The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Environmental Impact Assessment for a Chinese Pre-stressed Concrete Continuous Rigid-frame Bridge Based on LCA

Pang Bo[1)],* Wang Yuanfeng[2)] and Zhang Jie[3)]

[1), 2)] School of Civil Engineering, Beijing Jiaotong University, Beijing, China
[3)] School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China
[2)] cyfwang@bjtu.edu.cn

ABSTRACT

Lots of bridges have been built in China over the past decades, but the environmental impact caused by the bridges has not been evaluated sufficiently. Based on the theory of Life Cycle Assessment (LCA), this paper presented an end-point damage model for bridges environmental impact quantitative analysis methods, where 3 categories of environmental impact (ecosystem, human health, energy and resources) were selected, using the Eco-indicator 99 method. In this way, a case analysis has been adopted to confirm the applicability of this model for environmental performance evaluation for a pre-stressed concrete continuous rigid frame bridge.

1. INTRODUCTION

During the past three decades, about 600,000 bridges have been built in China(Feng Maorun 2011) and further 200,000 new-constructed bridges by 2020(Web.1). Therefore, it is quite significant to quantitatively evaluate the impact of these bridges on environment.

Although the bridge design in China considered the environmental impacts after the promulgation of Specifications for Environmental Impact Assessment of Highways(JTG B03—2006) in 2006, the environmental impact caused by the bridges has not been evaluated sufficiently as there are very few researches focused on quantifiable bridge environmental impact analysis in China and even in the world.

Life Cycle Assessment (LCA) is a technique to assess environmental impacts throughout all the stages of a product's life from-cradle-to-grave, which has been adopted widely to quantify the environmental impact of many products in recent decades. However, concerning the application of LCA for bridges, only several papers published over the past years.

Horvath and Hendrickson (1998) did their pioneer work by applying economic input–output life cycle assessment (EIO-LCA) to evaluate steel and steel reinforced concrete bridge girders. The EIO-LCA method traces economic transactions throughout the supply chain of a product system and evaluates resource requirements and environmental emissions using a commodity input–output model coupled with key environmental impact datasets.

The achievement of Horvath and Hendrickson (1998) has not been paid much more attention; after five years, Steele et al. (2003) still discussed the necessity of environmental evaluation for bridges and focused on brick arch bridges as a category in presenting a case for what environmental improvement can be achieved. The objective of Steele et al. (2003) was to present a methodology (LCA) that enables the environmental impact of highway bridges to be investigated. It has been found that bridge construction represents the single biggest contributor to environmental impact over an entire bridge life cycle.

Even in recent years, although the environmental impact of highway bridges has been considered as an important issue, it is still not a hot research topic. Limited works mainly focused on comparing the environmental impact of different bridge projects (Gregory et al. 2005, Lina and Robert 2009, Johanne et al. 2011).

Gregory et al. (2005) presented a comparative LCA of two bridge deck systems over a 60 year service life: one using conventional steel expansion joints and the other based on a link slab design using a concrete alternative, engineered cementitious composites (ECC). A life cycle model was developed accounting for materials production and distribution, construction and maintenance processes, construction-related traffic congestion, and end-of-life management. Results indicate that the ECC bridge deck system has significant advantages in environmental performance. Construction related traffic congestion is the greatest contributor to most life cycle impact categories.

Lina and Robert (2009) present a simplified life cycle assessment on an innovative bridge structure, made of wood and ultra high performance concrete. Results show that the most energy needed is in the production phase, which represents 73.4% of the total amount. Moreover, the renewable energy is about 70% of the production energy. Wood, through its biomass CO_2, contributes positively to the environmental impact. It was concluded that no scenario can be the winner on both impacts.

Johanne et al. (2011) compared three bridges– a steel box girder bridge, a concrete box girder bridge and a wooden arch bridge - already built and in use in Western Norway. The study shows that the construction phase causes relatively less impacts; the use phase contributes more significantly, mainly due to resurfacing with asphalt. The environmental issues global warming, abiotic depletion and acidification are found to be the most important given the assumptions made in this study. A comparison of the three bridges shows that the concrete bridge alternative performs best environmentally on the whole, but when it comes to global warming, the wooden bridge is better than the other two.

