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Life cycle assessment based environmental impact estimation model for pre-stressed concrete beam bridge in the early design phase

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ABSTRACT

The late rise in global concern for environmental issues such as global warming and air pollution is accentuating the need for environmental assessments in the construction industry. Promptly evaluating the environmental loads of the various design alternatives during the early stages of a construction project and adopting the most environmentally sustainable candidate is therefore of large importance. Yet, research on the early evaluation of a construction project's environmental load in order to aid the decision making process is hitherto lacking. In light of this dilemma, this study proposes a model for estimating the environmental load by employing only the most basic information accessible during the early design phases of a project for the pre-stressed concrete (PSC) beam bridge, the most common bridge structure. Firstly, a life cycle assessment (LCA) was conducted on the data from 99 bridges by integrating the bills of quantities (BOQ) with a life cycle inventory (LCI) database. The processed data was then utilized to construct a case based reasoning (CBR) model for estimating the environmental load. The accuracy of the estimation model was then validated using five test cases; the model's mean absolute error rates (MAER) for the total environmental load was calculated as 7.09%. Such test results were shown to be superior compared to those obtained from a multiple-regression based model and a slab area base-unit analysis model. Henceforth application of this model during the early stages of a project is expected to highly complement environmentally friendly designs and construction by facilitating the swift evaluation of the environmental load from multiple standpoints.

1. Introduction

The Paris Agreement of Conference of the Parties 21 (COP21) allotted all countries with a responsibility to reduce greenhouse gas emissions. Under this agreement, each country must decide on its Intended Nationally Determined Contributions (INDC), and report on updated goals for greenhouse gas reduction every 5 to 10 years (UNFCCC, 2016). In upholding the Paris Agreement, the Republic of Korea has set aims to reduce greenhouse gas emissions by 37% from business-as-usual (BAU) standards by 2030 (UNFCCC, 2015), and is taking actions to reduce emissions in each of its industries. In the Korean construction industry, efforts to minimize the environmental footprint has manifested in the Ministry of Land, Infrastructure and Transport's "Guide-line to Assessment of CO^2 Emission for Facilities" of 2011, for application in the detailed design phases of a construction project. This ministry is currently conducting various research in the subject matter.

In the construction industry, the processing, production and transportation of materials, along with the physical construction, gives rise not only to greenhouse gas emissions but also to a wide range of pollutants. These are hazardous to the environment and to humans, and have been causing many issues lately. For instance, asbestos had been widely used as building material, but is now banned due to reports of its toxicity to humans (Light and Wei, 1977). To this day, environmental problems have been caused during the process of deconstructing aged facilities containing asbestos. As can be seen in the example of asbestos, numerous materials used in construction can act as immediate and long lasting pollutants. Thus the need for an environmental assessment when undertaking a new construction project is evident. Hence, the Leadership in Energy and Environmental Design (LEED) v4 is advising the implementation of life cycle assessments (LCA) on construction materials in order to assess the environmental problems caused in construction (USGBC, 2010).

However, a comprehensive LCA on the entire construction business is lacking. This is due to the fact that unlike manufactured items, facilities of the exact same specifications may require different types and amounts of material and equipment inputs depending on its structure and surroundings, meaning that making an estimation on the environmental load of a structure with any significant degree of accuracy is

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very difficult. Much research is currently devoted to overcoming such difficulties and providing a means to measure or predict the environmental loads produced in construction projects. Some of these research analyze the characteristics of environmental loads unique to each type of bridge, using information from the detailed designs (Horvath and Hendrickson, 1998). Others directly measured pollutants emitted from construction equipments in order to quantify the environmental load produced in the construction phase (Ahn et al., 2013). Although much research effort is currently in the various phases of a construction project (Haapio and Viitaniemi, 2008; Jang et al., 2015; Park et al., 2016; Radhi and Sharples, 2013), those devoted to the early phases are relatively few.

As the project matures into the later phases, implementing alternatives become increasingly difficult, and the benefits of implementing alternatives dwindle. However, current LCA utilize at least semi-conclusive bills of quantity (BOQ) and construction cost data, which are only available after a basic design is completed, in order to reach an estimate on the environmental load. Thus, the current analyses are limited by the fact that an implementation of alternative designs, or parts of designs, cannot be accounted for. In order to reduce the environmental loads posed by construction projects, alternatives that take into account environmental factors must be decided on during the early phases (Díaz and Antón, 2014). If the environmental load can be taken into consideration in the early phases, the optimal design can be devised, leading to an environmentally economical design, and save the troubles of extra cost and schedule delays that would result from change orders in the construction phase.

