Lifecycle Analysis of Steel Bridge Paint Systems

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Abstract

Steel bridges are usually protected from corrosion by paint systems. Since repainting is required several times during the service lives of typical bridges, the maintenance of bridge paint systems has a great influence on the lifecycle cost (LCC) and lifecycle environmental impact. The paint industry has been making efforts to cut down the hazardous materials in the paint, and recently succeeded to develop bridge paints that have much less volatile organic compounds (VOC) than before. The lifecycle analysis (LCA) of steel bridge paint systems in this study considers lifecycle VOC emissions (LCVOC) as well as lifecycle CO_2 emissions ($LCCO_2$) for rationalized bridges. The LCA of the conventional bridges, I-girder and truss bridges, was also performed and compared with those of the rationalized bridges. The characteristics of LCC, LCVOC and $LCCO_2$ of those bridges found from the analyses were discussed in this paper. It was found that there is a trade-off relationship between LCC and LCVOC of the low-VOC paints. In order to solve this trade-off problem, further advances in the paint technology are required.

Keywords: Lifecycle Cost, Lifecycle CO_2 Emission, Rationalized Bridge

1. INTRODUCTION

Various efforts have been made to achieve sustainable development and protect the global environment in many countries. Also in the construction industry, research efforts and technological developments have been made to reduce not only the cost but also the environmental impact of the civil structure during the construction, maintenance and replacement stages [1, 2].

In Japan, the environmental impact of construction is usually estimated from the CO_2 emission that is a typical greenhouse gas. In a study by the Public Works Research Institute of Japan [3], the CO_2 emission and the cost of structures were compared between the conventional construction method and the energy saving method. The study identified a construction method to be achieving both low cost and low environmental impact. The Global Environment Committee of the Japan Society of Civil Engineers [4] improved basic units to calculate a CO_2 emission of civil constructions and estimated CO_2 emissions during construction of structures, including dams and tunnels in 1996. Itoh et al. [5] presented the bridge type selection system in 1996 considering the environmental impact in addition to cost, traveling performance and landscape.

Steel structures are protected from corrosion to improve durability. Steel bridges are usually protected by painting. The cost and environmental impact of painting to maintain steel bridges can be significant because repainting is required several times during the service lives of typical bridges. Therefore, the mitigation of the maintenance of painting will reduce the lifecycle cost (LCC) and lifecycle CO_2 emission ($LCCO_2$) of steel bridges.

In recent years, many new technological developments have been made to mitigate the maintenance expenditure of steel bridges. In the Japanese bridge industry, newly developed bridges, which are less costly than conventional bridges by simplifying structural members, have come into wide use recently. These bridges are also considered to cut down maintenance costs. The maintenance costs of bridge painting can be mitigated by using high durability coating reducing painting areas [6]. Itoh et al. [7-13] quantitatively examined the LCC and $LCCO_2$ of the rationalized bridges, and showed that the rationalized bridges offer the lower cost and lower environmental impact when compared with the conventional bridges.

When assessing the environmental impact based on the CO_2 emission, the CO_2 emission is typically calculated by multiplying the basic unit of each material by the amount of the material used. Therefore, the larger the amount of the used material, the more the CO_2 emission is. However, because the total amount of coating in a steel bridge is relatively small when compared with the amount of all different materials in the entire bridge, the $LCCO_2$ of the steel bridge stemming from the painting is insignificant relative to the total $LCCO_2$ of the steel bridge. Itoh et al. [8] found that the $LCCO_2$ of the painting in some types of steel bridges are very low. According to the Japan Iron and Steel Federation [14], for the superstructure, a cost of the painting accounts for about 11% of the total cost, but the CO_2 emission from the painting accounts for only about 2% of the total emission, although, in recent years, it is well known that the environmental impact of the painting is not only the CO_2 emission.

In 2001, chemicals management based on PRTR (Pollutant Release and Transfer Registers) began, and information on designated chemicals, including transaction volumes, amount of releases and transfer as a waste, must be reported. Therefore, the paint industry has also been developing the environmental impact assessment system [15]. Because coatings contain chemical substances and heavy metals that present a danger to public health, the paint industry aims to control and reduce toxic substances. For example, the auto industry is reducing a volatile organic compound (VOC) from the coatings by introducing facilities that increase the coating application efficiency and by using water-based coating.

The bridge industry assesses durability and workability of newly developed coatings including low-VOC coatings and non-solvent coatings, and is performing researches and making further developments for the practical applications [16]. As described above, the paint industry has been trying to reduce VOC in the coating, and it is a trend that VOC is treated as one of the environmental impacts.

Therefore, the lifecycle analysis (LCA) of the steel bridge paint system must consider the amount of toxic substances in the coating and their emissions in addition to the amount of the CO_2 emission. Horvath [17] performed the environmental impact assessment of steel bridge painting considering toxic substances, but the study was focused on a construction stage, and did not consider other stages of a bridge life. Therefore, in this study, the LCC, $LCCO_2$ and lifecycle VOC emissions (LCVOC) of steel bridge paint system were calculated quantitatively for a lifecycle of a bridge. Based on the LCC, $LCCO_2$, and LCVOC, the LCA of conventional bridges and rationalized bridges was performed.

2. TOXIC SUBSTANCE IN BRIDGE PAINTING

The coating includes toxic substances including hazardous chemicals, hazardous heavy metals, and VOC. A familiar example of the hazardous chemicals is formaldehyde. Because this is the main causative chemical of the sick house syndrome, a law was enacted to restrict usage of formaldehyde [15]. Lead and chrome are hazardous heavy metals, and they are chiefly contained in the color pigments and the rust prevention pigments. These are known to be harmful to the human body. And, especially to lead, a restriction is imposed by the Industrial Safety and Health Law for the lead poisoning prevention [15]. The durability assessment of a lead and chrome free coating by Kasei et al. [18] is a recent study related to hazardous chemicals in the painting. Kasei et al. pointed out some issues in the lead and chrome free paint including durability and costs.

Toluene and the xylene that are chiefly contained in an organic solvent are examples of VOC. These are harmful to the human body, and are known to be the main causative chemicals of the suspended particulate matter (SPM) and photochemical oxidant. There are many domestic laws about the VOC. Among them, the amended air pollution control law promulgated in 2004 aims to reduce the amount of the VOC emissions by 30% of the emission in the fiscal year 2000 by 2010 [19]. Therefore, the conversion into water-based coatings to reduce the usage of organic solvents is currently progressed.

Coatings used for steel bridges also contain hazardous heavy metals in the rust prevention pigment and hardening accelerator and VOC in solvents. As for the painting, it is a surface preparation process when the hazardous heavy metal has the most environmental impact. Therefore, when the lifecycle environment impact of hazardous heavy metals is assessed, it is necessary to calculate how much of the hazardous heavy metals disperse into the atmosphere when surface preparation is performed. However, because cover sheets for the dispersion prevention are typically used as a rule when the surface preparation is performed on the site, it is also possible to think that there is no environmental impact if it is assumed that the sheets prevent the dispersion perfectly. On the other hand, because the VOC is discharged from coating, it is necessary to calculate the amount of the emission during painting.

