Environmental Impact Assessment Review 57 (2016) 123–133

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Comparative analysis of methods for integrating various environmental impacts as a single index in life cycle assessment

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ARTICLE INFO

Article history:
Received 17 September 2015
Received in revised form 2 November 2015
Accepted 3 November 2015
Available online xxxx

Keywords:
Life cycle assessment
Integration
Normalization
Weighting
Monetary valuation
Comparative analysis

ABSTRACT

Previous studies have proposed several methods for integrating characterized environmental impacts as a single index in life cycle assessment. Each of them, however, may lead to different results. This study presents internal and external normalization methods, weighting factors proposed by panel methods, and a monetary valuation based on an endpoint life cycle impact assessment method as the integration methods. Furthermore, this study investigates the differences among the integration methods and identifies the causes of the differences through a case study in which five elementary school buildings were used. As a result, when using internal normalization with weighting factors, the weighting factors had a significant influence on the total environmental impacts whereas the normalization had little influence on the total environmental impacts. When using external normalization with weighting factors, the normalization had more significant influence on the total environmental impacts than weighing factors. Due to such differences, the ranking of the five buildings varied depending on the integration methods. The ranking calculated by the monetary valuation method was significantly different from that calculated by the normalization and weighting process. The results aid decision makers in understanding the differences among these integration methods, and, finally, help them select the method most appropriate for the goal at hand.

1. Introduction

With increasing concerns and interests in environmental problems, the building industry has also been required to reduce the environmental impacts of buildings. The life cycle assessment (LCA) is a representative method for evaluating the potential environmental impacts of products, services, and systems by considering their life cycle (International Organization for Standardization (ISO), 2006a). Over the last two decades, therefore, many LCA methods, which evaluate the various environmental impacts of buildings, such as global warming potential (GWP) and ozone layer depletion potential (ODP), have been developed and used in the building industry (Bilec et al., 2006; Chang et al., 2013; Collinge et al., 2013; Guggemos and Horvath, 2006; Hong et al., 2012; Jang et al., 2015; Jeong et al., 2015; Ji et al., 2014a; Kofoworola and Gheewala, 2008; Lee et al., 2009; Li et al., 2010; Li, 2006; Lim and Park, 2009; Sharrard et al., 2008). In several previous studies, LCA methods have often been used to determine the most environment-friendly building by comparing the environmental impacts of building alternatives (Du et al., 2014; Guggemos and Horvath, 2005; Hong et al., 2012; Ji et al., 2014b; Proietti et al., 2013; Saiz et al., 2006; Tae et al., 2011). However, most of previous LCA studies have only included characterization, the mandatory step in life cycle impact assessment (LCIA) (Zhou and Schoenung, 2007). It contains a problem in that the characterized environmental impacts cannot be compared across the impact categories since they are expressed in different units. Thus, it is difficult for decision makers without sufficient environmental expertise to determine the most environment-friendly alternative based on the characterized environmental impacts. In particular, the selection of the most environment-friendly alternative is more difficult in a situation where there is no one dominant alternative that performs best in all of the impact categories. Therefore, the integration method, which is capable of representing a single index by integrating all of the characterized environmental impacts, is required when determining the most environment-friendly alternative with the simultaneous consideration of multiple environmental impacts.

The characterized environmental impacts can be integrated as a single index through the normalization and weighting process, which are optional steps in LCIA (International Organization for Standardization (ISO), 2006a, b). Previous LCA studies have suggested a variety of normalization and weighting methods, but most of them considered normalization and weighting separately (Bare et al., 2006; Erlandsson and Lindfors, 2003; Finnveden, 1999; Finnveden et al., 2002; Gloria et al., 2007; Hong et al., 2012; Lee, 1999; Lippiatt, 2007; Myllyviita et al.,

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http://dx.doi.org/10.1016/j.eiar.2015.11.013
0195-9255/

2014; Norris, 2001; Seppälä and Hämäläinen, 2001; Soares et al., 2006; Wenzel et al., 1997). Normalization and weighting should be considered together in order to integrate the characterized environmental impacts. On the other hand, several LCA studies have suggested LCIA methods which represent environmental impacts as a monetary value (i.e., cost) (Itsubo and Inaba, 2003; Itsubo et al., 2004; Park and Kim, 2010; Steen, 1999). Thus, the characterized environmental impacts can be integrated as a single index (i.e., cost) by using these LCIA methods.

These integration methods can support the decision making by simultaneously considering a variety of environmental impacts. However, since these integration methods have totally different contents for integration, the integrated result may differ depending on the integration methods. Especially, according to ISO 14044, the weighting is based on the value-choices and is not scientifically based. For this reason, the weighted results may differ depending on the participated individuals, organizations, and societies who may have different preferences (International Organization for Standardization (ISO), 2006c). Undesirable results might arise, regardless of the decision making goal, if decision makers use a certain method without understanding the characteristics of the integration methods. Although a previous research provided a stochastic approach as the way for considering the differences depending on integration methods (Prado-Lopez et al., 2014), it is still necessary to understand clearly the characteristics of the integration methods and the differences among them for the decision to be made.