This study targets the pre-stressed concrete (PSC) beam bridge, which is the most prevalently applied road facility, to present a method of quantifying the environmental load using limited amount of information available in the early design phases. The result of this study is expected to be of great pragmatic assistance in environmentally-friendly construction in the future, by aiding the decision of alternatives in the early design phases of a project.

2. Reviews of current literature

The construction projects usually take significant time and cost large amounts. Therefore, the decisions made in the early stages of a construction project have large effect. Fig. 1 displays the influences that have an effect on the success of a project and the expenditures required to implement changes (Gibson et al., 1995). As can be seen in the figure, the earlier into the pre-project planning phase a change is made, the larger its influence and the lower the expenditures. That is, alternative designs considered during the early design phases may have significant effects on the later stages of the project in many regards.

Despite the advantages adopting alternatives as early as possible, most existing LCA are conducted after the completion of the design phases by employing the information available from the completed design to reach a calculation. Current LCA can be categorized into those that adopt the input-output model (I-O model) to analyze energy inputs (Treloar et al., 2001; Sharrard et al., 2008; Rowley et al., 2009; Jeong et al., 2015) and those that utilize the BOQ and a life cycle inventory database (LCI DB) constructed beforehand to conduct an LCA (Cho et al., 2017; Park et al., 2016; Surawong and Soralumn, 2014; Islam et al., 2015). The former method of analysis, which provides an estimate of the environmental load based on the energy usage and the cost of a similar project using an I-O model, is simpler than the latter which employs the LCI DB. However, as the former method relies on regional and temporal economic activity data, it lacks in accuracy when considering the characteristics unique to each project. Also, while the latter methodology produces relatively accurate estimations of the environmental load by making comparisons of the actual material input of a project with a verified LCI DB.

Horvath and Hendrickson (1998) applied an input–output-based LCA method to compare the environmental loads, emissions, and characteristics thereof, for the steel bridge and steel reinforced concrete bridge. Dequidt (2012) discussed the methods of applying LCA to bridges using the LCI DB, and analyzed the characteristics of the environmental loads projected by the post-tensioned concrete box-girder bridge. Hammervold et al. (2013) presents a detailed comparative environmental life cycle assessment (LCA) case study of three built bridges- a steel box girder bridge, a concrete box girder bridge, and a wooden arch bridge- in Norway. In this research, a program named “BridgeLCA” (RAMBOLL, 2012) was used, which conducted an LCA by synchronizing the quantity of material input with the LCI DB provided by Ecoinvent (2015). Lee et al. (2017) estimated the environmental load using the LCI database and calculated the construction cost and period by using the standards of estimate and price information. Based on this data, this study proposed a selection method for paving work equipment combination considering the construction cost, construction period and environment load simultaneously. Lim et al. (2016) presented a method for calculating the daily and cumulative amount of carbon emissions for each and every activity based on the resources (i.e., material, equipment, and labor) on activities obtained from Primavera P6.

Completed research discussed above uses data from detailed designs as the input to estimate the environmental load as the output, through a rather complex calculation process. The reason that LCA research was

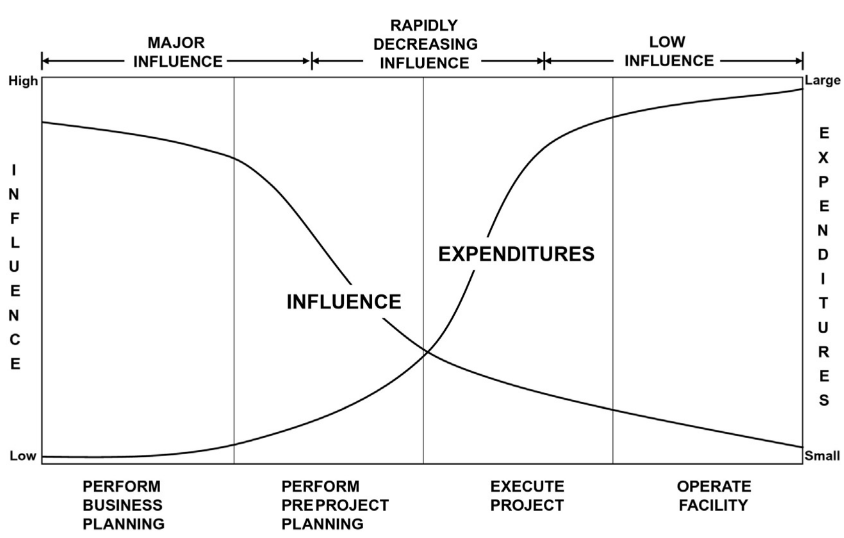

Fig. 1. Influence and expenditures curve for project life cycle (Gibson et al., 1995, pp. 312).