In this research, it is assumed that the VOC is the only toxic substance emission during painting and the dispersion prevention sheets can completely eliminate the environmental impact of the hazardousness heavy metal. The LCA of the paint system is, then, performed considering LCVOC as one of the environmental impact indicators in addition to $LCCO_2$.

3. LCA OF BRIDGES

3.1. Introduction

The LCA of bridges in this study performed according to the process shown in Fig. 1 [5], [8-13]. This process is considered to be applicable in the social infrastructure facilities referring to the ISO LCA method [7].

The lifecycle was classified at the first stage of the LCA. In this research, the bridge lifecycle contains the construction, maintenance and replacement stages only, and these stages are set as the range of the analysis.

At the LCA second stage, basic units etc. necessary for the evaluation were collected.

In this research, the CO_2 emissions basic units basically were used the recommended values of the Global Environment Committee LCA subcommittee of the Japan Society of Civil Engineers [20]. By this committee, how to combine the input-output analysis method and the summation method was proposed and CO_2 emission basic units were contributed. Table 1 shows the main basic units using this research. If each amount of use (each unit) is multiplied by the basic unit, it becomes CO_2 emissions. Table 2 shows basic units of paint systems. These values were multiplied the amount of the VOC of each paint system included the per unit area, and calculated by this research.

At the LCA third stage, the LCC, $LCCO_2$, and LCVOC of the targeted steel bridge were actually calculated.

At the LCA fourth stage, an alternative form and the construction method were discussed. In this stage, the LCC, $LCCO_2$, and LCVOC by the difference of the span length etc. were compared.

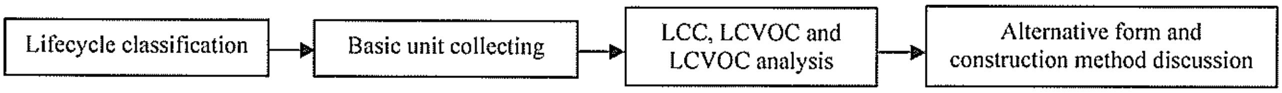


Fig. 1 Process of LCA in this research

Table 1 CO_2 emission basic units

	Unit	Basic unit (kgC/unit)
Painting	t	452
Scaffolding	t	128
Steel material	t	411
Concrete	m^3	84.9
Asphalt	t	11.3

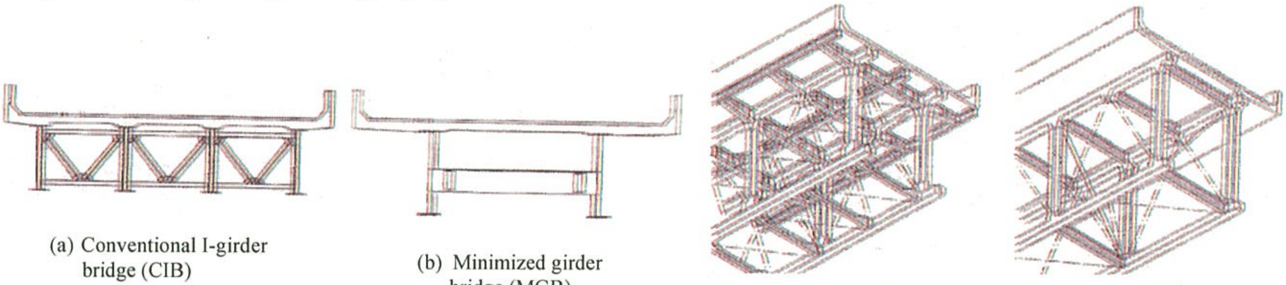
Table 2 VOC content basic units

	Basic unit (g/m^2)
A-1 paint system	184.9
a-1 paint system	74.8
I paint system	303.3
c-1 paint system	285.8

3.2. Targeted Bridges

Four types of the bridges, conventional I-girder bridge (abbreviated as CIB below), minimized girder bridge (abbreviated as MGB below), conventional and rationalized truss bridges (abbreviated as CTB and RTB below), were targeted [13]. Each structural drawing is shown in Fig. 2 and the data are shown in Table 3 and Table 4. MGB is constructed with only two main girders by making decks from prestressed concrete (PC) and significantly simplified the transverse minor girders and other components. The PC decks adopted in RTB are able to reduce the amounts of the main longitudinal girders and brackets. Therefore, the materials required to construction a RTB are reduced drastically. To be easily comparable, it was assumed that these bridges have the same width of 10.5 m and the same span allotment (Steel 3-span continuous non-composite bridge).

Fig. 3 and Fig 4 show the steel weight and painting area versus the span length of targeted bridges. And Table 5 shows steel weight and painting area reduction ratios of the rationalized bridge to its conventional bridge. Data of CIB, MGB and CTB in Table 5 referred to the data based on results of the Japan Bridge Association [6]. Because construction results of RTB were limited, it calculated the reduction rates compared with CTB by using shown in Ref. [6]. Therefore, the decrease rate of steel weight and painting area of RTB became constant. The range of the span length was assumed to be from 80 m to 100 m with I-girder bridges and from 30 m to 60 m with truss bridges, with an interval of 10 m respectively. The vertical axis represents the comparison value based on I-girder bridges. CIB is changed into concave downward parabolic curve as shown in Fig. 3 and Fig. 4. Therefore, there was a difference in the result from the I-girder bridge when the span length changed [13].



(a) Conventional I-girder bridge (CIB)

(b) Minimized girder bridge (MGB)

(c) Conventional truss bridge (CTB)

(d) Rationalized truss bridge (RTB)

Fig. 2 Targeted bridges

Table 3 Data for I-girder bridges

	CIB	MGB
Super structure type	Steel 3-span continuous non-composite	
Bridge length	90• 180 m	
Bridge width	10.5 m	
Span length	30• 60 m	
Deck tyoe	RC deck	PC deck
Number of main girders	4	2

Table 4 Data for truss bridges

	CTB	RTB
Super structure type	Steel 3-span continuous non-composite	
Bridge length	240• 300 m	
Bridge width	10.5 m	
Span length	80• 100 m	
Deck tyoe	RC deck	PC deck

Table 5 Steel weight and painting area reduction ratios of the rationalized bridge

Span length (m)	Steel weight reduction ratio (%)	Painting area reduction ratio (%)
MGB 30 m	108	59
MGB 40 m	94	49
MGB 50 m	82	41
MGB 60 m	72	35
RTB 80 m	95	80
RTB 90 m	95	80
RTB 100 m	95	80

