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LIFECYCLE ASSESSMENT APPLICATION FOR BRIDGE TECHNOLOGY DEVELOPMENT

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Abstract

Lifecycle assessment (LCA) has developed to be an efficient and indispensable methodology for evaluating the development of new industrial products since 1970s, in particular since the ISO 14000 was issued as an international standard in 1995. In recent years, new types of bridges have continued to appear with the development of construction technologies and functional requirements in Japan. However, lifecycle assessment was rare to be used to evaluate such new types of civil infrastructures and new constructed projects. In this research, the general lifecycle assessment methodology is modified for evaluating the new types of civil infrastructures. Furthermore, this modified methodology is applied for comparing the lifecycle performance of a conventional bridge and a minimized girder bridge, which is a new type of bridges and has been constructed in the second Tokyo-Nagoya expressway. Finally, a detailed study is carried out to determine the effects of several parameters onto the lifecycle assessment of bridges, including the service life and the recycled ratio.

KEYWORDS: *lifecycle assessment (LCA), lifecycle cost, lifecycle environmental impact, minimized girder bridges*

1. Introduction

In recent years, global environment has drawn worldwide attention to reduce the emissions of greenhouse gases. As a project of international collaboration for the prevention of global warming, the United Nations Framework Convention on climate Change (UNFCC) was adopted in May 1992 with the aim of stabilizing the greenhouse gas concentrations in the atmosphere. In the third conference of parties (COP3) of UNFCC, numerical targets for reducing greenhouse gas emissions by industrial nations are proposed as the Kyoto protocol (UNFCC 1997). Most industrialized nations are required to reduce the greenhouse gases emissions by a certain percentage of the 1990 level in 2012. For example, Japan and USA have proposed to reduce the greenhouse gases emissions by 6% and 7%, respectively.

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However, the greenhouse gas emissions of the industrial nations were not decreased after 1997, but increased about 20% because some countries have not approved this proposal and it is also difficult to reduce the greenhouse gas emission in practice. This proposal urges every industrial nation towards finding effective ways of reducing greenhouse gases emissions from all sectors of the national development. Since the construction industry is one major sector of national development, there will be pressure on the construction industry to find ways of reducing its share of greenhouse gases emissions.

Due to the use of the construction materials and equipment, and the consumption of the fossil fuels during the related industrial activities, the emissions of greenhouse gases are caused from construction activities. For example, the manufacture of cement, a major construction material, contributes a significant portion of the carbon dioxide (CO_2) emissions (IPCC 1997). It contributes about 2.4% of total CO_2 emission from industrial sectors. The construction sector is mainly associated with the natural resources consumption and industrial activities, and the major greenhouse gas from this sector is CO_2. The construction sector in Japan is consuming about 3.10×10^{14} kcal of energy and contributing about 30.3 million metric tons of CO_2 emissions every year (PWRI 1993). Compared to the total national figure of Japan, this makes about 8% and 10% of total energy consumption and CO_2 emissions, respectively. Since all civil engineering, building construction and maintenance are related to construction activities, the total of construction activities account about 19% of total national annual energy consumption and 23% of total national annual CO_2 emission. Other portions of energy consumption and CO_2 emissions are mainly from the sectors of transportation, industries, land use and so on.

Lifecycle assessment (LCA) has developed to be an efficient and indispensable methodology for evaluating the development of new industrial products since 1970s (EEA 1998), especially since the ISO 14000 was in draft international standard form in 1995 (Clements 1996). In recent years, new types of bridges have continued to appear with the development of construction technologies and functional requirements in Japan. However, lifecycle assessment was rare to be used to evaluate such new types of civil infrastructures and new construction projects. In this research, the general lifecycle assessment methodology is modified for evaluating the new types of civil infrastructures. Furthermore, the modified methodology is applied for comparing the lifecycle performance of a conventional bridge and a minimized girder bridge, which is a new type of bridges and has been constructed in the second Tokyo-Nagoya expressway. Finally, a detailed study is carried out to determine the effects of several parameters including the service life and the recycled ratio onto the lifecycle assessment of bridges.

2. Current Condition and Development of Bridge Technology

2.1 Current Condition of Bridges in Japan

The bridge construction in Japan increased rapidly from the first five-year highway construction plan that started in 1954, and gradually decreased from the later half of the 1970s. During the period from 1956 to 1975, about 61,000 highway bridges were built, which were almost the half of the existing bridges (Nishikawa et al. 1996). Giving that the service life of a bridge is 50 years old, a number of bridges will need major rehabilitation or replacement by early next century as shown in Figure 1. According to the statistical annual report on highway bridges (*Annual* 1999), the number of highway bridges over 15 *m* in their length reached 135,161 in 1996. The total length of these bridges was about 7,879 *km*. Both the number of bridges and their total length have been steadily increasing with an annual ratio of more than 2% since 1988. It was predicted in the White Paper on Construction of Japan that the maintenance cost of all civil infrastructure systems will increase to about 50% of total public works investment up to 2020 (*White* 1994). In 1990, the cost was only 19%. The infrastructure crisis will soon provide a challenging task for the bridge engineers, and the bridge engineers should pay more attention to the development of bridge technologies to prolong the service life of a bridge, such as the development of minimized girder bridges.

