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Development of Environmental Load Estimation Model for Road Drainage Systems in the Early Design Phase

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Abstract. Due to the increasing concern about climate change, efforts to reduce environmental load are continuously being made in construction industry, and LCA (life cycle assessment) is being presented as an effective method to assess environmental load. Since LCA requires information on construction quantity used for environmental load estimation, however, it is not being utilized in the environmental review in the early design phase where it is difficult to obtain such information. In this study, computation system for construction quantity based on standard cross section of road drainage facilities was developed to compute construction quantity required for LCA using only information available in the early design phase to develop and verify the effectiveness of a model that can perform environmental load estimation. The result showed that it is an effective model that can be used in the early design phase as it revealed a 13.39% mean absolute error rate.

1. Introduction

Due to the growing interest and concern about influencing factors of climate change such as greenhouse gas emission, and the emphasis on international cooperation, the Paris Agreement, which aims for limiting the degree of global temperature increase to 1.5℃, was signed by leaders of various countries in December 2015. Climate change is no longer an issue limited to certain countries and it is becoming a global issue threatening the survival of humankind.

Roads being constructed as infrastructure use numerous materials and equipment during construction process and a large amount of greenhouse gas is discharged [8]. For reducing greenhouse gas occurring as a result of such road construction projects, economic feasibility & environmental reviews must be performed in the early road planning and design phase of the project. Therefore, it is necessary to develop a rational environmental impact estimation method that can provide basic data in the decision-making process to select eco-friendly materials and methods in the early design phase.

As a method that can quantitatively perform such environmental impact estimation, LCA presented in the environmental management system the ISO 14000 series of the International Organization for Standardization is receiving attention. In the case of road construction projects, however, it is not being used to assess environmental impact in the early design phase since it is not possible to obtain information to perform LCA before completing the design.

This study however, aims to develop a model that can perform LCA-based environmental impact estimation using only information available in the early design phase of project for road drainage facilities and present it as a rational environmental impact estimation tool that can be utilized in the early design phase.

2. Scope and method

For developing an environmental load estimation model in the early design phase, this study will be conducted in the order of theoretical basis, concept definition and development of model, as shown in figure 1, and drainage facilities of road will be selected as the research target. Road drainage facilities perform the function of not only draining rainwater gathered on the road and ensure the safety of road surface but also draining discharged water flowing to other areas than road. Accordingly, drainage facilities require a review of various materials and types in the design and decision-making processes to be determined. However, it is not possible to assess environmental impact on numerous materials and types of drainage facilities by only using information available in the early design phase. However, the model being developed in this study will be able to provide useful information in the eco-friendly decision-making process.

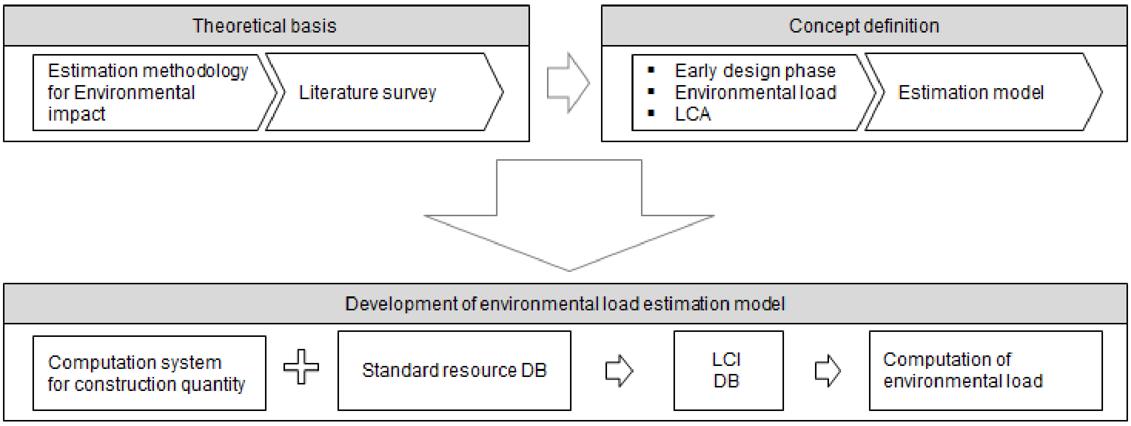

Figure 1. Research procedure and method

For performing LCA for construction projects, it is necessary to obtain information on construction quantity of each work and according resources. For computing construction quantity, this study will develop computation system for construction quantity with information available in the early design phase to reflect it in the model. In addition, amount of resources will be computed by utilizing the standard resource DB (database) of the Design Guide of National Highway [6] used in Korea to design roads. Additionally, LCI DB(life cycle inventory database) provided by ecoinvent [2] and Korean LCI DB [5] will be used in conjunction to compute the amount of environmental loads of resources used for each construction type.