Recently, Horvath (2009) suggested a set of general principles for environmental analysis of bridges via the implementation of the Life Cycle Assessment methodology. He recommended including all life cycle stages in the analysis, including the planning and the design phases, to make the optimal decisions. Horvath (2009) also suggested taking a special care to the particularities due to the location of the structure, such as the used materials or the technologies locally available. Since the bridge designers have to deal with long lifespan, Horvath (2009) insisted on the importance of assessing the performance of the construction materials over time, and of predicting the future maintenance schedules and the feasible end-of-life actions after decades of operation. Horvath (2009) finally argued that a good LCA should include the assessment of a wide range of pollutants to the air and water, as well as the generation of wastes, instead of being only focused on the minimization of the emissions of greenhouse gases (GHG).

Although LCA is a good tool to assess the environmental performance of bridges, the results of LCA are mostly not straightforward. Therefore, A so-called Eco-indicator 99 is used in this paper. This methodology has proved to be a powerful tool to aggregate LCA results into easily understandable, and it is a "damage oriented" impact assessment method with clearly detailed steps such as fate, exposure, effect and damage analysis. Based on the Eco-indicator 99, a LCA method framework is used in this paper to conduct a partial LCA for bridges, from materials production, construction (including transportation), to operation phase, aiming at establishing an end-point damage model for bridges environmental impact quantitative analysis methods, where 3 categories of environmental impact (ecosystem, human health, energy and resources) were selected.

2. LIFE CYCLE ASSESSMENT

2.1. LCA

A life-cycle assessment (LCA, also known as life-cycle analysis, ecobalance, or cradle-to-grave analysis) (US Environmental Protection Agency 2010) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). An internationally accepted framework for LCA methodology is defined in AS/NZS ISO 14040 (ISO 14040 Standard 1997). These standards define the generic steps when conducting a LCA. Four different phases of LCA can be distinguished, shown as Fig.1.

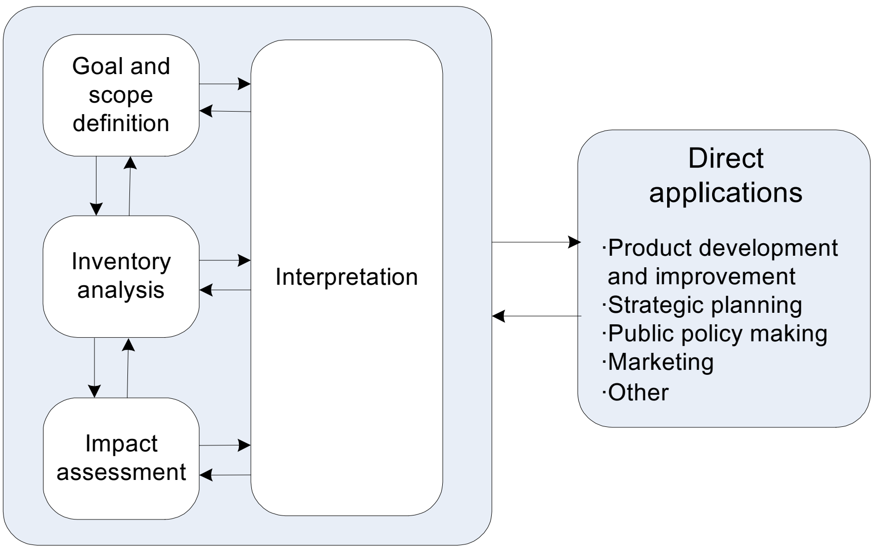

Fig.1 Life cycle assessment phases and applications

2.2. Eco-indicator 99

Methods for LCIA（Life Cycle Impact Assessment） are categorized in two groups. The first group uses a “mid-point” approach as these methods stop somewhere in the environmental mechanism between environmental exchanges and endpoint. The other group uses a so-called “end-point” approach as they model the potential damage on value items (Arne Remmen 2009).