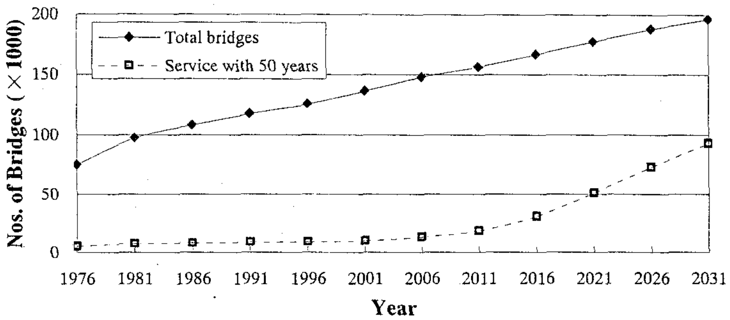

Figure 1. Increase of Bridge Numbers in Japan

2.2 Needs and Development of Minimized Girder Bridges

The minimized girder bridge is a relatively new developed type of bridges. It was first constructed in the second expressway between Tokyo and Nagoya in Japan in 1994 (EXTEC 1995). The major idea of the minimized girder bridge is to reduce the numbers of main girders and secondary girders by rationalizing the bridge structural components such as by increasing the rigidity of the deck. A board of investigation and study containing near 50 bridge experts including the first author of this paper from both sides of universities and bridge corporations was founded in 1994 to service for the design, construction and service monitoring of this expressway. Figure 2 shows the conceptual graphs of a conventional bridge (abbreviated as CB in figures) and a minimized girder bridge (abbreviated as MGB in figures). Six main girders are needed if a conventional bridge is designed and constructed, while a minimized girder bridge is constructed with only three main girders in practice.

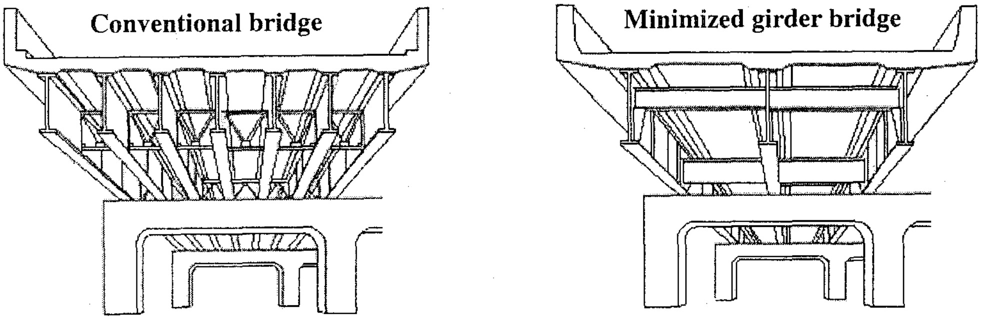

Figure 2. Conceptual Graphs of a Conventional Bridge and a Minimized Girder Bridge

In order to study the lifecycle performances of this new developed type of bridges, two typical bridges are formulated under similar conditions. One is designed and constructed under conventional bridge technologies and the other is a minimized girder bridge. Both bridges are assumed to be located in Nagoya with the same environmental conditions. The basic data of these two bridges are shown in Table 1. Because the lengths and widths of two bridges are not same, the calculation values of costs and environmental impacts in the following of this research presented in this paper are in form of the unit area of the bridge deck for the purpose of comparison.

Table 1. Bridge Data for the Lifecycle Assessment

	Conventional Bridge	**Minimized Girder Bridge**
Superstructure type	Steel continuous non-composite I girder bridge	
Bridge length (m)	199.7	173.4
Bridge width (m)	15.73	15.5
Spans (m)	40.5, 42.6, 49.5, 67.1	39.6, 40.3, 42.5, 51.0
Deck type	RC deck	PC deck
Deck thickness (cm)	24	27
Number of main girders	6	3
Height of main girder (m)	2.5	2.9
Connection	Bolt connection	Welding on site

3. Lifecycle Assessment of Bridges

3.1 Development of Lifecycle Assessment

The lifecycle assessment (LCA) was originally developed for analyzing the lifecycle of a new type of industrial product from the purchase stage of raw materials, production stage, shipment stage to customer, use stage by final customer, secondary use stage by customer, to the final product disposition stage from the viewpoints of environmental impact, cost and so on, and comparing this new industrial product with the available products or with alternative strategy in which at least one stage is of different contents. The first studies to look at lifecycle aspects of products and materials date from the late 1960s and early 1970s (EEA 1998). In 1969, for example, the Coca Cola Company funded a study to compare the resource consumption and environmental releases associated with beverage containers. Meanwhile, in Europe, a similar inventory approach was being developed, which was later known as the Ecobalance. Despite three decades of development, LCA is still a young tool (EEA 1998). Lifecycle assessment usually contains four distinct phases that are scooping, inventory, impact analysis and improvement analysis (Clements 1996). The main tasks at these four phases are to define the goals to apply the lifecycle assessment, to collect the necessary data, to carry out the potential impact assessment of an available product or a new product, and to carry out the impact assessment of an alternative improvement product, respectively. Lifecycle assessment does not have a fixed methodology and there is no single way to conduct. It has to be modified with the specific characters of the product. In addition, the lifecycle assessment is not the only way to assess the lifecycle performance and other methods must be used to supplement the assessment, such as the input-output table analysis. At the end of LCA, a report in significant detail and clarity should be created to the management to outline the discovery and how to improve the situation for the decision-making.

3.2 Modified Lifecycle Assessment for Bridges

In this research, the LCA methodology is modified for the development of bridge technologies into four phases based on the above-mentioned four phases for the general lifecycle assessment of a new product. The main tasks at each phase are described in Table 2 and they are interrelated each other during the LCA process.

