY (chronic bronchitis)	0.18

* The table shows variables whose rank correlation coefficient is 0.1 or more.

Figure 1.3-5: (a) Result of uncertainty analysis and (b) result of sensitivity analysis of the damage factor (when PM2.5 is emitted from a factory in Tokyo) after additional survey

The variation coefficient decreased due to the reexamination of D-R coefficient (chronic death). In addition, the result of sensitivity analysis indicates that the impact of the variable on the uncertainty of the damage factor decreased.

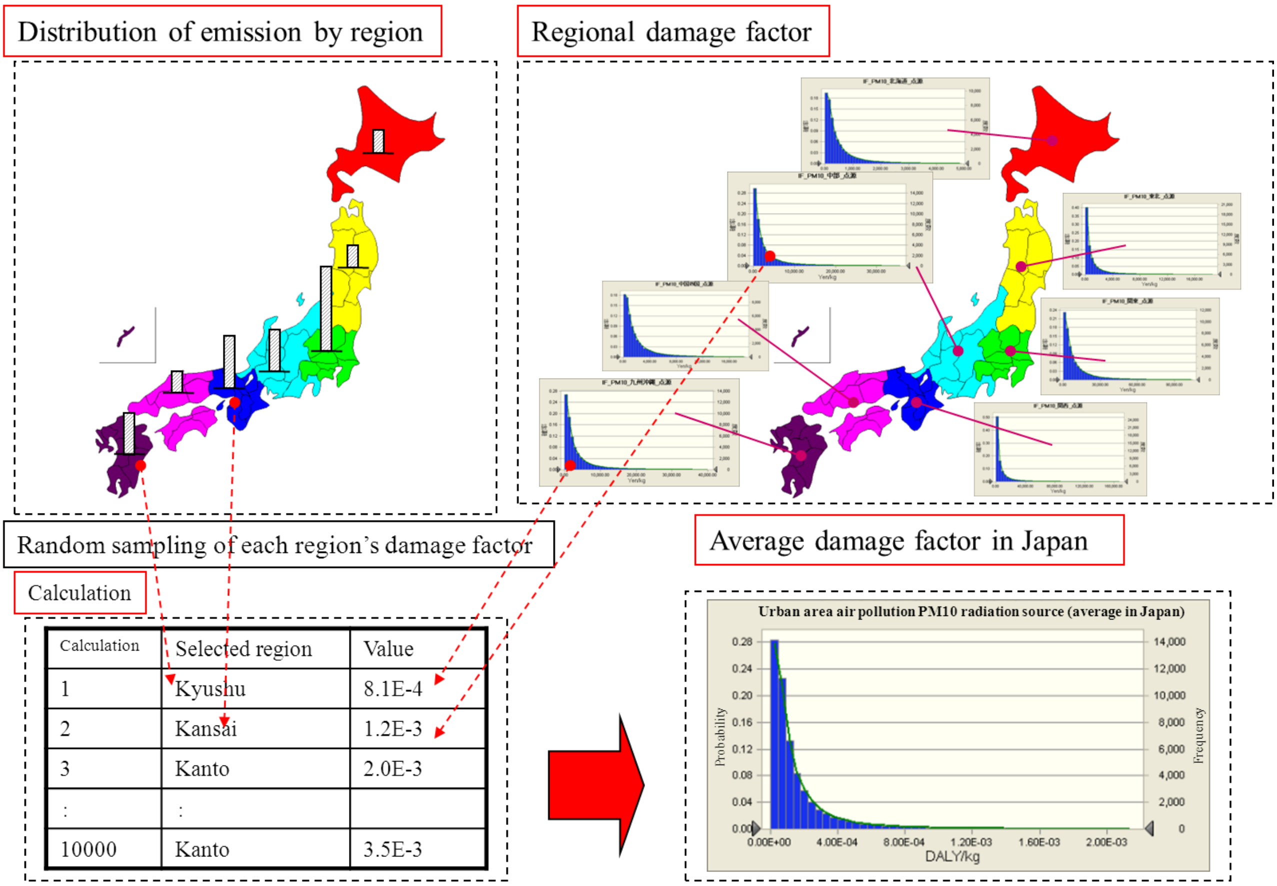
1.3.5 Reflection of geographical variability

Environmental impact differs depending on where an environmental burden occurs. If inventory data contain geographical information, it is possible to assess environmental impact appropriately by the use of the corresponding assessment factors. On the other hand, if inventory data do not contain geographical information, the national average factor is used, in view that the factors specific to the region cannot be used. Because of this, it is desirable that the list of assessment factors should include factors specific to a certain region and national average factors.