The “end-point” approach is the new trend of international LCIA, and a representative example applying this approach is the Dutch Eco-indicator 99 (Goodkoop and Spriensma 2000). This method models the influence on the end-points and goes one step further as it aggregates the end-point in three categories which express damage to human health, ecosystems and resources. The Eco-indicator uses one single score calculated for the total environmental impact. The higher the indicator, the greater the environmental impact. In order to calculate the figure, three steps are needed: Inventory, Calculation and Weighting. In the Fig.2 these steps are illustrated.

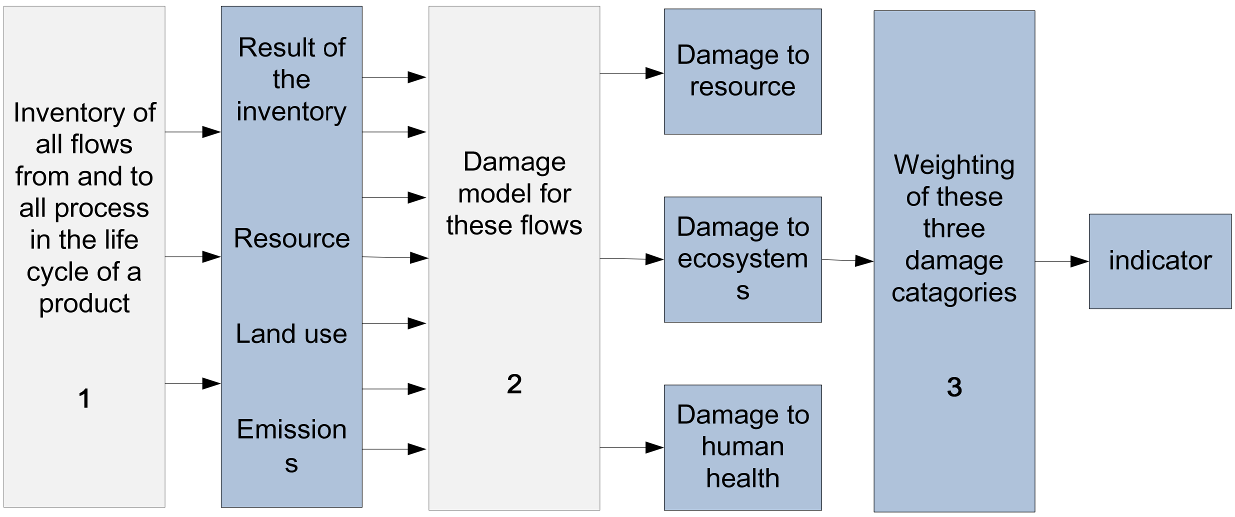

Fig.2 General procedure for the calculation of Eco-indicators 99.

3. ENVIRONMENTAL IMPACT ASSESSMENT OF BRIDGEs, A CASE STUDY

3.1. Goal and scope definition

Based on the theory of LCA, the paper aims at establishing an end-point damage model for bridges environmental impact quantitative analysis methods, where 3 categories of environmental impact (ecosystem, human health, energy and resources) were selected using the Eco-indicator 99 method. In this way, a prestressed concrete continuous rigid frame bridge in China was selected as a case study to validate the applicability of this bridge-LCA mode.

This mode focuses on materials production, construction (including transportation), to operation stages, but excludes the environmental impact of vehicle emissions. In this study functional unit is considered as one kilometer of bridge deck. The boundaries to the LCA are presented in Fig.3.