Table 2. Lifecycle Assessment Phases for the Development of Bridge Technologies

Phases	Tasks
1	Defining the goals of lifecycle assessment, decomposing the lifecycle into several stages, and identifying the elemental items at each lifecycle stage
2	Studying the approach to determine the resource consumption of each elemental item, and collecting the unit value for each assessment purpose
3	Applying the lifecycle assessment for the conventional bridge technology, and determining the parametric values
4	Applying the lifecycle assessment for the new bridge technology, and comparing with the conventional bridge technology

Phase 1: The lifecycle of a bridge cover several stages including the planning, design, construction, service and monitoring, maintenance, and demolition stages in which different organizations and engineers take the key roles. In this research, however, the bridge lifecycle represents the construction stage, the maintenance stage and the replacement stage only, which cover the major on-site activities and resource consumption. The elemental items at each lifecycle stage are discussed in detail in the following chapter. The lifecycle assessment goals are specified as the lifecycle environmental impact and the lifecycle cost.

Phase 2: In this stage, the main tasks are to determine the quantity of each elemental item, and the unit value for each assessment goal. The volume or weight of materials is calculated for a bridge lifecycle based on the design manuals and interview with bridge engineers. Similarly, the duration of construction equipment used in various construction, maintenance and demolition activities are found by the databases depicting the past experiences and interview. The CO_2 emission from the unit volume or the unit weight or the unit duration is taken from the results of studies by PWRI (1994) and JSCE (1997). The PWRI values are obtained by input-output analysis of Japan. The JSCE values are calculated with LCA method in which all processes are accounted for making a product. This LCA method is supplemented by the input-output analysis. Since JSCE values are new and cross-checked with both LCA and the input-output analysis, the JSCE values are used in this research to calculate the lifecycle environmental impact of bridges. However, the unit CO_2 emissions of some construction materials that are not included in JSCE analysis are calculated according to the PWRI values. The unit cost value is determined according to several cost manuals and the interview.

Phase 3: In this stage, a conventional bridge is studied from the lifecycle environmental impact and cost points of view, and the possible effects of the assessment scopes, the setting assessment period, and the recycling and so on. These selected scopes are usually considered to directly relate the functions of a bridge.

Phase 4: The new type of bridge technology, minimized girder bridge, is assessed in detail and the results are compared with the conventional bridge with the similar conditions. The conclusions should be stated from the viewpoints of lifecycle assessment goals to comment the application prospect of this new bridge technology.

4. Basic Assumptions for Lifecycle Assessment of Bridges

4.1 Basic Assumptions for Each Lifecycle Stage of Bridges

The lifecycle analysis has played an important role in the bridge management by considering all bridge lifecycle stages at the same time. Most of the previous researchers focused their research efforts onto the lifecycle cost analysis (Frangopol et al. 1997, Liu and Itoh 1997). Lifecycle analysis approach has also applied for the reliability analysis (Ellis et al. 1995). The environmental issues during the bridge lifecycle were also dealt with in several previous research efforts by the research group led by the first author (Itoh et al. 1996, Itoh et al. 1999, Itoh et al. 2000a, and Itoh et al. 2000b). In this research, the bridge lifecycle contains the construction, maintenance and replacement stages only, and therefore the lifecycle environmental impact and cost could be summed as follows:

$$E_t = E_c + E_m + E_r \tag{1}$$

$$C_t = C_c + C_m + C_r \tag{2}$$

where, E_t and C_t are the environmental impact and cost within the whole lifecycle of a bridge, respectively; E_c and C_c are the environmental impact and cost from the construction stage, respectively; E_m and C_m are the environmental impact and cost from the maintenance stage, respectively; and E_r and C_r are the environmental impact and cost from the replacement stage, respectively.

4.1.1 Basic assumptions for construction stage

The lifecycle assessment at the construction stage needs the primary data of a bridge including its cross section data, span arrangement, superstructure type, substructure type, foundation type and others. In the previous research, a bridge type selection system was developed to determine these primary data and the environmental impact and cost from the construction stage of a bridge with the selected type (Itoh et al. 1996, Itoh et al. 2000b). These outputs are parts of the lifecycle environmental impact and cost of a bridge. The environmental impact from the construction stage contains the environmental impact from both the construction materials and the construction machine, and can be formulated in the following equation:

$$E_c = \sum_{n=1}^{N} M_n \times U_{CO2}(n) + \sum_{j=1}^{J} (G(j) \times U_g(j) + W_w(j) \times U_w(j)/W_l(j)) \times W_h(j) \tag{3}$$

where, M_n and $U_{CO2}(n)$ are the quantity of one kind of construction material (n) and the CO_2 emission due to its consumption per unit; $G(j)$, $U_g(j)$ and $W_h(j)$ are the energy consumption per hour, the CO_2 emission due to the consumption of energy per unit, and the working hours for one construction machine (j); and $W_w(j)$, $U_w(j)$ and $W_l(j)$ are the weight, the CO_2 emission per weight, and the service life for one construction machine (j), respectively. The symbols N and J are the numbers of kinds of materials and machine, respectively. The similar formulations are used for calculating the environmental impact from both the construction materials and the construction machine during the maintenance and demolition stages. The cost during the construction stage covers the costs of construction materials, construction machine and labor, which are determined according to the design and construction manuals of bridges and the interviews with the practical bridge engineers.

4.1.2 Basic assumptions for maintenance stage

The maintenance requirements and specific techniques of a bridge or its components are determined according to the periodic inspection and the further testing in detail if necessary. Based on the existing bridge inspection manual and the hearing with the practical engineers, eight types of bridge components needs more maintenance, which are the pavement, deck, painting, expansion joint, support, girders, guard fence, and pier (abutment) due to the structural deterioration due to the service and material aging. Among these eight components, however, the girder, guard fence and pier are usually damaged by some unpredicted events such as the earthquake and traffic accidents, and therefore it is difficult to determine the maintenance needs and the maintenance period of such a bridge component. In this research, only five bridge components are considered for the lifecycle evaluation, namely the pavement, deck (PC deck and RC deck), painting, expansion joint, and support. The maintenance period (service life) of these components are assumed as the mean values in Table 3 by hearing with the practical engineers and referring some publications such as Nishikawa 1994.