3. Literature Review

In construction industry, LCA has been receiving attention as a tool to assess environmental loads, and various studies are being conducted on its methods and applications. In addition, there are various types of studies conducted not only on environmental impact of overall project but also the impact of materials, equipment and construction methods used in regards to the area of LCA application. In regards to some specific research trend on LCA in construction area includes the following:

Treloar et al. (2004) proposed hybrid LCA method for road construction and usage, and Cass et al. (2011) developed a method to quantify greenhouse gas emission during the entire process by using LCA. In addition, Yue et al. (2008) revealed that LCA is the most valid method for assessing environmental impact in road construction projects, and Chowdhury et al. (2010) applied LCA to assess environmental impact according to materials used in road construction projects. Moon et al. (2014) computed environmental loads of the collected case projects through LCA, which were then converted into basic unit to present environmental loads that occur when constructing 1km of road. Kwon (2008) computed environmental loads of infrastructure through LCA, which were converted into currency value to present an environmental economic feasibility estimation model. Meanwhile, Liu et al. (2013) computed and compared the environmental loads of rock-filled dam and conventional concrete dam through LCA, while Parrish et al. (2014) have performed LCA on sustainable infrastructure.

In regards to studies on construction area related to environmental load estimation through LCA, the majority of studies focused on the phase during which information construction quantity and resources can be obtained according to the characteristics of LCA performance technique, namely, studies using data of project that is being constructed or has been completed. Accordingly, this study, which aims to develop a model to perform environmental load estimation through LCA in the early design phase, can be differentiated from previous studies.

4. Theoretical review on LCA

An index used in this study to quantitatively show the degree of environmental impact of construction project is environmental load. It is a quantification of the degree of global environmental burden on factors influencing global environmental (greenhouse gas, ozone depleting gas, acid rain causing gas, harmful wastes, etc.) throughout the life cycle of facilities [9], and it can be computed through LCA presented in the environmental management system ISO 14000 series of the International Organization for Standardization.

As shown in figure 2, LCA consists of four phases, namely, goal and scope definition, inventory analysis, impact assessment and interpretation, and it is a method quantifying environmental burden of a product or function throughout life cycle from energy and fuel acquisition to disposal [4]. Accordingly, estimating environmental load of construction project through LCA has the advantage of being able to consider impact from not only energy and resources used in the construction phase but also fossil fuel used to produce construction materials for environmental load [14].

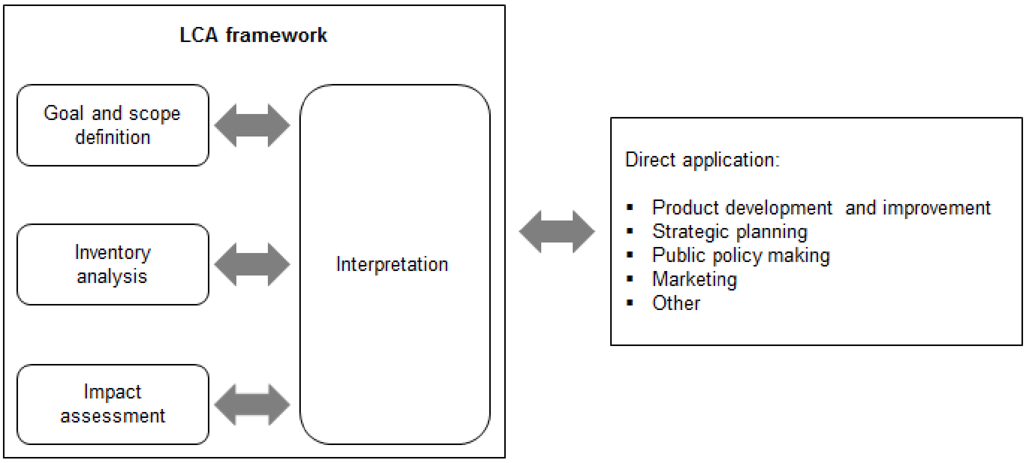

Figure 2. Phases of an LCA (source: ISO 14040)

5. Development of model

5.1. Environmental load characteristics of drainage works

Road drainage facility consists of various materials and types such as gutter, culvert, open channel and sewer pipe, and work is performed differently according to the type of drainage system. Accordingly, environmental load characteristics on drainage facility reflect in road design were analyzed prior to the model development. For analyzing environmental load characteristics, 100 road project cases implemented in Korea were collected to compute environmental load of each case project through LCA.