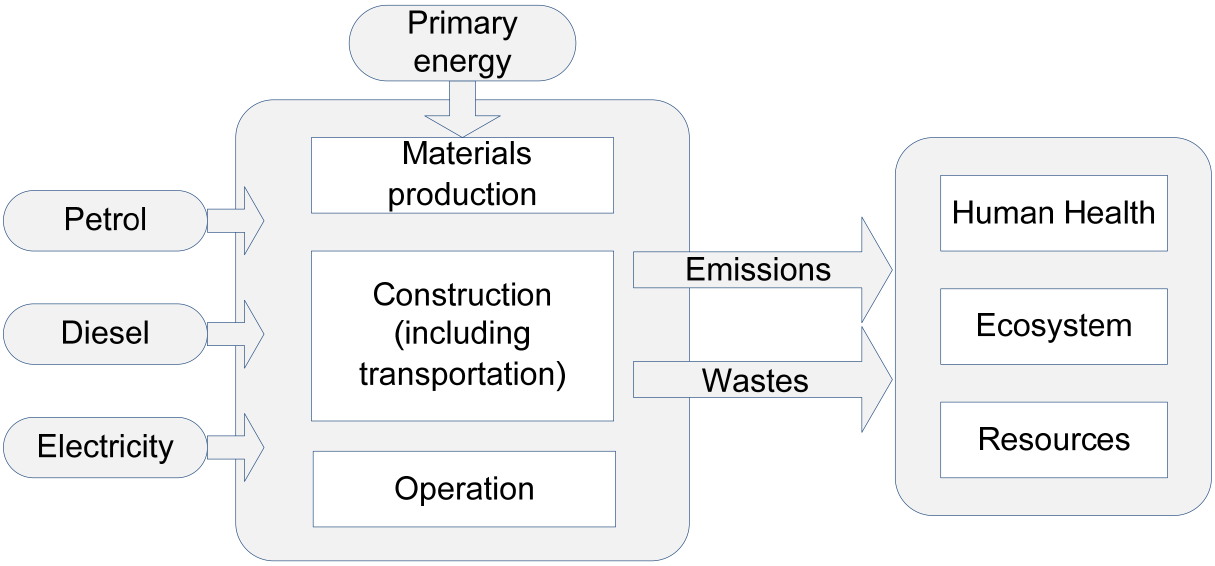

Fig.3 The background and foreground system of study

3.2. Inventory analysis

The inventory of bridge is basically dependant on the bill of quantities (shown as Tab.1 and Tab.2), to evaluate energy and material resource consumption, air and water pollutant emissions, and finally the damage from the bridge life cycle.

Tab.1 Major projects list during construction stage (including transportation)

	Material	Unit	Quantity
1	Plain reinforcement	t	1020
2	Ribbed reinforcement	t	7754
3	Prestressed reinforcing steel	t	42
4	steel strand	t	2120
5	Corrugated pipe	t	107
6	Rolled steel	t	139
7	Steel plate	t	259
8	Steel pipe	t	94
9	C50 concrete	m^3	39700
10	C30 concrete	m^3	18124
11	C25 concrete	m^3	28480
12	Petrol	L	66849
13	Diesel	L	637286
14	Electricity	kwh	4351270
15	Water	m^3	150576

3.3. Impact assessment

The LCIA includes three steps: classification and characterization, normalization, and weighting.

The first step: classification and characterization.

Tab.2 Major projects list during operation stage

	Material	Unit	Quantity
1	C40 concrete	m^3	912
2	Petrol	L	320
3	Diesel	L	4778
4	Electricity	kwh	48960
5	Water	m^3	171

Classification is assigning emission and resource use into the three types of damage: human health, ecosystem quality and resources, shown as Tab.3.

Tab.3 Classification of Environmental Impact Substances

Damage categories	Impact categories	Substances
Damage to human health	Damages to human health caused by climate change	CO_2 、CH_4 、N_2O
	Respiratory effects on humans caused by organic substances	VOC 、CH_4
	Respiratory effects on humans caused by inorganic substances	PM10、 CO 、NO_X 、SO_X
Damage to ecosystem quality	Damage to Ecosystem Quality caused by the combined effect of acidification and eutrophication	NO_X 、SO_X
Damage to mineral and fossil resources	Damage to Resources caused by extraction of minerals	Limestone、Ironstone、Manganese ore
	Damage to Resources caused by extraction of fossil fuels	Coal equivalent、crude oil

The calculation involves the conversion of LCI (Life Cycle Inventory) results to common units and the aggregation of the converted results within the impact category. This conversion uses characterization factors, shown in Tab.4 to Tab.6. The outcome of the calculation is a numerical indicator result.