Table 3. Maintenance Cycles of Bridge Components (year)

Components	Service life
Pavement	15
PC deck	50
RC deck	30
Painting	20
Expansion joint	20
Support	30

The environmental impact and cost from the maintenance stage contains the environmental impact and cost from both the construction materials and the construction machine, and are formulated in the following equations:

$$E_M = \sum_{i=1}^{5} (E_{iMm} + E_{iMw}) \frac{L}{L_i} \tag{4}$$

$$C_M = \sum_{i=1}^{5} (C_{iMm} + C_{iMw}) \frac{L}{L_i} \tag{5}$$

where, E_{iMm} and C_{iMm} are the total environmental impact and cost during the maintenance stage from the construction materials for the bridge component i, respectively; E_{iMw} *and* C_{iMw} are the total environmental impact and cost during the maintenance stage from the construction machine for the bridge component i, respectively; and L and L_i are the analysis period and the service life of the bridge component i, respectively. Estimations of costs and environmental impacts from maintenance activities of these bridge components are difficult for the time being and the values used in this research are adopted from the previous literature and interview with practical bridge engineers (Itoh et al. 1999).

4.1.3 Basic assumptions for demolition stage

There have been existing several common bridge replacement methodologies, such as (1) closing the traffic while replacing, (2) constructing a temporal bridge instead of the existing bridge under the replacement, and (3) closing a part of the bridge and keeping the other part for the service. The selection of such a replacement method is dependent on the bridge type, the site condition, the traffic condition and so on. To determine the environmental impact and cost due to the replacement activity, the consumptions of materials and machinery of each replacement operation are essential. However, such data have not been summarized well so as to be able to be utilized for the further calculation. Therefore, the environmental impact and cost from the replacement stage in this research are assumed to be constants without considering the possible change due to the different method. The environmental impact and cost from the replacement stage contains the environmental impact and cost from both the demolition of the old bridge and the construction of a new bridge, and are formulated as follows:

$$E_r = E_{rd} + E_c \tag{6}$$

$$C_r = C_{rd} + C_c \tag{7}$$

where, E_{rd} and C_{rd} are the environmental impact and cost due to the demolition of the old bridge, respectively. These values are difficult to estimate from every section in detail. In this research, only the environmental impact from the demolition machine is considered, and the demolition cost is obtained from the interview. The demolition costs of several past demolished bridges in Nagoya city are collected and represented by the way of per unit of deck area. The average value and the standard deviation of these demolition costs are 226 thousand Yen/m^2 and 41 thousand Yen/m^2, respectively. This average value is about the 2.5 times of the construction cost of a new bridge per square meter of the deck area, which is near the number of 2.8 concluded in another research (PWRI 1997). The environmental impact and cost due to the construction of a new bridge are considered as a part of the environmental impact and cost at the demolition stage, however they are not included into the demolition cost if only one lifecycle is analyzed.

4.2 Scopes for Lifecycle Assessment

The environmental impact of a civil infrastructure is usually considered due to the consumption of materials and machinery. The environmental impact of a construction machine is from the energy consumption during the utilization and its manufacturing process. It is interesting to compare the CO_2 emission values from the material consumption and the machine utilization for constructing a bridge or a bridge component. Table 4 shows the CO_2 emission from various materials and machine for constructing 100 square meter of pavement.

Table 4. Environmental Impact for Pavement Construction (per 100 m^2)

	Consumed Values	**Environmental Impact (tC)**
Asphalt	19.05 (t)	1.960
Water-proof sheet	100 (m^2)	1.156
Finisher	0.37 hour	0.040
Road roller	0.37 hour	0.015
Tier roller	0.37 hour	0.031
Total		3.203

It is clear that the environmental impact from the construction machine is very small compared to the value from the materials consumption and is less than 3% of the total CO_2 emission. The similar results can be found for other bridge components. Therefore, the environmental impact usually means the environmental impact from the material consumption only excluding the environmental impact from the machinery. Furthermore, in the case of the lifecycle assessment of a vehicle, the environmental impact from its manufacturing machine is usually ignored too.

It is widely noticed that the discount rate has a large effect onto the results of the lifecycle assessment. However, it is very difficult to predict the exact values of discount rate at each year within the lifecycle because of the long cycle and the difficulty of the long-term prediction. The effect of the discount rate (abbreviated as Rate) of 0%, 0.5%, and 2% after every round of 5 years within the lifecycle of 120 years is shown in Figure 3 in the ratios to the construction cost of a conventional bridge. The lower indices of a minimized girder bridge represent that it is economical over a conventional bridge for each given value of the discount rate. It is much obvious between 60 and 100 years that are the service lives of a conventional bridge and a minimized girder bridge, respectively. On the other hand, the commodity prices usually increase year by year due to the inflation, which plays an opposite role in the lifecycle assessment to the discount rate. Therefore, no discount rate is considered in the following part of this paper. In addition, no discount rate is applied in the environmental impact, which is the common approach for the lifecycle environmental assessment at the time being.