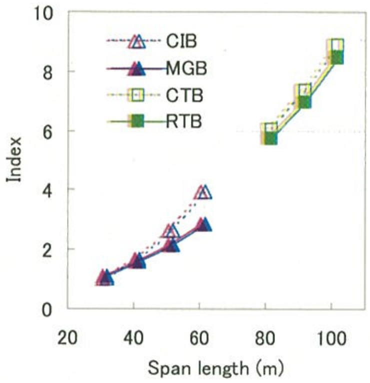


Fig.3 Steel weight versus span length

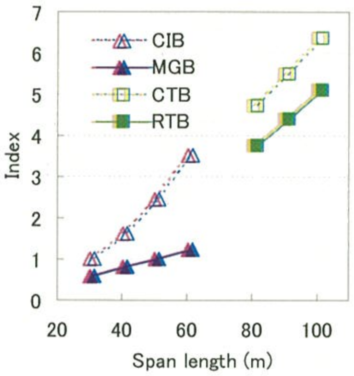


Fig.4 Painting area versus span length

3.3. Adopted Paint Systems

In this paper, conventional bridges and rationalized bridges adopt a different paint system in consideration of the paint system used for actual bridges. Table 6 shows the paint system adopted for each bridge. A-1, a-1, and c-1 and I paint systems were provided by the old painting manual for steel highway bridges [22] and old Japan Highway Public Corporation [23], respectively. Conventional bridges adopt the A paint system which had been most often-used system in Japan, and the repainting system which is the repainting system of the A paint system, respectively. Rationalized bridges adopt the I paint system which corrosion protection performance is higher than the A paint system and the c repainting system which is repainting system of the C paint system preformed highest corrosion protection.

Table 7 shows the using paints and basic usages of A-1 and a-1, and Table 8 shows that of I and c-1, respectively. In this paper, it is assumed that the spray is used in the factory and a brush on the field when the painting is performed. Repainting foundation adjustments adopt the grade 2 cleaning. The grade 3 cleaning that falls by one grade is multiuse in an actual painting. This grade classifies into three patterns depending on the rush development area. In other words, the surface preparation corresponding to local rust is performed. Local rusts were not considered in the LCA of this research for easiness, and grade 2 cleaning was adopted. The grade 2 cleaning was taken off coatings including local rusts.

Table 6 Paint system adopted for each bridge

	Conventional bridges	Rationalized bridges
First painting	A-1	I
Repainting	a-1	c-1
Repainting surface preparation	Grade 2 cleaning	Grade 2 cleaning

Table 7 Using coatings and basic usages of A-1 and a-1

	Used coating, (Heating residue)	Basic usage (g/m^2/times)			
		A-1		a-1	
Primer	JIS K5633 type2 etching primer, (0.19)	Factory	130 (Spray)	-	-
Under coat	JIS K5633 type1 lead suboxide, (0.92)		170 (Spray)	Site	140 (Brush)
Under coat	JIS K5633 type2 lead suboxide, (0.92)		170 (Spray)		140 (Brush)
Intermediate coat	Long-oil phthalic resin paint, (0.82)	Site	120 (Brush)		120 (Brush)
Final coat	Long-oil phthalic resin paint, (0.72)		110 (Brush)		110 (Brush)
Toal		700		510	

Table 8 Using coatings and basic usages of I and c-1

	Used coating, (Heating residue)	Basic usage (g/m^2/times)			
		I		c-1	
Primer	Functional primer, (0.51)	Factory	200 (Spray)	-	-
Under coat	Organic zinc rich paint, (0.86)		700 (Spray)	Site	300 (Brush)
Under coat	Modified epoxy resin paint, (0.68)		-		240 (Brush)
Under coat	Modified epoxy resin paint, (0.68)		-		240 (Brush)
Intermediate coat	Polyurethane resin paint, (0.69)		170 (Spray)		140 (Brush)
Final coat	Polyurethane resin paint, (0.61)		140 (Spray)		120 (Brush)
Total		1210		1040	

3.4. LCA approach for bridges

The LCC (C_T), LCCO$_2$ (E_T) and LCVOC (Y_T) in this research were calculated by using following equations referring to the assumption of Ref. [8]. The discount rate of the LCC, LCCO$_2$, and LCVOC was assumed to be 0% [8].

$$C_T = C_C + C_M + C_R \tag{1}$$

$$E_T = E_C + E_M + E_R \tag{2}$$

$$V_T = V_C + V_M + V_R \tag{3}$$

where, C_C, E_C and V_C are the cost, CO$_2$ emission and VOC from the construction stage, respectively; C_M, E_M and V_M are that from the maintenance stage, respectively; and C_R, E_R and V_R are that from the replacement stage, respectively. The service life of the bridge was set to 100 years according to the Specifications for highway bridges [24].

(1) The Cost and Environmental Impact in the Construction Stage

In this stage, costs and environmental impact of construction materials, including main girders (steel and painting), bearings, decks, pavement and expansion joints, were calculated. C_C and E_C ware calculated referring to Ref. [8], and V_C was calculated from the following eqation.

$$V_C = \sum_{i=1}^{n} (P_{Ci} - P_{Ci} \times r_i) \tag{4}$$

where, P_{Ci} is basic usage of using paintings in construction stage; r_i is solids content of using paintings; and n is number of painting layers, respectively. Eq.(4) shows that coating usages minus the amount that remains without volatilizing equal V_C. For example, V_C of the JIS K5633 type 2 etching primer using A-1 paint system is calculated using the solids content and the basic usage shown in Table 7 as 130−(130×0.19)=105.3 (g/m^2).

(2) The Cost and Environmental Impact in the Maintenance Stage

In this stage, the maintenance cycles of each components of bridge was set, and it was assumed that each component ware replaced as soon as facing their service lives and exchange of them was continued with a fixed maintenance cycle until the end of the service lives of the bridge [8]. In order to consider the difference of the maintenance cycle by construction site, two kinds of maintenance cycles were set which it was constructed in the mountain and the urban areas. Table 9 shows setting maintenance cycles of each component within I-girder bridge. These values actually experimented and were examined by Japan Bridge Association [6].

As in the stage of the construction, C_M and E_M were calculated referring to Ref. [8], and V_M was calculated from the following eqations.

$$V_m = \sum_{i=1}^{n} (P_{mi} - P_{mi} \times r_i) \tag{5}$$

$$V_M = V_m \times \frac{L - L_C}{L_m} \tag{6}$$

where, V_m is VOC emission in the repainting of one time; P_m is basic usage of using repainting; L is service life of bridge; L_C is maintenance cycle of initial painting; and L_m is maintenance cycle of repainting, respectively.