The human health damage characteristic value HD （yr）can be calculated by Eq.(1).

$$HD = \sum_i HD_i = \sum_i \sum_j M_{ij} \times \lambda_{ij} \tag{1}$$

Where,

M_{ij} = the mass of j-th substance in i-th damage category, kg

λ_{ij} = the human health damage characterization factors of j-th substance in i-th damage category

HD_i = the human health damage characteristic value of i-th damage category

Tab.4 Characterization of damage factor of human health

Impact categories	Substances	Characterization factors ε_i (DALY/kg)
Damages to human health caused by climate change	CO_2	2.10E-07
	CH_4	4.40E-06
	N_2O	6.90E-05
Respiratory effects on humans caused by organic substances	VOC	6.46E-07
	CH_4	5.46E-05
Respiratory effects on humans caused by inorganic substances	PM10	1.28E-08
	CO	3.75E-04
	NO_X	7.31E-07
	SO_X	8.91E-05

The ecosystem damage characteristic value ED (PDF) can be calculated by Eq.(2).

$$ED = \sum_i ED_i = \sum_i \sum_j M_{ij} \times \varepsilon_{ij} \quad (2)$$

Where,

M_{ij} = the mass of j-th substance in i-th damage category, kg

ε_{ij} = the ecosystem damage characterization factors of j-th substance in i-th damage category

ED_i = the ecosystem damage characteristic value of i-th damage category

Tab.5 Characterization of damage factor of eco-system

Impact categories	Substances	Characterization factors λ_i (PDF·m2·yr/kg)
Caused by the combined effect of acidification and eutrophication	NO_X	5.71E+00
	SO_X	1.04E+00

The resources damage characteristic value RD (MJ) can be calculated by Eq.(3).

$$RD = \sum_i RD_i = \sum_i \sum_j M_{ij} \times \eta_{ij} \quad (3)$$

Where,

M_{ij} = the mass of j-th substance in i-th damage category, kg

η_{ij} = the resources damage characterization factors of j-th substance in i-th damage category

RD_i = the resources damage characteristic value of i-th damage category

Tab.6 Characteristics of the damage factor of resources and energy

Impact categories	Substances	Characterization factors η_i (MJ/kg)
Damage to Resources caused by extraction of minerals	Limestone	2.04E-02
	Ironstone	5.10E-02
	Manganese ore	3.13E-01
Damage to Resources caused by extraction of fossil fuels	Coal equivalent	2.04E+00
	Crude oil	3.40E+00

The second step: normalization

The three damage categories all have different units and a set of dimensionless weighting factors could be applied to make these damage categories dimensionless. The obvious way is to use a normalization step by using normalization factors. Tab.7 lists the Eco-indicator 99 normalization factors for the substance lists involved in most popular bridge LCA databases.

The human health damage normalized value $HD_N(yr)$ can be calculated by Eq.(4).

$$HD_N = \sum_i HD_{Ni} = \sum_i \sum_j HD_{ij} / f_{ij} \tag{4}$$

Where,

HD_{ij} = The human health damage characteristic value of j-th substance in i-th damage category

f_{ij} = the human health damage normalization factors of j-th substance in i-th damage category

HD_{Ni} = the human health damage normalized value of i-th damage category

The ecosystem damage normalized value $ED_N(PDF)$ can be calculated by Eq.(5).

$$ED_N = \sum_i ED_{Ni} = \sum_i \sum_j ED_{ij} / g_{ij} \tag{5}$$

Where,

ED_{ij} = the ecosystem damage characteristic value of j-th substance in i-th damage category

g_{ij} = the ecosystem damage normalization factors of j-th substance in i-th damage category

ED_{Ni} = the ecosystem damage normalized value of i-th damage category

The resources damage normalized value $RD_N(MJ)$ can be calculated by Eq.(6).

$$RD_N = \sum_i RD_{Ni} = \sum_i \sum_j RD_{ij} / h_{ij} \tag{6}$$

Where,

RD_{ij} = the resources damage characteristic value of j-th substance in i-th damage category

h_{ij} = the resources damage normalization factors of j-th substance in i-th damage category

RD_{Ni} = the resources damage normalized value of i-th damage category

The third step: weighting

As stated before, weighting is a purely normative step as weighting factors are assigned to the normalized results (ISO 14042 Standard 2000). Tab.7 lists the normalization and weighting factor of Eco-indicators 99.