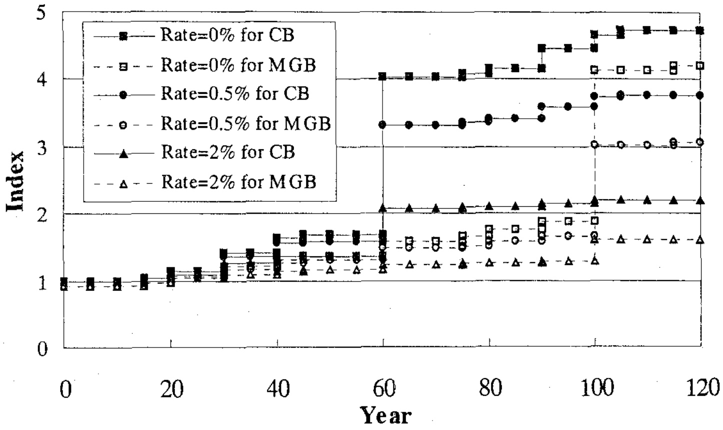

Figure 3. Effects of Discount Rate onto Lifecycle Cost

The service life of 120 years is used in this comparison and the remaining part of this paper. It is theoretically ideal to use the infinity as the analytical lifecycle, but it cannot be accepted from the viewpoint of bridge engineering.

5. LCA Applications for Conventional Bridges and Minimized Girder Bridges

5.1 Comparison of Conventional Bridges and Minimized Girder Bridges

According to the statistics and reports from the fabrication factories and the construction sites, during the fabrication and construction stage of a conventional bridge and a minimized girder bridge, the basic data of which are summarized in Table 1, the steel weight, the number of larger components, the number of small components, the weld length and the painting area of a minimized girder bridge are as low as around 89%, 25%, 43%, 64%, and 60% of a conventional bridge, respectively. These percentage values are shown in Figure 4. In particular, the number of large components of a minimized girder bridge decreases a lot due to the less number of main girders.

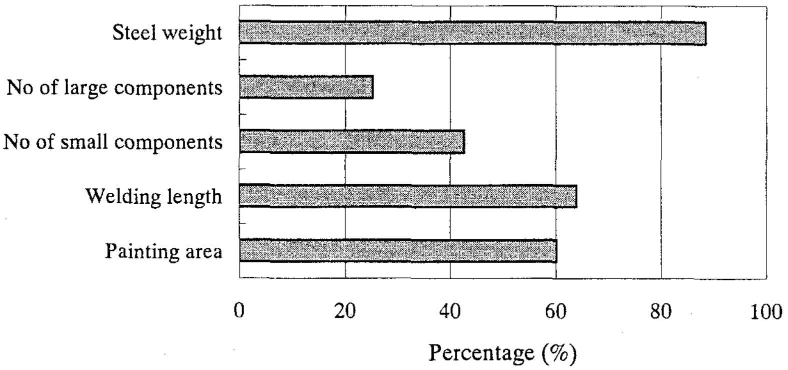

Figure 4. Material Consumption of a Minimized Girder Bridge versus a Conventional Bridge

Due to the decreases of volumes and weights of materials, the fabrication cost of a steel minimized girder bridge is about 60% of the fabrication cost of a conventional bridge. In addition, as shown in Figure 5 by taking the CO_2 emission of a whole conventional bridge as 100%, the CO_2 emission of a minimized girder bridge is only about 94%.

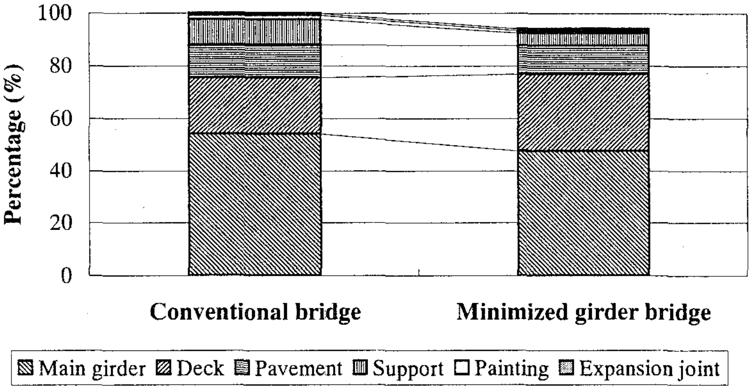

Figure 5. Comparison of CO_2 Emissions of the Construction of Bridge Components

According to Figure 5, the main girder, deck and pavement contribute the major portion of CO_2 emission during the construction stage of both a conventional bridge and a minimized girder bridge. The CO_2 emissions of most bridge components are also smaller in the case of a minimized girder bridge. However, the CO_2 emission of the deck is larger in case of a minimized girder bridge than that of a conventional bridge. Table 5 compares the volume and weight needed per square of deck for two types of bridges. It is very obvious that a minimized girder bridge takes more concrete, forms, reinforcement, and PC steel to construct a unit area of deck due to its higher thickness and the higher requirement of the structural rigidity.

Table 5. Comparison of Materials Needed for Bridge Deck Construction (/m^2)

	Conventional Bridge	**Minimized Girder Bridge**
Concrete Volume (m^3)	0.249	0.296
Form (m^2)	0.717	1.480
Weight of reinforcement (kg)	62.062	75.432
Weight of PC steel (kg)	0	10.214

5.2 Lifecycle Assessment of Conventional Bridges and Minimized Girder Bridges

Figure 6 shows the comparison of the lifecycle CO_2 emission and cost between a conventional bridge (CB) and a minimized girder bridge (MGB). The indices of the CO_2 emission and cost at a certain year represent the relative values by taking the CO_2 emission and cost values of a conventional bridge at the construction stage as one. The increasing tendencies of the cost and CO_2 emission with years are very similar for both a conventional bridge and a minimized bridge. However, the indices of the environmental impact and the cost of a conventional bridge at the end of 120 years are higher than the indices of a minimized girder bridge although all indices at the starting year are very near due to the near cost and CO_2 emission from the construction stage. The differences may reach the doubles if the service lives are between 60 and 100 years.

