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Environmental impact assessment and eco-friendly decision-making in civil structures

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ABSTRACT

This study develops two useful procedures in performing an environmental-impact assessment. One is the advanced life-cycle assessment (LCA) method, which effectively tracks the flow of materials and considers the recycling and demolition of a civil structure. The other is an eco-friendly decision-making procedure, which may effectively apply when determining the prototype of a civil structure. The advanced LCA method differs from traditional LCA procedure, as it classifies the input material prior to the impact assessment. Classification work is performed to establish independent life-cycle stages for each material. The processes of recycling and demolition are appropriately added to the life-cycle stages. The impact assessment is performed separately for the materials, and results are aggregated at the end of the analysis.

The eco-friendly decision-making procedure enables designers to choose an economical, and environmentally friendly, alternative during the planning phase of the construction project. This procedure rationally amalgamates economical value and environmental effects into a single indicator. The life cycle cost (LCC) of a structure can be analysed by using conventional LCC tools, whereas the environmental impact is estimated by LCA. The results from LCC and LCA are then integrated by using either a CO_2 conversion method or an analytical hierarchy process (AHP). The CO_2 conversion method presents the result as a monetary value, whereas the AHP presents the result as a non-dimensional value. A practical example using a steel box girder bridge and a pre-stressed concrete (PSC) box-girder bridge is also given in order to aid the understanding of the presented procedure.

1. Introduction

Industrial developments in our society accelerate the use of energy resources, and steep increases in energy consumption cause serious environmental damage in various ways. In order to protect the environment from pollution, the governments of advanced countries are now encouraging construction of environmentally friendly, sustainable infrastructures. LCA is an innovative concept for estimating environmental impacts related to various kinds of products. For LCA to accurately estimate the degree of environmental impact, a vast range of materials should be considered, and the results should be collected in a database. Some commercially available LCA software programmes, such as SimaPro 7 and Gabi 4.2, are known to improve the accuracy and reliability of analyses through the use of worldwide LCA databases. Judging from the databases and from reliable, analytic tools, LCA is one of the most promising methods for achieving environmentally friendly designs in civil engineering. However, some difficulties exist in the application of LCA to civil structures due to intricate material inputs and outputs and a lack of well-defined demolition and recycling plans at the outset of projects. The demolition and recycling plan for the structure is the most uncertain throughout the life cycle of a civil structure. In addition, the structure requires large amounts of construction materials to be transported from many locations.

In order to overcome these challenges, this study proposes an advanced LCA method that can effectively estimate the environmental impacts of a structure's demolition and recycling. Unlike the traditional procedure, this method categorizes the input and output materials throughout a product's life cycle before performing the LCA. By doing so, it is easy to identify the total amount of input and output of materials and their possible recycling processes. In order to show the effectiveness of the proposed method, a case study has been

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performed for a steel-box girder bridge. This study proposes an eco-friendly decision-making procedure that minimizes the environmental impact of structures while attaining the lowest possible cost for the structure's life cycle. This procedure effectively integrates environmental impact and economic value into one measurement. The proposed procedure is tested in a simple decision-making example to show its practical use. By applying this procedure, the economic and environmental feasibility for the design process of the civil structure studies (and, by extension, other civil structures of similar scope and materials usage) is rationally evaluated.

2. Method

2.1. The advanced LCA method

The construction industry has made attempts to minimize environmental effects in the field; however, to date, few efforts have been made to perform rational analyses (through LCA) that consider the characteristics of civil structures. Unlike goods produced in factories, the life cycle of civil structures is often quite long and contains many uncertainties: the structures have different features and life spans and are of different scale. Such facts imply that LCA should be performed on every single civil structure of concern. Furthermore, anticipating and considering the environmental impact from demolition and recycling is problematic.

With these problems in mind, the first problem could be solved by generalising LCA results from various civil structures and databases; however, performing an LCA for every civil structure of concern is a very time consuming task. This study focuses on solving the second problem by presenting an advanced LCA method wherein disposal and recycling processes can be successively considered by categorizing the inventory data based on the material concerned.

The advanced LCA method is effectuated by categorizing the inventory data for the input and output materials. The life cycle inventory analysis (LCIA) is conducted separately for each category; therefore, the results of the LCA will be drawn, according to categorized materials. Among the various construction stages, there are several stages that do not require any material inputs. Excavation work and soil compaction are good examples. Environmental impacts estimated from these, especially from oil usage, are estimated by following ordinary procedures of the LCA. Fig. 1 compares the frameworks for the ordinary process of LCA (ISO/DIS, 1996) and the proposed method.