For example, in the case of the assessment factors for urban area air pollution, after the development of factors at the prefectural level, factors at the regional level and at the national level were developed. The bootstrap method was used for the calculation of assessment factors at the regional level and the national level. Figure 1.3-6 shows the procedure for calculating assessment factors at the national level by use of the bootstrap method. This method uses the previously calculated statistics of damage factors in each region and the amount of emission of the target substances in each region. First, a region is selected randomly based on the breakdown of the amount of emission. Because the damage factors in the selected region have a certain distribution, they are randomly picked out from this distribution. If such a procedure is repeated 10,000 times, for example, it is possible to calculate the statistic of the damage factor at the national level, taking into consideration the distribution of the amounts of emission in Japan.

Figure 1.3-7 shows damage factors (point source of PM2.5) in the Kanto Region and in Japan. Compared with Figure 1.3-5 (a), it is found that the variation coefficient of the damage factor in Tokyo is the smallest and, the greater the width of the area for which the damage factor is calculated in the Kanto Region and in Japan, the larger the variation coefficient. Table 1.3-5 shows the result of sensitivity analysis of damage factors in Japan. This indicates that the existence and scope of the geographical variability by the bootstrap method have great impact on the reliability of damage factors.

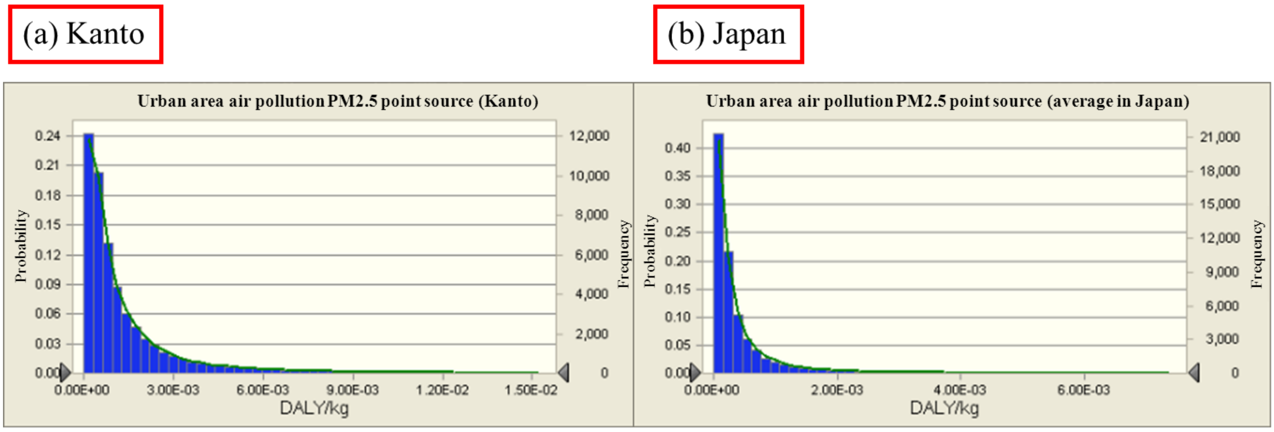
Figure 1.3-8 shows a comparison between the damage factors for urban area air pollution in LIME1 and LIME2. Except for some parts, the variation coefficient of the damage factors in LIME 2 is smaller than that in LIME1, which indicates that the reliability has generally been improved. In addition, as shown in the results of PM, because of the inclusion of geographical variability, the variation coefficient of the damage factors at the prefectural level is larger than that at the national level. Therefore, it is expected that, when inventory data are applied, the identification of points of emission will lead to more appropriate assessment.



Calculation	Selected region	Value
1	Kyushu	8.1E-4
2	Kansai	1.2E-3
3	Kanto	2.0E-3
:	:	
10000	Kanto	3.5E-3

Figure 1.3-6: Method of calculating the average damage factor in Japan by the use of the Bootstrap method

After areas are identified from the regional distribution of amount of environmental burden, damage factors are randomly selected from the frequency distribution calculated beforehand for each region.
This result is repeated several times to obtain a nationwide damage factor.