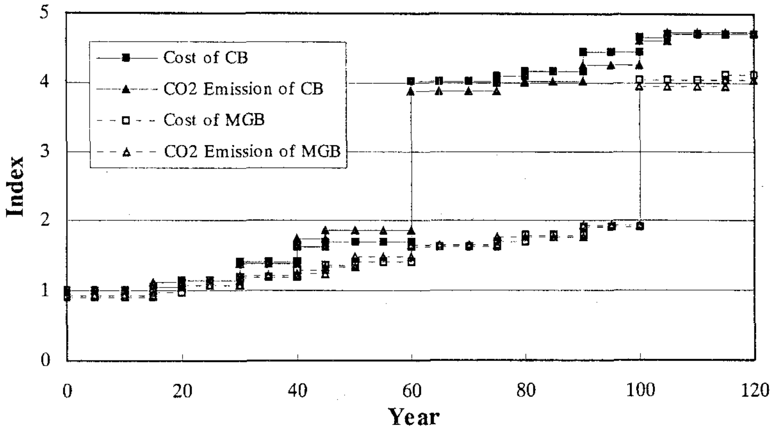

Figure 6. Comparison of the CO_2 Emission and Cost

Further comparison is carried out for the annual CO_2 emission and cost within one life cycle of a conventional bridge and a minimized girder bridge from various lifecycle stages. Figure 7 shows the relative percentages by taking the total lifecycle CO_2 emission and cost values of a conventional bridge as one. The differences between a conventional bridge and a minimized girder for a given lifecycle stage are rather large no matter for the cost or for the CO_2 emission, and the prolonged service life of a minimized girder bridge takes an important effect to increase these differences as well as its simplified structural characters.

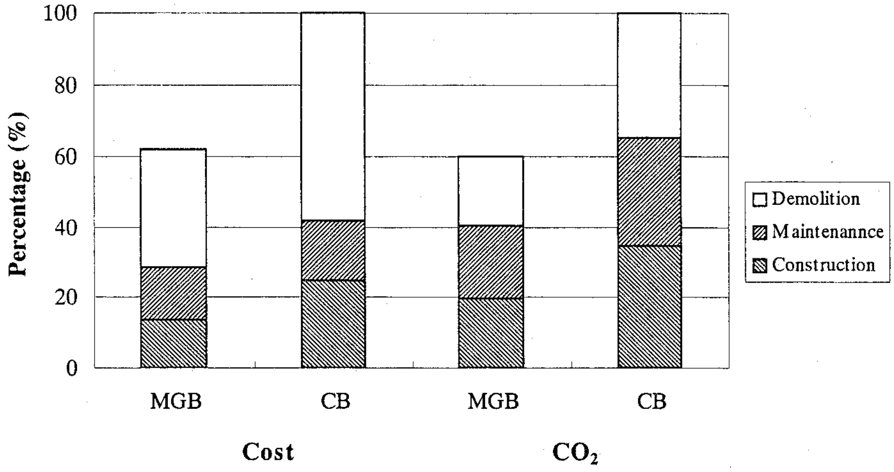

Figure 7. Comparison of the Annual CO_2 Emissions and Costs

Figure 8 shows the relative percentages of the annual cost and CO_2 emission of a conventional bridge and a minimized girder bridge from the maintenance performance of each bridge component by taking the total cost and CO_2 emission values of a conventional bridge as one. The minimized girder bridge could reduce about 15% and 30% of the annual cost and CO_2 emission of a conventional bridge induced due to the maintenance activities. In the case of a conventional bridge, the deck maintenance is very costly and contributes more CO_2 emission than other bridge components, and however the pavement become a more noticeable component for a minimized girder bridge. The orders of the percentages of the costs from various maintenance activities are different for a conventional bridge and a minimized girder bridge. The similar conclusions could be stated for the environmental impact, too.

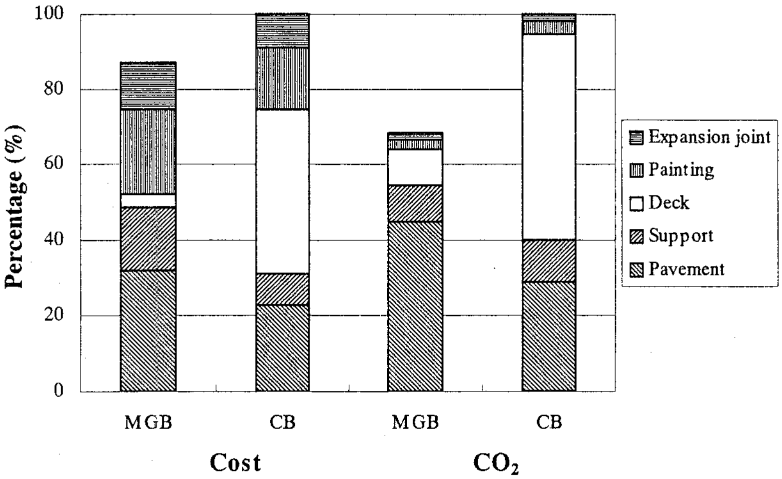

Figure 8. Comparison of the CO_2 Emission and Cost due to the Maintenance Activities

5.3 Effects of Service Life onto Lifecycle Assessment

Further comparison study on the CO_2 emission and cost consumption from each lifecycle stage has been performed by considering three cases of replacement cycles (short service life, standard service life and long service life) of each major bridge component as shown in Table 6. For the purpose of comparison, it is assumed that all bridge components have one same deteriorating speed of these three cases. The unit in the table is year. The standard lives of these five bridge components are used in the previous calculation and comparison.