The human health damage weighted value $HD_W(yr)$ can be calculated by Eq.(7).

$$HD_W = \sum_i HD_{Wi} = \sum_i \sum_j HD_{Nij} \times p_{ij} \tag{7}$$

Where,

HD_{Nij} = the human health damage normalized value of j-th substance in i-th damage category

p_{ij} = the human health damage weighting factors of j-th substance in i-th damage category

HD_{Wi} = the human health damage weighted value of i-th damage category

The ecosystem damage weighted value $ED_W(PDF)$ can be calculated by Eq.(8).

$$ED_W = \sum_i ED_{Wi} = \sum_i \sum_j ED_{Nij} \times q_{ij} \tag{8}$$

Where,

ED_{Nij} = the ecosystem damage normalized value of j-th substance in i-th damage category

q_{ij} = the ecosystem damage weighting factors of j-th substance in i-th damage category

ED_{Wi} = the ecosystem damage weighted value of i-th damage category

The resources damage weighted value $RD_W(MJ)$ can be calculated by Eq.(9).

$$RD_W = \sum_i RD_{Wi} = \sum_i \sum_j RD_{Nij} \times r_{ij} \tag{9}$$

Where,

RD_{Nij} = the resources damage normalized value of j-th substance in i-th damage category

r_{ij} = the resources damage weighting factors of j-th substance in i-th damage category

RD_{Wi} = the resources damage weighted value of i-th damage category

After these three steps, the eco-indicator of the bridge $EI(capita \cdot yr)$ can be

Tab.7 Normalization and Weighting factor of Eco-indicators 99

Damage categories	Impact categories	Substances	Normalization factors	Unit	Weighting factors
Damage to human health	Damage to human health caused by climate change	CO_2 CH_4 N_2O	2.39E-03	DALY/captia·yr	0.22
	Respiratory effects on humans caused by organic substances	VOC CH_4	1.08E-02	DALY/ captia·yr	
	Respiratory effects on humans caused by inorganic substances	PM10 CO NO_X SO_X NO_X	6.84E-05	DALY/ captia·yr	
Damage to ecosystem	Damage to Ecosystem Quality caused by the effect of acidification and eutrophication	SO_X	3.75E+02	PDF·m^2·yr/captia·yr	0.23
Damage to resources	Damage to Resources caused by extraction of minerals	Limestone Ironstone Manganese ore	1.50E+02	MJ/ captia·yr	0.55
	Damage to Resources caused by extraction of fossil fuels	Coal equivalent Crude oil	5.79E+03	MJ/ captia·yr	

calculated by Eq.(10).

$$EI = HD_W + ED_W + RD_W \tag{10}$$

3.4. Interpretation

Previously in the LCI and LCIA, the process of structuring information has been completed to provide an overview of the results of these earlier phases, which facilitates the determination of important and environmentally relevant issues, as well as the conclusions and recommendations. On the basis of this structuring process, any subsequent determination is performed using analytical techniques.

Based on the structuring of information in LCIA, Tab.8 and Tab.9 list the environmental damage from the bridge during its life cycle. The quantitative analysis of characteristic value and weighted value throughout all the stages has been illustrated.

Tab.9 represents the human health damage from one functional unit, which is 97.1 Disability Adjusted Life Years (DALYs). DALYs expresses the number of year life lost and the number of years lived disabled. This figure, it shows that materials production stage is the greatest contributor to human health damage, accounted for 85.3 DALYs.

Damage to ecosystem is expressed as the loss of species over a certain area, during a certain time, using the unit Potentially Disappeared Fraction of Species (PDF·m^2·yr).In this case study, the ecosystem damage is 1.74×10^6 PDF·m^2·yr, which means over the bridge life span (hypothesized as 100 years) all species disappear from 1.74×10^2 m^2 during one year. The materials production stage has the largest proportion of 80%, partially because the emission of NO_x during the materials production stage accounted for more than 50% which resulted in the most significant effect of acidification and eutrophication.