Mean value	Median	Standard deviation	Variation coefficient
1.76E-03	7.43E-04	4.86E-03	2.75

Mean value	Median	Standard deviation	Variation coefficient
5.77E-04	1.93E-04	2.46E-03	4.26

Figure 1.3-7: Impact of geographical variability on the credibility of the damage factor (PM2.5 (a) Kanto, (b) Japan)

The variation coefficient of the factor at the regional or national level is larger than that at the prefectural level (Figure 1.3-5 (a)).

Table 1.3-5: Result of sensitivity analysis of the damage factors in Kanto and in Japan (PM2.5)

Kanto Area

Type of variable	Rank correlation coefficient
Geographical variability (Kanto)	**0.52**
D-R coefficient (chronic bronchitis, adult)	0.34
DALY (chronic death)	0.21
D-R coefficient (chronic death)	0.21
Fate model PM2.5 (Chiba)	0.15
Fate model PM2.5 (Ibaraki)	0.13
DALY (chronic bronchitis)	0.13
Fate model PM2.5 (Saitama)	0.12

Japan

Type of variable	Rank correlation coefficient
D-R coefficient (chronic bronchitis, adult)	0.32
Geographical variability (Japan)	**0.28**
DALY (chronic death)	0.20
D-R coefficient (chronic death)	0.19
DALY (chronic bronchitis, adult)	0.14

- Variables whose rank correlation coefficient is 0.1 or more are picked out.
- The table shows the great impact of random sampling of emission areas by the Bootstrap method.

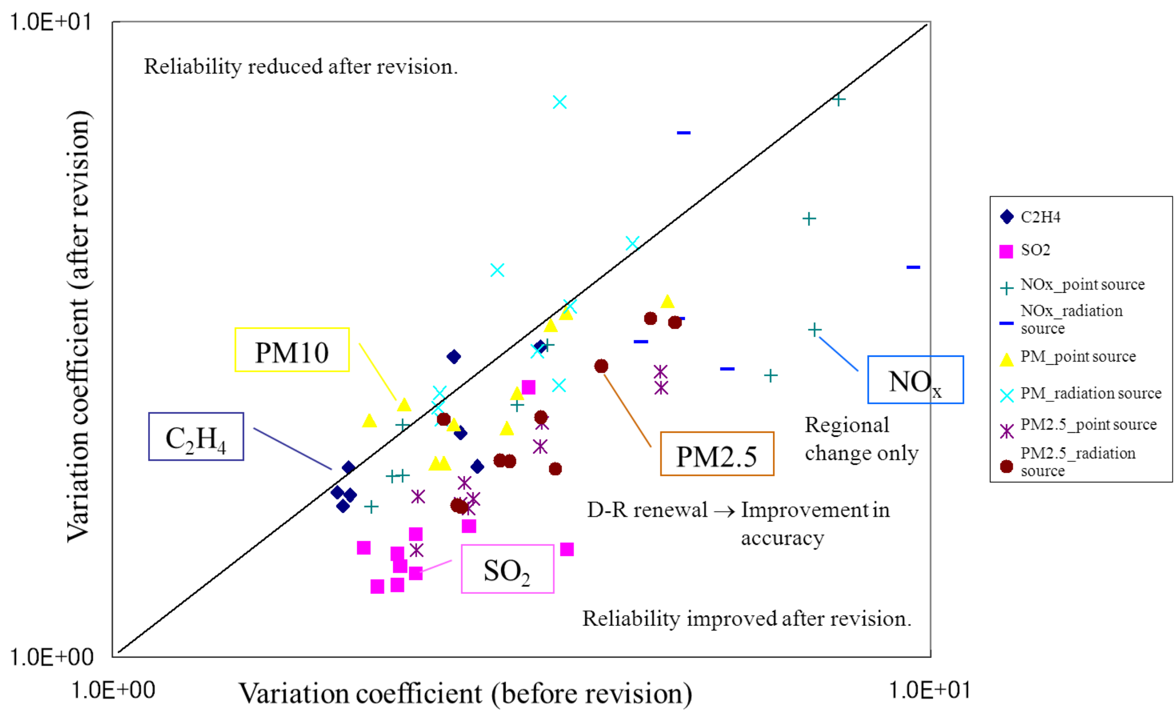


Figure 1.3-8: Changes in the variation coefficients of damage factors before and after reexamination

This figure shows relative improvement in the reliability of many damage factors.

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