The environmental load of drainage facility construction of road project occupies 33.68% of environmental load occurring from entire works. This is the second highest amount of environmental load next to paving work. In regards to the distribution of environmental load according to drainage facilities, gutter construction with 48.11% causes nearly half of total environmental loads caused by entire drainage facility construction, as shown in figure 3. In addition, top 4 drainage facilities such as culvert, open channel and sewer pipe including gutter occupy 90.59% of total drainage facility loads. This shows that about 90% of total environmental load of drainage facility construction can be explained with the environmental load of only top 4 drainage facilities.

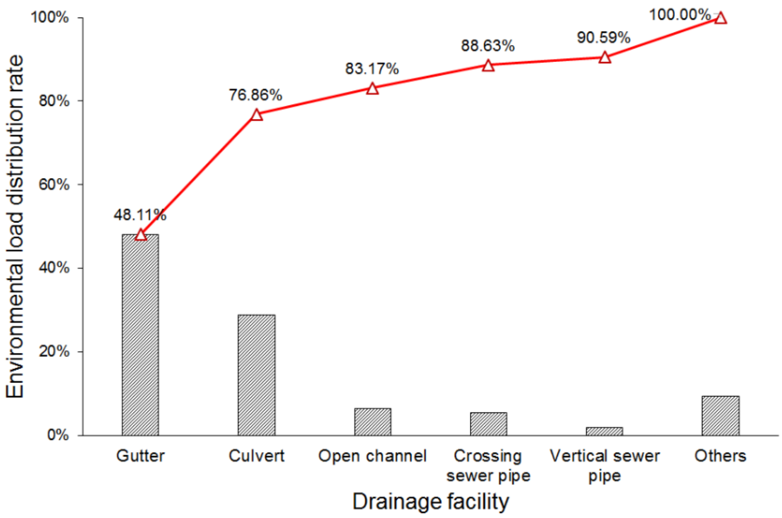

Figure 3. Drainage facility-specific environmental load distribution

Primarily, an environmental load estimation model was developed on 4 types of major items, namely, gutter, culvert, open channel and sewer pipe, and the model was designed to reflect through ratio minor items such as drainage well and manhole.

Table 1. Information available in the initial design phase.

	Candidate Group	Selected Input Variables
Information Inventory	Administrative district,	Administrative district,
	Project type	Project type
	Road division	Road division
	Number of lane	Number of lane
	Geographical feature	Geographical feature
	Design speed	Design speed
	Road area	Road area
	Road length	Road length
	Material of pavement	-
	Thickness of material	Thickness of material
	Road height	Road height
	Road width	Road width
	Horizontal radius curvature	Horizontal radius curvature
	Maximum longitudinal slope	Maximum longitudinal slope
	Constructing site area	Constructing site area

5.2. Input variables selection

In regards to input variables to be used for environmental load estimation from the as-developed model, 15 types of information inventory were deduced that can be obtained in the early design phase through previous literature survey and advice from design personnel before making final selection, as shown in table 1, by considering the fitness of the study.

Among road component facilities, bridge and tunnel have their own drainage systems and since the impact of their specifications is expected to be very insignificant, they were not considered in this study. Accordingly, road area and road length of candidate group were changed into area of earthwork and length of earthwork except bridge and tunnel length to incorporate them, while excluding material of pavement from inventory.

5.3. Construction quantity computation system

Using the input variables in table 1, construction quantity computation system was developed based on the correlation between input variables and construction quantity as a computation system that can estimate construction quantity regarding the major items (gutter, culvert, open channel, sewer pipe) of drainage facilities. This was designed to utilize input variables to compute construction length of each drainage facility from regression equation and apply unit quantity (construction quantity per unit length) computed from standard cross section. In regards to standard cross section, standard cross section of drainage facilities used for road design in Korea was used.