(3) The Cost and Environmental Impact in the Replacement Stage

In this stage, costs and environmental impacts from the demolition of the substructure of the old bridge ware calculated. Referring to Ref. [8], it was assumed that C_R is the cost of the old bridge demolition and E_R is the CO$_2$ emission by construction machines used when demolishing the bridge. Assuming that the VOC was discharged only when painting

Table 9 Setting maintenance cycles of each component within the I-girder bridge [16]

		CIB		MGB	
		Mountain area	Urban area	Mountain area	Urban area
Deck	Update	50 year		100 year	
	Maintenance	Thickness Increasing Method 25 year		Filling concrete renewal 50 year	
Paint system (Repainting)		A-1 (a-1)		I (c-1)	
		15 year (15 year)	10 year (10 year)	30year (40 year)	20year (30 year)
Bearing		Steel bearing 30 year		Rubber bearing 100 year	
Expansion joint		Finger joint 30 year			
Pavement		Normal asphalt pavement		High-function pavement	
		15 year	10 year	20 year	15 year

was done, this stage of V_R equals zero.

4. CALUCULATION RESULTS

4.1. Introduction

Results of the LCC, $LCCO_2$ and LCVOC are divided by area of deck and written in dimensionless form to compare each span length. Comparing difference bridge types and construction areas, CIB with a span length of 30 m was considered as a reference and its construction cost and environmental impact were both assigned to be 1.

4.2. Ratio of Painting in the LCC and $LCCO_2$

Fig. 5 shows the ratio of each component in the LCC and $LCCO_2$ of the truss bridge at the maintenance stage [13]. It is included costs and CO_2 emissions of scaffolding. These show the ratio to the LCC and $LCCO_2$ of the conventional bridge at the maintenance stage assumed to be 100%. If the painting ratio in the conventional bridge was focused, the CO_2 emission became about 20% though the cost became about 40 %. Therefore the CO_2 emission of conventional bridges was not influenced by the painting for its cost. Rationalized bridges ware also found the same knowledge.

Table 10 shows the values of the painting ratio. Because the LCC and $LCCO_2$ of each bridge at the maintenance stage assumed 100 %, real values are small if a ratio with rationalized bridges was larger than with conventional bridges. From Table 10, the painting ratio with the I-girder bridge has the same tendency as the truss bridge, or the CO_2 emission was regardless of the painting for its cost. This reason should be considered that the material used to painting was low compared with other member maintenance. Because CO_2 emissions are the product of the material usage and its basic unit, if the material usage was low, CO_2 emissions also decrease. Therefore, it was understood that the proportion of $LCCO_2$ of painting was smaller than that of LCC of painting.

4.3. Comparison of LCC and LCVOC Results between Two Bridge Types

LCC and LCVOC of the painting for I-girder bridge and truss bridge are compared and discussed in this section.

(1) LCC and LCVOC of the Painting for I-girder Bridge

Fig.6 shows the calculated LCC and LCVOC of I-girder bridges. The vertical axis of these graphs represents LCC and LCVOC values normalized by those of CIB with a span length of 30 m at the construction stage.

As can be seen in Fig.6 (a) and (b), LCC of the rationalized bridge was lower than that of the conventional bridge for 100 years after construction, and this difference for the urban area is larger than that for the mountain area. On the other hand, as can be seen in Fig. 6 (c) and (d), although LCVOC of the rationalized bridge is lower than that of the conventional bridge for 100 years after construction, which is similar to LCC, this difference becomes smaller as the span length decreases in both the mountain and the urban areas.

The LCVOC plots in Fig. 6 are replotted only for span lengths of 30 m and 60 m as shown in Fig. 7 (a) and (b), respectively. In the case of a span length of 30 m as shown in Fig. 7 (a), the VOC emission in the construction stage is found to be more or less the same, and 100 years after construction, the LCVOC of conventional bridges is greater by about 20% in the mountain area and by 40% in the urban area when compared with rationalized bridges.

On the other hand, in the case of a span length of 60 m, conventional bridges show a larger LCVOC by about 80% of that of the rationalized bridges in the construction stage, and 100 years after construction, the LCVOC of conventional bridges is greater by about 110% in the mountain area and by about 130% in the urban area when compared with rationalized bridges. When LCVOC values are compared between the mountain area and the urban area, regardless of the span length, the LCVOC in the urban area is greater by about 50% than that in the mountain area for conventional bridges, while LCVOC in the urban area is greater by about 30% than that in the mountain area for rationalized bridges,

As a result, it is found that LCVOC of CIB depends on the span length, but that of a rationalized bridge is not affected by the span length significantly, implying that the difference between a conventional bridge and a rationalized

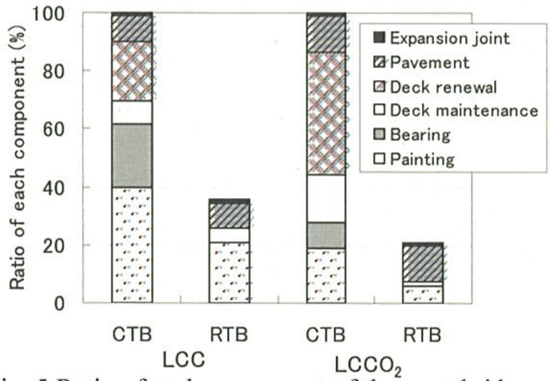


Fig. 5 Ratio of each component of the truss bridge at the maintenance stage

Table 10 Painting ratios (%)

	LCC		$LCCO_2$	
	Con.	Rat.	Con.	Rat.
I-girder	34.7	39.4	16.0	27.5
Truss	39.8	59.2	19.1	29.6

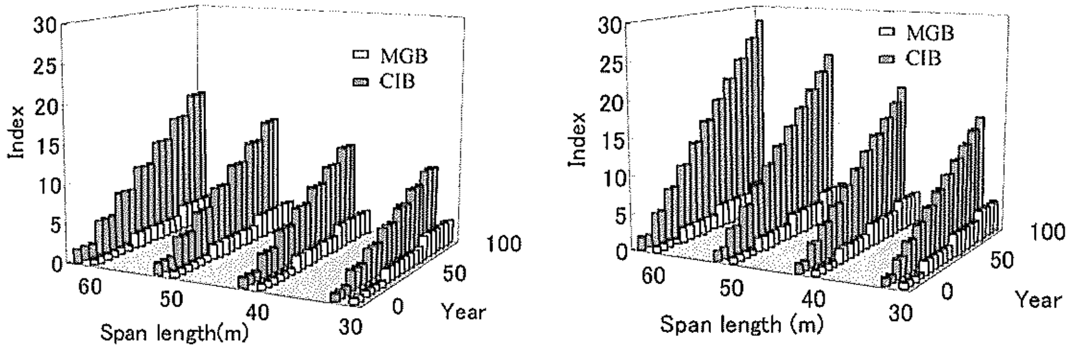
bridge increases with a span length. This is because the VOC emission is greatly related to the painting area. As shown in Fig. 4, the difference in the painting area between a conventional bridge and a rationalized bridge increases with a span length.