Eco-indicator 99 uses “surplus energy” to indicate damage to resources, and in this case study the surplus energy is 1.03×10^8MJ, namely 1.03×10^8MJ surplus energy is needed for future extractions of minerals and fossil fuels. The materials production stage still has the most significant share, 91.7%. This is easily understood, for large amounts of fossil fuels and mineral resources have been consumed during this stage.

After normalization and weighting, it is better to understand the relative magnitude for each indicator of the bridge system. It is observed in Fig.4 to Fig.6 that, during every stage the energy and resources consumption, the most serious damage, has approximately accounted for 70% of the environmental damage, followed by human health (20%) and ecosystem (5%).

Tab.8 Quantitative analysis of characteristic value

	Materials production stage		Construction stage		Operation stage		Total
	Characteristic value	percentage	characteristic value	percentage	Characteristic value	percentage	
Human health	8.53E+01	87.89%	4.02E+00	4.14%	7.74E+00	7.97%	9.71E+01
Ecosystem	1.37E+06	78.47%	1.85E+05	10.63%	1.90E+05	10.90%	1.74E+06
Resources	9.17E+07	88.81%	5.24E+06	5.08%	6.31E+06	6.11%	1.03E+08

Tab.9 Quantitative analysis of weighted value

	Materials production stage		Construction stage		Operation stage		Total
	Weighted value	percentage	weighted value	percentage	weighted value	percentage	
Human health	3.12E+03	16.64%	1.68E+02	21.54%	2.86E+02	22.31%	3.57E+03
Ecosystem	8.37E+02	4.47%	1.13E+02	14.55%	1.16E+02	9.08%	1.07E+03
Resources	1.48E+04	78.89%	4.98E+02	63.91%	8.79E+02	68.61%	1.62E+04
total	1.87E+04	100.00%	7.79E+02	100.00%	1.28E+03	100.00%	2.08E+04