Regarding a regression model to compute construction length of each drainage facility, 100 cases used in the analysis of environmental load characteristics in paragraph 5.1 were used for deduction through regression analysis using input information as independent variables. Regression analysis was conducted by dividing cross section shape and drainage structure shape to allow the characteristics of drainage facilities to be incorporated. Namely, gutter was divided into L-type, U-type and V-type that are frequently used in road project, while dividing sewer pipe into crossing and vertical sewer pipes according to installation direction.

Table 2. Results of multiple regression analysis.

	R	R^2	Adj. R2	Sig.
L-type gutter	0.938	0.881	0.842	2.233×10^{-10}
U-type gutter	0.831	0.691	0.590	8.633×10^{-4}
V-type gutter	0.945	0.893	0.858	3.925×10^{-11}
Crossing sewer pipe	0.895	0.800	0.735	1.353×10^{-6}
Vertical sewer pipe	0.705	0.497	0.333	0.1504
Culvert	0.919	0.845	0.717	0.1591
Open channel	0.901	0.812	0.657	0.5681

As shown in table 2, multiple regression analysis result showed high R2 values of 0.590-0.858, with the shape of cross section and crossing sewer pipe showing high R2 value of 0.735, thereby suggesting that it is a significant regression model. Since gutter is installed in parallel to road in general, it was found to be highly related to attribute information such as length of road. Since crossing sewer pipe is also a facility crossing road, its impact on the height and width of road was significantly reflected. On the other hand, vertical sewer pipe, culvert and open channel were found to be insignificant regression model as they about significance probability of about 15%-57%, with reason being that hydraulic analysis result becomes an important element in determining length of construction instead of attribute information of road in the case of vertical sewer pipe, culvert and open channel.

Accordingly, construction quantity computation system was developed by using regression model for L-type, U-type and V-type gutter and crossing sewer pipe, and using information on length of construction determined in the early design phase for vertical sewer pipe, culvert and open channel through user input. Construction quantity obtained through the construction quantity computation system was used to compute amount of resources for each work to estimate environmental load in connection to standard resource DB. Figure 4 is a diagram of the construction quantity computation system.

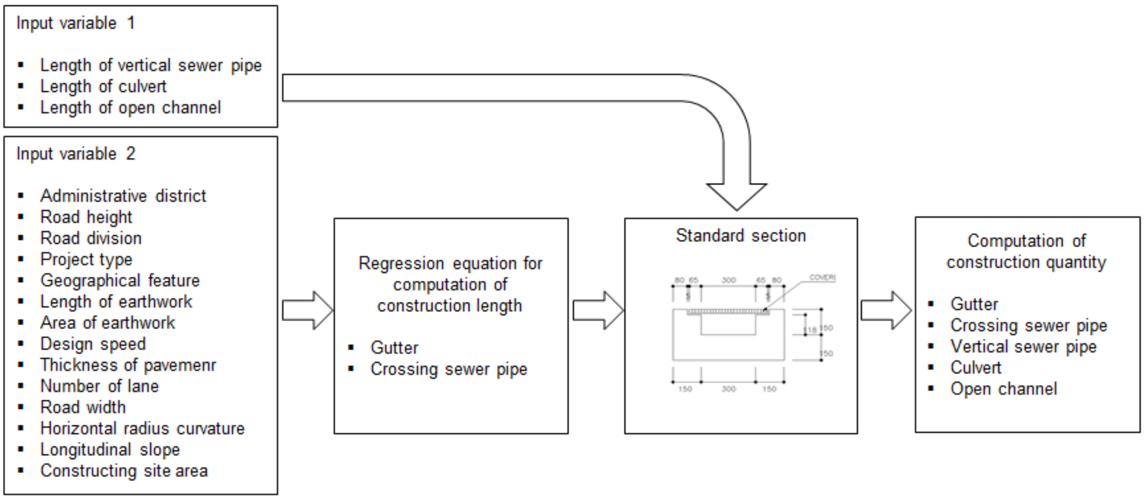

Figure 4. Overview of construction quantity computation system

5.4. Environmental load estimation model for road drainage system

As shown in figure 5, as-developed model applies LCI DB to the specific construction type-specific resources of major items that have been determined for their input amount through the construction quantity computation system and standard resource DB to compute environmental load on major items of road drainage system and apply the ratio of minor items to compute total environmental load of road drainage system.