The environmental impact at the construction stage in the mountain area does not differ between the conventional and the rationalized bridges. It is because the paint system adopted with the rationalized bridge requires twice the amount of paint required for the conventional bridge although the total painting area of the rationalized bridges is reduced. Therefore, the reduction in the painting area counterbalances the amount of paint usage.

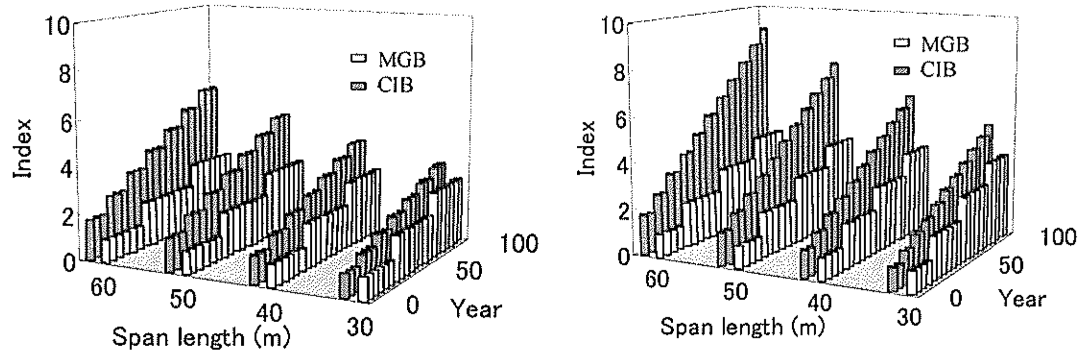
(2) LCC and LCVOC of the Painting for Truss bridge

Fig. 8 shows LCVOC of painting for span length of 80m and 100m. The vertical axis of these figures represents LCC and LCVOC values normalized by those of CIB with a span length of 30 m at the construction stage, as same as the case of I-girder bridge. Fig. 8 (a) shows the comparison with span length of 80 m and 100 m in the urban area, and Fig. 8 (b) shows the comparison in mountain area and urban area with a span length of 100 m.

In the case of a span length of 80 m as shown in Fig. 8 (a), the VOC emissions of a rationalized bridge in construction stage is greater by about 30% when compared with a conventional bridge, and 100 years after construction, LCVOC of rationalized bridges is greater by about 10%. As a result, it is found that VOC emission of rationalized bridge is larger than

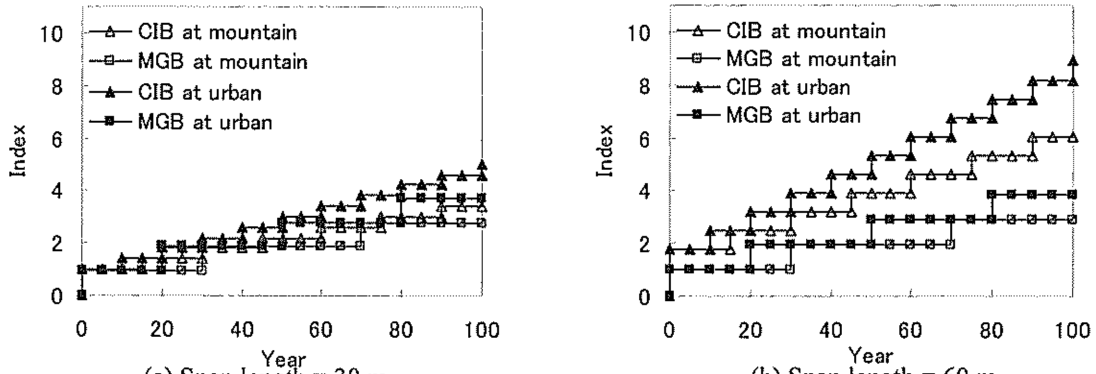


(a) LCC at mountain area (b) LCC at urban area



(c) LCVOC at mountain area (d) LCVOC at urban area

Fig. 6 LCC and LCVOC of I-girder bridges



(a) Span length = 30 m (b) Span length = 60 m

Fig. 7 LCVOC of the painting for span lengths of 30 m and 60 m conventional bridge for a lifecycle of a bridge. Similarly, in the case of span length of 100 m, VOC emissions do not differ between the conventional and the rationalized bridge when 100 years after construction.

On the other hand, in the case of a span length of 100 m as shown in Fig. 8 (b), when 100 years after construction, VOC emissions of conventional bridge is smaller by about 10% in mountain area when compared with a rationalized bridge. In the urban area does not differe between the conventional and the rationalized bridges. When LCVOC values of each conventional bridge and rationalized bridge are compared between the mountain area and the urban area, the LCVOC in the urban area is greater by about 50% than that in the mountain area for a conventional bridge, while the LCVOC in the urban area is greater by about 30% than that in the mountain area for a rationalized bridge. This tendency is similar to LCVOC of the I-girder bridge.

From above findings, it is clarified that LCVOC of the truss bridge does not differ between the conventional and the rationalized bridges. It is because the reduction rate of painting area of the rationalized bridge is lower than the I-girder bridges as shown in Table 5, although the painting area of rationalized bridge is less than the conventional bridge. As a result, the LCVOC of rationalized I-girder bridge is able to reduce by counterbalanced to influence of the coating usage, but the LCVOC of rationalized truss bridge can not decrease because it is not possible even to counterbalance.

Therefore, it is clarified that LCVOC is regard of the painting area and the coating usage and LCVOC of rationalized bridge is not necessarily lower although the painting areas have been reduced more than the conventional bridge. So it is necessary to consider not only simpler structure but also use material as the painting when the technological development for the low environmental impact is done in the future. In the painting, decreasing the VOC content is preferable to advance development for the practical use of paintings.

4.4. Comparison of LCC and LCVOC Results between Difference Repainting Cycles

LCA of the steel bridge is great affected by the assumption of maintenance cycle of each member. So the accurate assumption is very important to assess realistic LCA. Therefore many study and research aiming to grasp and forecast of maintenance cycles have been done, and it becomes one great challenge for the bridge industry.

In previously calculations, it was assumed that the maintenance of the first painting and repainting, or the first and second or later repainting cycles were not change. However, when the number of repainting increases, it is understood that the repainting cycle tends to shorten in fact [25]. The cause of it is that adhesion salinity and the rust is very difficult to remove perfectly before repainting in the field [26].