2.2. Eco-friendly decision-making procedures in civil structures

Many international agreements (i.e. AGENDA21 and Kyoto protocol) call for reduction of effects; however, there are no specific guidelines so far quantitatively regulate the environmental effect in civil engineering field. Although the environmental effects are not quantitatively considered by current design codes, the life-cycle cost (LCC) is often evaluated and the result is often used as one of the important indices while designing the structure. In order to associate the environmental effects with LCC, this study proposes a decision-making procedure to be used when constructing civil structures that satisfies the need to produce a minimal environmental effect. This procedure not only considers environmental aspects, but also satisfies the need to minimize the life cycle cost (LCC). LCC and LCA analyses are performed simultaneously to satisfy both economic and environmental metrics. The results from these two analyses have different units, and a special measurement is needed to compare them via quantitative interpretation. For this purpose, the CO_2 conversion method and the analytical hierarchy process (AHP; Saaty, 1980) have been developed to compare the two analysis results. Both methods rationally integrate environmental effects and the economic value into a single indicator. A practical application using both methods is given in the Section 4.

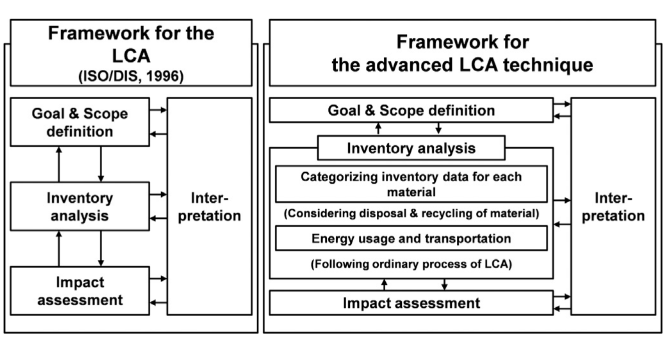

Fig. 1. The framework of life cycle assessment presented in ISO 14040 (ISO/DIS, 1996) and the advanced LCA technique proposed in this study.

2.2.1. CO_2 conversion method

The CO_2 conversion method simply adds the cost estimated from LCC analysis and the cost converted from the amount of CO_2 emission. Two prices can be considered for the conversion of CO_2: one is the carbon credit, and the other is the carbon tax. A carbon credit is a tradable certificate, or permit, that represents the right to emit one ton of CO_2 equivalent; this credit was developed in order to control pollution by providing economic incentives to reduce pollutant emissions. The European Union Emission Trading Scheme (EU-ETS) applied the carbon credit widely to European countries. However, the carbon credit has a high liquidity risk, which is closely related to the global economy, and continues to face several problems, including over-allocation, windfall profits, and price volatility (Gilbertson and Reyes, 2009).

Carbon tax is an environmental tax assessed on the carbon content of fuels; it is closely related to the domestic Social Cost of Carbon (SCC), which is the marginal cost of emitting one extra ton of carbon at any point in time (Yohe et al., 2007). It is currently applied in some advanced countries, such as the United Kingdom, Denmark, the Netherlands, and the Scandinavian countries, and is in the process of being implemented in additional countries. The carbon tax provides a potentially cost-effective means of reducing CO_2 emissions, as it is a type of Pigovian tax, or tax that is levied to correctly price the negative externalities of a given activity in the absence of market-driven pricing that reflects these externalities (Helm, 2005). Carbon taxes cannot regulate the upper limit of emissions; however, they are less influenced by market conditions and have less liquidity risk. On the basis of these facts, this study used carbon tax as a conversion index of CO_2 emissions, rather than applying a carbon credit.

2.2.2. Analytical hierarchy process (AHP)

An AHP has been developed to address the complex, difficult-to-quantify elements that inform decisions for this case study. Conventionally, this process is composed of three steps. During the first step, users break their problem down into a hierarchy composed of elements that can be independently analysed. The next step in the process is to compare the results from lower-level elements in the hierarchy with respect to their impact on items higher up the hierarchy (i.e. higher-level elements). Both human judgment and actual data can be used during this comparison process, and the consistency of human judgment is evaluated through the use of an 'inconsistency index', which enables the determination of whether human decision remain consistent towards the elements in the hierarchy. An optimal decision is then made for the problem at hand.