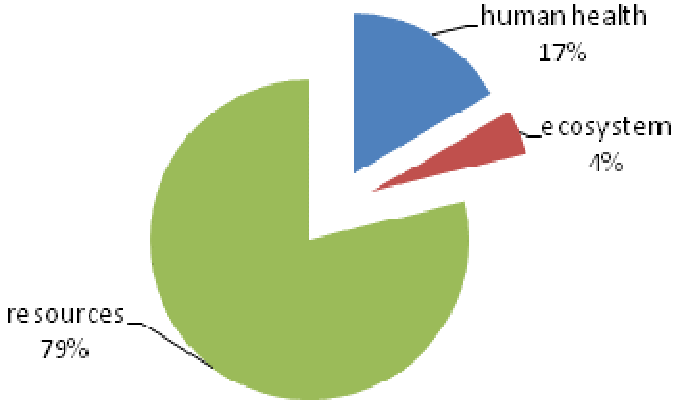

Fig.4 Proportion of Weighted value in materials production stage

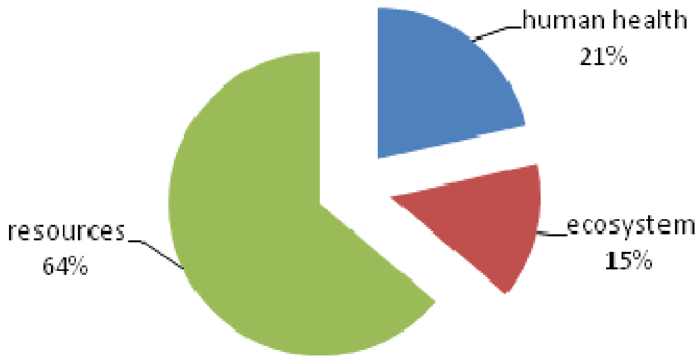

Fig.5 Proportion of Weighted value in contruction stage

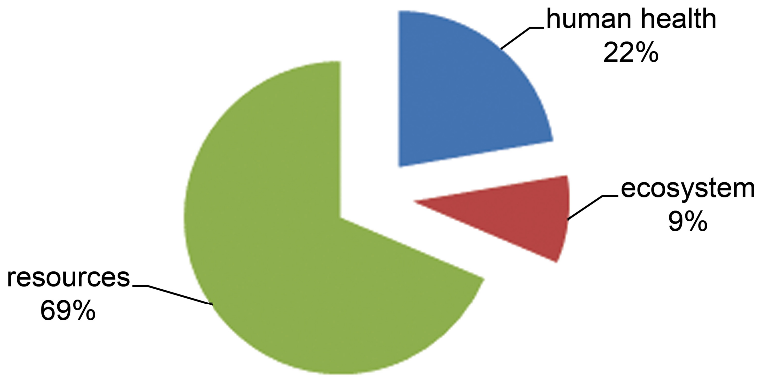

Fig.6 Proportion of Weighted value in operation stage

CONCLUSION

A LCA framework is used in this paper to conduct a partial LCA for bridges, from materials production, construction (including transportation), to operation phase. Based on the theory of LCA, the paper established an end-point damage model for bridges environmental impact quantitative analysis. With the model a pre-stressed concrete continuous rigid frame bridge in China was selected as a case study to validate the applicability of this bridge-LCA model. The results indicate that:

(1) The human health damage from one functional unit is 97.1DALYs, while the ecosystem damage is 1.74×106 PDF·m2·yr, and the resources 1.03×108MJ.

(2) The energy and resources consumption is the most serious damage during every stage, which approximately accounted for 70% of the environmental damage, followed by human health (20%) and ecosystem.

REFERENCES

Arne Remmen, Eskild Holm Nielsen, Jannick Schmidt, Jette Egelund Holgaard Per Christensen et al (2009). “Tools for Sustainable Development”, Aalborg University Press, Denmark

Feng Maorun. (2011). “The research on techmology adrancement and construction management of China’s highway bridge”, Engineering Sciences, Vol. **13**(10), 93-98.

Goedkoop and Spriensma. (2000). “Eco-indicator 99: A damage oriented method for Life Cycle Assessment”, Amersfoort: Pré Consultants.

Gregory A. Keoleian et al (2005). “Life Cycle Modeling of Concrete Bridge Design: Comparison of Engineered Cementitious Composite Link Slabs and Conventional Steel Expansion Joints.” Journal of infrastructure systems, 2005,11(1).

Horvath, A., and Hendrickson, C. (1998). “Steel versus steel-reinforced concrete bridges: Environmental assessment.” J. Infrastruct. Syst.,4(3), 111–117.

Horvath, A. (2009).”Principles of using Life-Cycle Assessment in Bridge Analysis.” Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials Sapporo, Japan, October 21-22,2009.

ISO 14040 Standard (1997), “Life Cycle Assessment: Principle and Framework”, International Standard organization.

ISO 14042 Standard (2000), “Environmental management ——Life cycle assessment —— Life cycle impact assessment”, International Standard organization.

Johanne Hammervold, Marte Reenaas and Helge Brattebø (2011). “Environmental Life Cycle Assessment of Bridges.” Journal of Bridge Engineering., October 20, 2011

JTG B03—2006. “Specifications for Environmental Impact Assessment of Highways”, Ministry of Transportation of the People's Republic of China.
http://news.ifeng.com/history/special/30yearsproject/200811/1128_5125_899493.shtml

K.N.P. Steele et al (2003).”The Application of Life Cycle Assessment Technique in the Investigation of Brick Arch Highway Bridges.” Civil Engineering. 2003, 156, Pages 176–182

Lina Bouhaya, Robert Le Roy (2009). “Simplified Environmental Study on Innovative Bridge Structure.” Environ. Sci. Technol. 2009, 43, 2066–2071

US Environmental Protection Agency. (2010)." Defining Life Cycle Assessment (LCA)."
http://www.gdrc.org/uem/lca/lca-define.html
Web. 1. XinHua News Agency, Remarkable achievements of China's bridge construction during 30-year Reform and Opening up.