This study aims to determine the characteristics of the integration methods and the differences among them. This study, therefore, presents two types of normalization methods (i.e., internal and external normalization), three types of weighting factors (i.e., weighting factors provided by the Building for Environmental and Economic Sustainability (BEES) panel, the US Environmental Protection Agency (EPA) science advisory board, and the Netherlands Oil and Gas Exploration and Production Association (NOGEPA) panel), and a monetary valuation method using the KOrean Life cycle Impact assessment index based on a Damage oriented (KOLID), which is one of the LCIA methods. These methods were selected because they directly convert the characterized environmental impacts to a single index and show the total environmental impacts quantitatively, allowing comparisons of results obtained by different methods. In the case study, the characterized environmental impacts of five elementary school buildings are assessed and integrated by the integration methods. Then, the characteristics of the integration methods were determined by comparing the total environmental impacts depending on different integration methods. This study considered the six environmental impact categories (i.e., GWP, ODP, abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP)), which have been considered as typical environmental impacts in previous LCA studies (Hospido et al., 2003; Jeong et al., 2015; Lee, 1999).

2. Materials and methods

2.1. Integration methods

2.1.1. Normalization and weighing

The purpose of normalization is to combine the different units of the characterized environmental impacts (International Organization for Standardization (ISO), 2006a). Therefore, the normalization converts the characterized environmental impacts of different units to the normalized environmental impacts (Erlandsson and Lindfors, 2003; Finnveden et al., 2002; Norris, 2001). Two normalization methods have been typically used in LCA: internal and external normalization. Each of the normalization methods is based on different methodological principles.

In internal normalization, the normalized environmental impact is calculated by dividing the characterized environmental impact by the maximum characterized environmental impact of alternatives as shown in Eq. (1) (Lippiatt, 2007; Myllyviita et al., 2014; Norris, 2001).

$$NEI_i = \frac{CEI_i}{{}_{\max}CEI_i} \tag{1}$$

where, NEI_i is the normalized environmental impact of category i; CEI_i is the characterized environmental impact of category i; and ${}_{\max}CEI_i$ is the maximum value of the characterized environmental impact of category i.

In external normalization, the reference values are used instead of the maximum value of alternatives. Thus, the externally normalized environmental impacts are calculated by dividing the characterized environmental impact of each impact category by the reference value of the same impact category as shown in Eq. (2) (Finnveden et al., 2002; Norris, 2001; Wenzel et al., 1997). The reference values can be selected on the basis of various dimensions: system basis (e.g., a region or an economic sector), spatial scaling (e.g., nation or continent), temporal scaling (e.g., per year), or additional magnitude scaling (e.g. per capita) (Bare et al., 2006; Heo et al., 2000; Sleeswijk et al., 2008; Wenzel et al., 1997). For instance, the reference values could be defined as the current level of characterized environmental impacts for a period of one year in a country. Several studies have suggested the reference values available for the external normalization in various countries and continents around the world: Australia, Denmark, the Netherlands, South Africa, South Korea, the United States, the European Union, and the wider world (Bare et al., 2006; Breedveld et al., 1999; Chung et al., 1997; Heo et al., 2000; Huijbregts et al., 2003; Lautier et al., 2010; Lundie et al., 2007; Seppälä, 2007; Seppälä and Hämäläinen, 2001; Sleeswijk et al., 2008; Strauss et al., 2006). These reference values can be used for the external normalization. Since this study uses elementary school buildings in South Korea for the case study, it is reasonable to use the reference value from South Korea. Therefore, this study uses the reference values reflecting the emissions for a period of one year in South Korea, which have been established by Heo et al. (2000), as shown in Table 1.

$$NEI_i = \frac{CEI_i}{RV_i} \tag{2}$$

where, NEI_i is the normalized environmental impact of category i; CEI_i is the characterized environmental impact of category i; and RV_i is the reference value of category i.

Weighting is a process of integrating a variety of the normalized environmental impacts as a single index by assigning the relative importance of each impact category to the normalized environmental impacts (International Organization for Standardization (ISO), 2006b). As shown in Eq. (3), the normalized environmental impacts are converted to the weighted environmental impacts by applying the

Table 1
The reference values for external normalization.

Category	Unit	Reference value
GWP	kg CO_2 eq./year	2.83E+11[a]
ODP	kg CFC-11 eq./year	4.13E+06
ADP	kg Sb eq./year	1.47E+08
AP	kg SO_2 eq./year	2.82E+09
EP	kg PO_4^{3-} eq./year	4.45E+08
POCP	kg C_2H_4 eq./year	3.69E+08

Note:
[a] 100 years is selected as the default time horizon.