Table 6. Replacement Cycles of Bridge Components (year)

	Short service life	Standard service life	Long service life
Pavement	10	15	20
PC deck	40	50	60
RC deck	20	30	40
Painting	15	20	25
Expansion joint	15	20	25
Support	25	30	35

Figures 9 and 10 represent the CO_2 emission and cost consumption from the whole lifecycle stages of both a conventional bridge (CB) and a minimized girder bridge (MGB) in three cases of service lives (short service life, standard service life, and long service life) by taking the CO_2 emission and cost consumption of a conventional bridge at the construction stage as 1, respectively. It is obvious that a conventional bridge contributes more CO_2 emission and needs more cost than a minimized girder bridge in each of the three cases of replacement cycles. On the other hand, from these figures, it is also made clear that prolonging the service life of a bridge component is invaluable for both a conventional bridge and a minimized girder bridge from the viewpoints of the lifecycle environmental impact and the lifecycle cost.

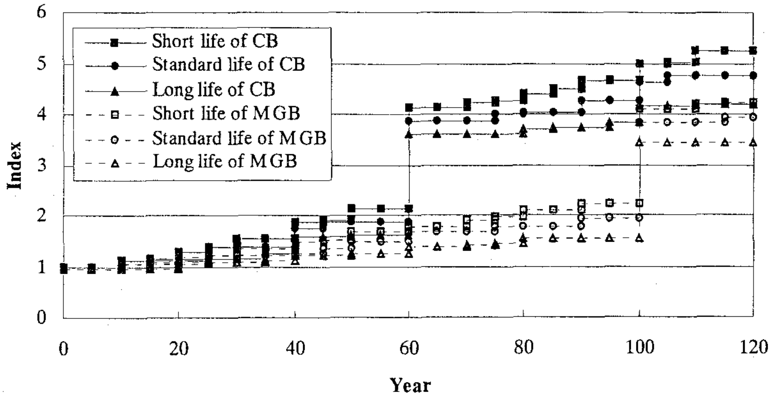

Figure 9. Effect of Service Life onto the Lifecycle CO_2 Emission

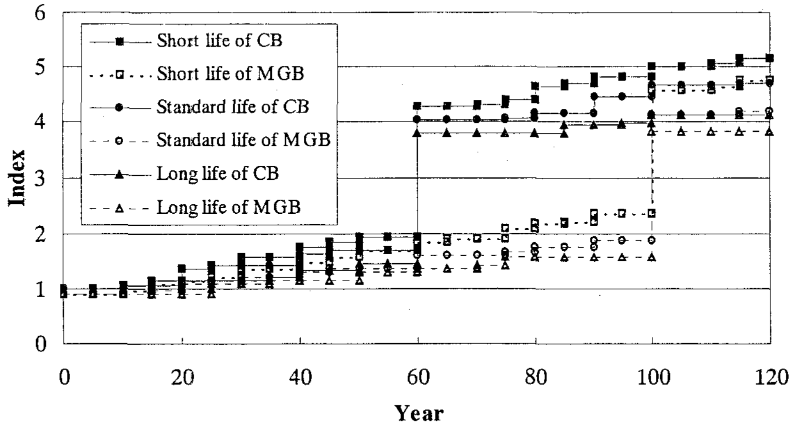

Figure 10. Effect of Service Life onto the Lifecycle Cost

5.4 Effects of Recycling onto Lifecycle Assessment

Recycling is an efficient way to reduce the environmental situation and has been applying in various fields. Although it is not encouraged to use the recycled materials for the bridge construction in Japan at the time being for the purpose of safety, it would be a tendency with the further development of recycling technology and the increasing burden of the environmental requirement. Three scenarios on the application of recycled materials in the bridge construction have been studies and compared for both a conventional bridge and a minimized girder bridge. Table 7 describes the differences within these three scenarios. The recycled materials contain three main portions: the steel recycled by melting it in the electric arc furnace and used in the superstructure, the recycled asphalt used in the pavement, and the concrete with 45% of the blast furnace slag cement.

Table 7. Scenarios of Application of Recycled Materials

Scenarios	Descriptions
O	New materials used for the whole lifecycle, including the construction, maintenance, demolition stages
A	Recycled materials used for the whole lifecycle, including the construction, maintenance, demolition stages
B	New materials used for the construction, and recycled materials used for the maintenance and demolition stages

Figures 11 and 12 compare the CO_2 emission and cost for the above three scenarios on the recycling strategies for a given period of 120 years, respectively. Recycling can cut the CO_2 emission down obviously for either a conventional bridge or a minimized girder bridge. However, its effect on the lifecycle cost is very minor because the recycle is still rather costly at the time being. This can be noticed from Figure 12, in which the three lines for a conventional bridge or a minimized girder bridge too close to be identified easily.