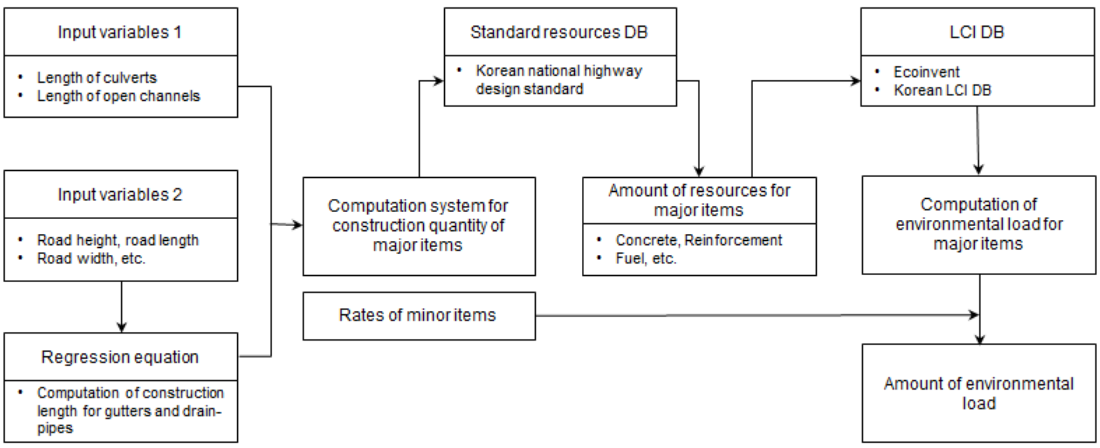

Figure 5. Overview of the road drainage system environmental road estimation model

As previously mentioned, drainage system's major items show coverage of 90.59%. Thus, the total environmental load of drainage work was estimated by reflecting 9.41%, which is the percentage of environmental load on remaining facilities other than 4 major items, as the percentage of minor items.

For evaluating the accuracy of the model, 10 road project data from 100 collected in this study were randomly selected to apply them to the as-developed model to compare between environmental load estimated from the as-developed model and environmental load computed by performing LCA.

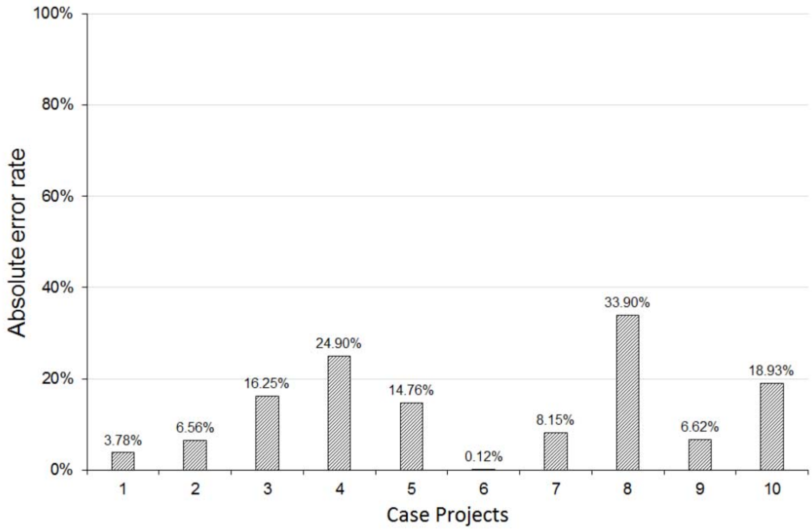

Figure 6. Accuracy verification result of the model

As shown in figure 6, the result of verifying the accuracy of the model showed minimum and maximum absolute error rates of respectively 0.12% and 33.90%, thereby showing 13.39% mean absolute error and 10.45% standard deviation. This is a relatively excellent accuracy level even though environmental load was estimated by using construction quantity computed through inference process of regression model. The result therefore shows that the environmental load estimation model developed in this study is a model that can be effectively used to conduct environmental review in the early design phase.

6. Conclusion

The following conclusions were deduced as a result of developing and verifying the effectiveness of a LCA-based environmental load estimation model for road drainage system only using information available in the early design phase with insufficient information to directly compute the environmental load.

First, drainage works in road project cause 33.68% of total environmental load, and gutter, sewer pipe, culvert and open channel occupy 90.59% of environmental load occurring from entire drainage facilities.

Secondly, an environmental load estimation model based on the construction quantity computation system of standard cross section was developed and its accuracy was verified, and the result showed favorable absolute error rate of 13.395 in average, thereby showing that the as-developed model is an effective model applicable to LCA-based environmental load estimation of road drainage system in the early design phase.

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