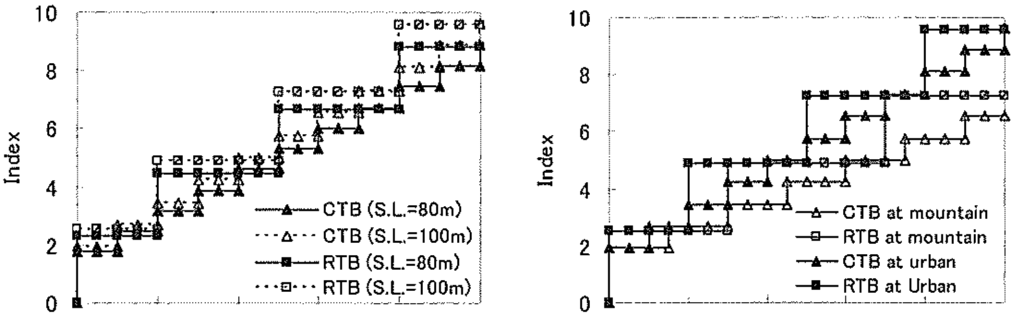
In this research, it is assumed that using a current repainting cycle is case 1, assuming shorter repainting cycles of the second or later are Case 2 and 3, and LCC and LCVOC of them are compared. Table 11 shows the repainting cycle of each case.

In the case 2, considering the data of real repainting cycles referred to Ref. [25], it is assumed that the second or later repainting cycles shorten more than the repainting cycle of first time painting by 20%.

In the case 3, the repainting cycle refers the result of the accelerated exposure test considering repainting presented by Itoh [27]. According to this test, repainting cycle of repainting test piece becomes about 36% or less compared with the repainting of first painting. Referring this data, in case 3 it is assumed that the second or later repainting cycles shorten more than the repainting cycle of first time by 64% as case of most severe condition area. LCC and LCVOC of the painting for I-girder bridge and truss bridge in the case 2 and case 3 are calculated, and compared below.

Fig. 9 and Fig. 10 show the LCVOC in urban area in the case of 1, 2 and 3 when the 100 years pass after construction. Fig. 9 shows LCVOC of I-girder bridges with a span length 30 m and 60 m, and Fig. 10 shows that of truss bridges with span length 80m and 100m.

As shown in Fig. 9 and Fig. 10, LCVOC is greater by about 20% in the case of 2 and by about 150% in the case of 3 when compared with in the case of 1 for all bridge. LCC of all bridge have the same tendency.



(a) Urban area (b) Span length = 100m

Fig. 8 LCVOC of painting for span length of 80m and 100m

Table 11 Repainting cycle of each case at mountain area (year)

	First time	Second times		First time	Second times
Conventional	A-1	a-1	Rational	I	c-1
Case 1	15	15	Case 1	30	40
Case 2	15	12	Case 2	30	32
Case 3	15	5	Case 3	30	14

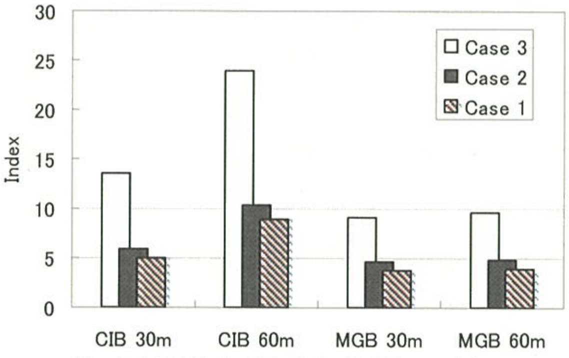


Fig. 9 LCVOC of I-girder bridges with a span length 30 m and 60 m

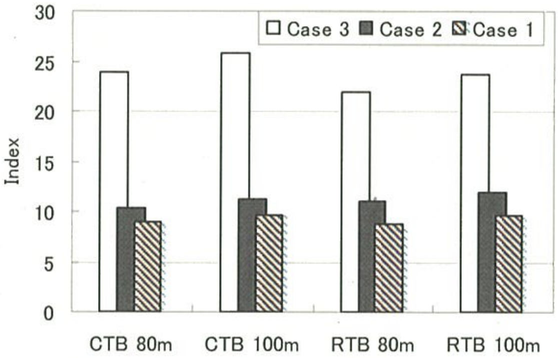


Fig. 10 LCVOC of truss bridges with a span length 80 m and 100 m

From these result, it is found that the LCC and LCVOC are significantly changed by assuming of second or later repainting cycles. Therefore, it is important that the more exact repainting cycles is grasped to assess more realistic LCC and LCVOC, and further study and research for that are required.

5. LOW-VOC COATINGS AND NON-SOLVENT COATINGS

In chapter 4, it was clarified that LCVOC of conventional and rationalized bridges regards of the painting area and used paint systems. Therefore cutting down the VOC content in used coating was more effective to reduce LCVOC.

Moriya [16] is experimentally made the earth-friendly coating systems which reducing VOC, including low-VOC coating and non-solvent coating. And he compare with a C paint system, which is provided by Steel Highway Bridge Painting Manual, from perspective of the durability and the workability. Table 12 shows the used paint items of non-solvent coatings and a C-4 paint system, respectively. In the paint system 1 and 2, the VOC content is decreased to 36.8% and 49.6% respectively by using a non-solvent item in under coat, and both cases are succeed in making the paint system of low-environmental impact. He has also tried the outdoor exposure test and the real bridge painting test to grasp corrosion protection performances of them. According to the interim finding of his research, corrosion protection performance does not differ between the low-VOC and the non-solvent coatings and the C-4 paint system witch have high corrosion protection performance.

Then, LCC and LCVOC are calculated in the case of that the paint systems shown in Table 12 is used, assuming to have the same corrosion prevention performance as for any paint system. Repainting cycles are set 30 years. This cycle is the repainting cycle of C-4 paint system in the coast area [28]. Table 13 shows the compared values of costs and VOC emissions of each paint system. These values bases on that of C-4 paint system. Fig. 11 and Fig. 12 shows the LCC and LCVOC.

Calculated of LCC and LCVOC results are show in Fig. 11 and Fig. 12. LCC and LCVOC values are difference between the C-4 paint system and the paint system 1 and 2 in the value shown in Table 13 because of assuming to have the same repainting cycle as for any paint system. The LCC of paint system 1 becomes 97% and the LCC of paint system 2 greater 5% respectively when compared with the C-4 paint system. On the other hand, the LCVOC of both paint system are drastically smaller than the C-4 paint system.

However, because the paint system 1 and 2 suffer from bad painting activity and early impression is not so good, the cost of painting increases more by its disadvantage, and the LCC and LCVOC of each paint system are a trade-off relationship. Therefore, further advances in the paint technology are required.