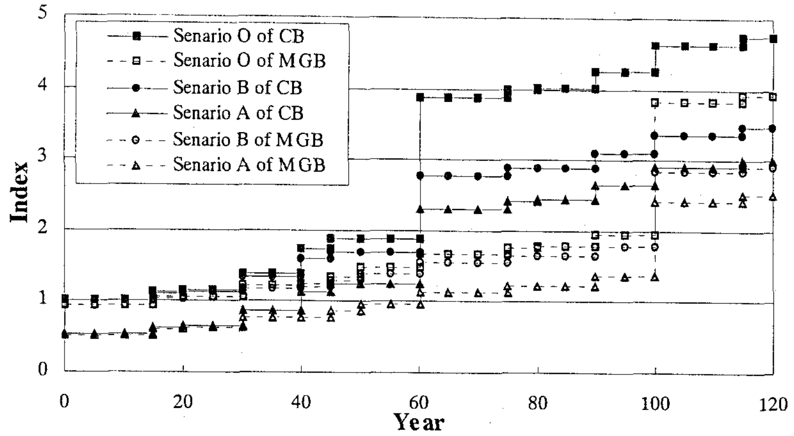

Figure 11. Effect of Recycling on Lifecycle CO_2 Emission

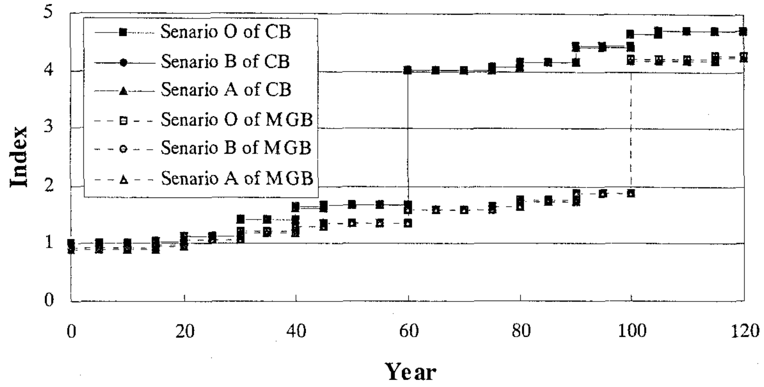

Figure 12. Effect of Recycling on Lifecycle Cost

Figure 13 shows the relative percentages of the CO_2 emission with and without recycling for a conventional bridge and a minimized girder bridge during the construction stage by taking the total CO_2 emission of a conventional bridge without recycling as 100%. The CO_2 emission of the deck in the case of a minimized girder bridge is relatively higher compared to a conventional bridge no matter with or without the application of the recycled materials. Particularly, in the case of a minimized girder bridge with recycle, the CO_2 emission of the deck is larger than the CO_2 emission of the main girder to become the top of the six bridge components. The values of other bridge components can be lessened efficiently. In addition, according to this figure, it is obvious that the recycling can reduce the CO_2 emission more efficiently than the development of a new type of bridges. Therefore, the environmental benefits from the application of the recycled materials challenge the engineers and managers to apply the recycled materials more with the civil infrastructure construction as well as to develop the technologies for producing the recycled materials to meet the structural and functional requirements of materials.

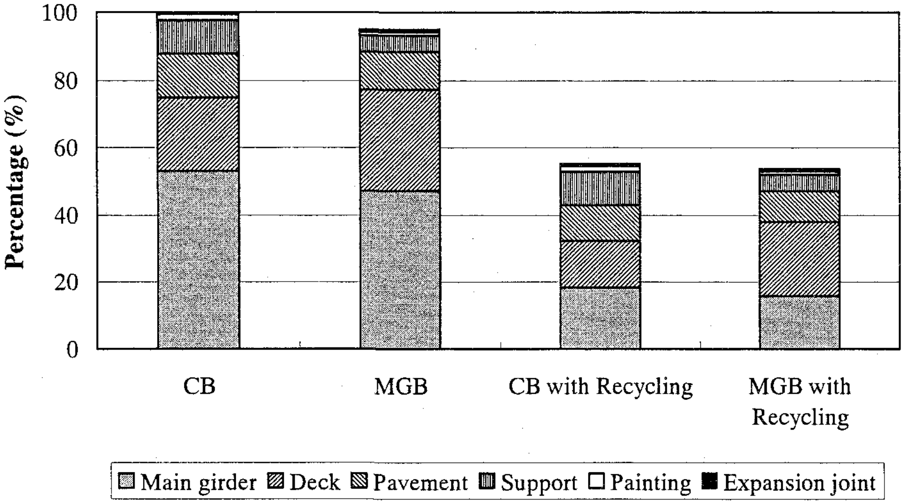

Figure 13. Sections of CO_2 Emission during the Construction Stage

6. Conclusions

This research aims to develop a lifecycle assessment methodology for the civil infrastructures and apply it for the development of a new type of bridge named minimized girder bridges. The following conclusions are obtained:

(1) The lifecycle assessment (LCA) methodology of ISO 14000 was modified for evaluating the development of bridge technologies. The tasks are made clear during each phase of the assessment process.

(2) The CO_2 emission and cost are formulated for each lifecycle stage of a bridge including the construction stage, the maintenance stage and the demolition stage. The resource consumption of the materials and machine for performing an elemental item within every stage is determined, and the CO_2 emission and cost of the resource consumption per unit are prepared for each elemental item based on the previous research works.

(3) The modified lifecycle assessment methodology was applied for assessing the lifecycle CO_2 emission and cost of the minimized girder bridges, and the results are compared with a conventional bridge. The minimized girder bridge diversifies the further development due to its less lifecycle environmental impact and cost.

(4) Numerical comparisons are carried out to determine the effects of the service life and the recycled ratio onto the lifecycle assessment of bridges. Generally, a conventional bridge contributes more CO_2 emission and needs more cost than a minimized girder bridge no matter the changes if the analytical service lives and the materials. For a given service life between 60 and 100 years, the differences of a conventional bridge and a minimized girder bridge may reach doubles in both the CO_2 emission and cost.

Because of the insufficiency of data such as the cost and CO_2 emission from the demolition of a bridge, some simplifications and assumptions were adopted in the research for the bridge lifecycle assessment based on a few documents and interviews. The numerical results could become more accurate with the accumulation of the necessary data. The authors would like to thank the Bridge Office of Nagoya City Civil Bureau and several bridge agencies for providing data and knowledge during the hearing. The partial financial support of the Ministry of Education, Science, Sports and Culture in Japan as the Foundation of Science (No. 11555124) is gratefully acknowledged.

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