6. CONCLUSIONS

In this research, the LCC, $LCCO_2$ and LCVOC for painting of both the conventional and rationalized bridges were assessed. Two types of bridge, I-girder and truss bridges, were taken into consideration. The following conclusions were obtained:

Table 12 Used paint items of non-solvent coatings and a C-4 paint system [16]

Paint system	Under coat	Under coat	Under coat	Intermediate coat	Final coat	Reduction rate (%)
C-4	Inorganic zinc rich paint 700g/m^2	Epoxy resin paint 160g/m^2	Epoxy resin paint (2 times) 300 g/m^2	Fluorine resin paint 170 g/m^2	Fluorine resin paint 140 g/m^2	Reference value
1			Non-solvent modified epoxy resin paint 300 g/m^2			36.8
2			Non-solvent modified epoxy resin paint (2 times) 300 g/m^2	—		49.6

Table 13 Compared value of costs and VOC contents

	C-4 painting system	Painting system 1	Painting system 2
Cost	1	0.97	1.05
VOC content	1	0.63	0.51

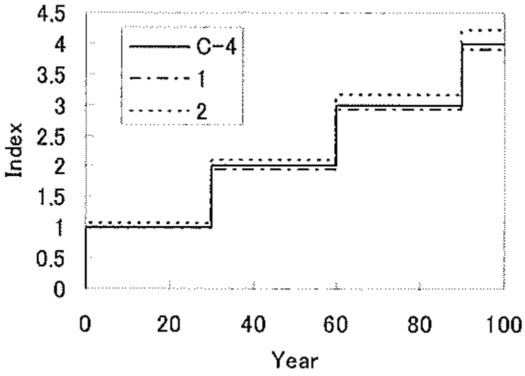


Fig. 11 LCC of paint system

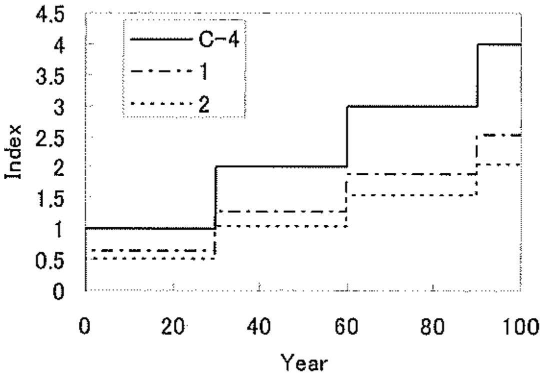


Fig. 12 LCVOC of paint system

1) The proportion of the LCCO$_2$ of paint system was about only a half compared with that of LCC of paint system, so the CO$_2$ emission was not influenced by the paint system for its cost.
2) The LCVOC of paint system, in urban area increase from about 30 to 50% compared with that in mountain area.
3) The LCVOC of I-girder bridges, although that of the conventional bridge in construction stage increases from about 0 to 80% compared with that of the rationalized bridge, at the 100 year after construction, the conventional bridge increase from about 20 to 130%.
4) In the LCVOC of I-girder bridges, the difference between the conventional bridge and rationalized bridge was increased as the span length became long.
5) In the LCVOC of truss bridges, the conventional bridge and the rationalized bridge were not much difference, because the reduction rate of painting area in the rationalized bridge from the conventional bridge was low, and the LCVOC of rationalized truss bridge was not decreased because it was not possible even to counterbalance.
6) The LCVOC of rationalized bridge was not necessarily lower although the painting areas have been reduced more than conventional bridge. So it was necessary to consider not only simpler structure but also use material as paint system when the technological development for the low environmental impact was done in the future.
7) The LCC and LCVOC of paint system changing repainting cycles were calculated. As results, when assumed the second or later repainting cycles shorten more than the first time by 64% as most severe condition, the LCC and LCVOC were larger by about 150% or more compared with case of those first and second or later repainting cycles were not change. Therefore, it was important that more exact repainting cycles were grasped to assess more realistic the LCC and LCVOC, and further study and research for that were required.
8) The LCC and LCVOC of the low-coating and the non-solvent coating were a trade-off relationship, so further advances in the paint technology were necessary.

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Lifecycle Analysis of Steel Bridge Paint Systems

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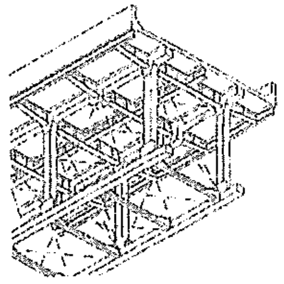
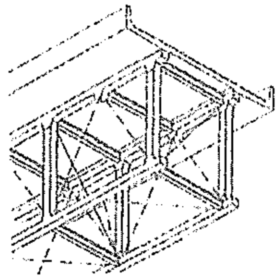
1. INTRODUCTION

In recent years, many new technological developments have been made to mitigate the maintenance expenditure of steel bridges. In the Japanese bridge industry, newly developed bridges, which are less costly than conventional bridges by simplifying structural members, have come into wide use recently. These bridges are also considered to cut down maintenance costs. The maintenance costs of bridge painting can be mitigated by using high durability coating reducing painting areas. When assessing the environmental impact based on the CO_2 emission, the CO_2 emission is typically calculated by multiplying the basic unit of each material by the amount of the material used. Therefore, the larger the amount of the used material, the more the CO_2 emission is. However, because the total amount of coating in a steel bridge is relatively small when compared with the amount of all different materials in the entire bridge, the $LCCO_2$ of the steel bridge stemming from the painting is insignificant relative to the total $LCCO_2$ of the steel bridge. However, in recent years, it is well known that the environmental impact of the painting is not only the CO_2 emission. Because coatings contain chemical substances and heavy metals that present a danger to public health, the paint industry aims to control and reduce toxic substances. Therefore, the paint industry has been trying to reduce the volatile organic compounds (VOC) in the coating, and it is a trend that VOC is treated as one of the environmental impacts. Therefore, the lifecycle analysis (LCA) of the steel bridge paint system must consider the amount of toxic substances in the coating and their emissions in addition to the amount of the CO_2 emission. In this study, the LCC, $LCCO_2$ and lifecycle VOC emissions (LCVOC) of steel bridge paint system were calculated quantitatively for a lifecycle of a bridge. Based on the LCC, $LCCO_2$, and LCVOC, the LCA of conventional bridges and rationalized bridges was performed.



(a) CTB



(b) RTB

Fig. 1 Truss bridges

$$C_T = C_C + C_M + C_R \quad (1)$$

$$E_T = E_C + E_M + E_R \quad (2)$$

$$V_T = V_C + V_M + V_R \quad (3)$$

2. LCA OF BRIDGES

In this research, the bridge lifecycle contains the construction, maintenance and replacement stages only, and these stages are set as the range of the analysis.

2.1. Targeted Bridges

Four types of the bridges, conventional I-girder bridge (abbreviated as CIB below), minimized girder bridge (abbreviated as MGB below), conventional and rationalized truss bridges (abbreviated as CTB and RTB below), were targeted. CTB and RTB drawing is shown in Fig. 1. To be easily comparable, it was assumed that these bridges have the same width of 10.5 m and the same span allotment (Steel 3-span continuous non-composite bridge). The range of the span length was assumed to be from 80 m to 100 m with I-girder bridges and from 30 m to 60 m with truss bridges, with an interval of 10 m respectively.

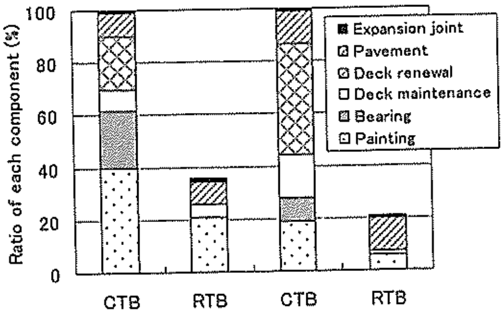


Fig. 2 Ratio of each component at the maintenance stage

2.2. Adopted Paint Systems

In this paper, conventional bridges and rationalized bridges adopt a different paint system in consideration of the paint system used for actual bridges. The surface preparation corresponding to local rust is performed. But local rusts were not considered in the LCA of this research for easiness, and grade 2 cleaning was adopted.

2.3. LCA approach for bridges

The LCC (C_T), $LCCO_2$ (E_T) and LCVOC (Y_T) in this research were calculated by using Eqs. (1)-(3). Where, C_C, E_C and V_C are the cost, CO_2 emission and VOC from the construction stage, respectively; C_M, E_M and V_M are that from the maintenance stage, respectively; and C_R, E_R and V_R are that from the replacement stage, respectively. The service life of the bridge was set to 100 years according to the Specifications for highway bridges. Assuming that the VOC was discharged only when painting was done, the replacement stage of V_R equals zero.

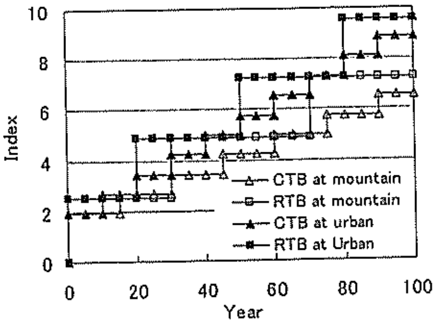


Fig. 3 LCVOC for span length of 100m

3. CALUCULATION RESULTS

Results of the LCC, $LCCO_2$ and LCVOC are divided by area of deck and written in dimensionless form to compare each span length. Comparing difference bridge types and construction areas, CIB with a span length of 30 m was considered as a reference and its construction cost and environmental impact were both assigned to be 1.

3.1. Ratio of Painting in the LCC and $LCCO_2$

Fig. 2 shows the ratio of each component in the LCC and $LCCO_2$ of the truss bridge at the maintenance stage. It is included costs and CO_2 emissions of scaffolding. From Fig. 2, the CO_2 emission of conventional bridges was not influenced by the painting for its cost.

3.2. Comparison of LCC and LCVOC Results of Truss Bridge

Fig. 3 shows LCVOC of painting for span length of 100m. From Fig. 3, when LCVOC values of each conventional bridge and rationalized bridge are compared between the mountain area and the urban area, the LCVOC in the urban area is greater by about 50% than that in the mountain area for a conventional bridge, while the LCVOC in the urban area is greater by about 30% than that in the mountain area for a rationalized bridge. Therefore, it is clarified that LCVOC of the truss bridge does not differ between the conventional and the rationalized bridges. It is because the reduction rate of painting area of the rationalized bridge is lower than the I-girder bridges, although the painting area of rationalized bridge is less than the conventional bridge. As a result, the LCVOC of rationalized I-girder bridge is able to reduce by counterbalanced to influence of the coating usage, but the LCVOC of rationalized truss bridge can not decrease because it is not possible even to counterbalance. Therefore, it is clarified that LCVOC is regard of the painting area and the coating usage and LCVOC of rationalized bridge is not necessarily lower although the painting areas have been reduced more than the conventional bridge. So it is necessary to consider not only simpler structure but also use material as the painting when the technological development for the low environmental impact is done in the future. In the painting, decreasing the VOC content is preferable to advance development for the practical use of paintings.

4. LOW-VOC COATINGS AND NON-SOLVENT COATINGS

The cutting down the VOC content in used coating is more effective to reduce LCVOC. Moriya is experimentally made the earth-friendly coating systems which reducing VOC, including low-VOC coating and non-solvent coating. Then, LCC and LCVOC are calculated in the case of that the earth-friendly coating systems, assuming to have the same corrosion prevention performance as for any paint system. Repainting cycles are set 30 years. This cycle is the repainting cycle of C-4 paint system in the coast area. Table 1 shows the compared values of costs and VOC emissions of each paint system. These values bases on that of C-4 paint system. Fig. 4 and Fig. 5 shows the LCC and LCVOC. Calculated of LCC and LCVOC results are show in Fig. 4 and Fig. 5. LCC and LCVOC values are difference between the C-4 paint system and the paint system 1 and 2 in the value shown in Table 1 because of assuming to have the same repainting cycle as for any paint system. The LCC of paint system 1 becomes 97% and the LCC of paint system 2 greater 5% respectively when compared with the C-4 paint system. On the other hand, the LCVOC of both paint system are drastically smaller than the C-4 paint system. However, because the paint system 1 and 2 suffer from bad painting activity and early impression is not so good, the cost of painting increases more by its disadvantage, and the LCC and LCVOC of each paint system are a trade-off relationship. Therefore, further advances in the paint technology are required.

Table 1 Compared value of costs and VOC contents

Painting system	C-4	1 low-VOC	2 low-VOC
Cost	1	0.97	1.05
VOC content	1	0.63	0.51

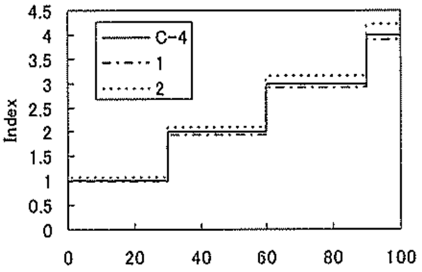


Fig. 4 LCC of paint system

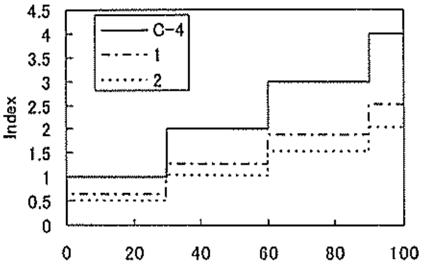


Fig. 5 LCVOC of paint system

5. CONCLUSIONS

In this research, the LCC, $LCCO_2$ and LCVOC for painting of both the conventional and rationalized bridges were assessed. The following conclusions were obtained:

1) In the LCVOC of truss bridges, the conventional bridge and the rationalized bridge were not much difference, because the reduction rate of painting area in the rationalized bridge from the conventional bridge was low, and the LCVOC of rationalized truss bridge was not decreased because it was not possible even to counterbalance.
2) The LCVOC of rationalized bridge was not necessarily lower although the painting areas have been reduced more than conventional bridge. So it was necessary to consider not only simpler structure but also use material as paint system when the technological development for the low environmental impact was done in the future.
3) The LCC and LCVOC of the low-coating and the non-solvent coating were a trade-off relationship, so further advances in the paint technology were necessary.