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Temporal discounting in life cycle assessment: A critical review and theoretical framework

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ABSTRACT

Temporal homogeneity of inventory data is one of the major problems in life cycle assessment (LCA). Addressing temporal homogeneity of life cycle inventory data is important in reducing the uncertainties and improving the reliability of LCA results. This paper attempts to present a critical review and discussion on the fundamental issues of temporal homogeneity in conventional LCA and propose a theoretical framework for temporal discounting in LCA. Theoretical perspectives for temporal discounting in life cycle inventory analysis are discussed first based on the key elements of a scientific mechanism for temporal discounting. Then generic procedures for performing temporal discounting in LCA is derived and proposed based on the nature of the LCA method and the identified key elements of a scientific temporal discounting method. A five-step framework is proposed and reported in details based on the technical methods and procedures needed to perform a temporal discounting in life cycle inventory analysis. Challenges and possible solutions are also identified and discussed for the technical procedure and scientific accomplishment of each step within the framework.

1. Introduction

Life cycle assessment (LCA), as a comprehensive analytical tool, has been widely employed for assessing environmental impacts of products and systems during their whole life cycle (Cooper and Fava, 2006; Elcock, 2007; Maurice et al., 2000). In accordance with ISO 14040 standards, a complete LCA includes four interdependent steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. Among these four steps, the core quantitative analysis parts are inventory analysis and impact assessment. In general, life cycle inventory (LCI) analysis is to compile a list of cradle-to-grave inventory data by counting the balance of flows involving inputs and outputs, such as materials and energies, during the entire life cycle of a product or system (Owens, 1997a). Life cycle impact assessment (LCIA) is to quantify the potential environmental impacts of the inventoried results, with foci primarily on resource use, human health consequences, and ecological consequences (ISO, 2006; Pennington et al., 2004).

In current LCA, a major problem is the temporal homogeneity of the inventory data (Hellweg et al., 2003; Pinsonnault et al., 2014; Potting and Hauschild, 2005; Riva et al., 2006; Shah and Ries, 2009; Yuan et al., 2009; Zhai et al., 2010). In LCA of a product, the consumption of energy, resources and the generation of wastes, emissions, are mostly from different time periods, while in current LCA, these data are aggregated directly without considering their temporal differences (Kendall et al., 2009; Reap et al., 2008a; Suh and Huppes, 2005; Zhai et al., 2010). As demonstrated in Fig. 1, various emissions spread along the whole life time of a product are aggregated on their nominal values directly into conventional life cycle inventory (Potting and Hauschild, 2005). By doing so, various emissions of a material generated from different time periods are treated as a single aggregated emission generated at one time during the life cycle of a product (Owens, 1997b). This aggregated result is not accurate because the aggregated emission amount never realistically exists (Owens, 1997b).

Ignoring the temporal differences of the life cycle inventory data could result in a number of issues in LCA practices, such as problems in decision support, difficulty in environmental management, and inaccuracy in environmental impact assessment.

1.1. Decision support issues in sustainability management and practices

Frequently, LCI results are directly used for decision support in sustainability management and practices. However, the lack of a temporal aspect in current inventory analysis creates large uncertainties and may result in misleading conclusions in real sustainability practices, especially on those long-lived products. Fig. 2 illustrates two products (a and b) with the same amount of an emission during their life cycles (accumulative emission in the same amount), while one product with a short lifetime (L_a), and the other a long lifetime (L_b). Since the accumulative emission is generated during the lifetime period of the two products, the long-lived product has a relatively lower emission intensity (emission amount per unit time) than the short-lived product,

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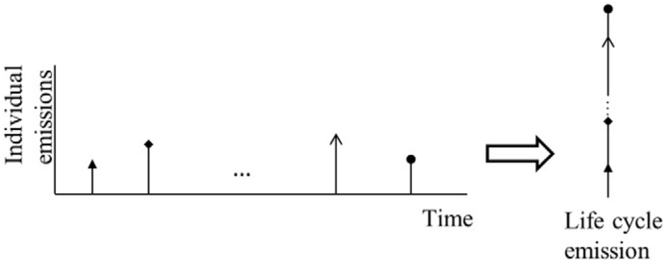

Fig. 1. Illustrative graph of emission inventory aggregation in conventional LCA.

as shown in Fig. 2. The actual environmental impacts of the emission from these two products are different because these emissions were generated across different time periods, which should be appropriately considered in decision support of environmental management and sustainability practices.

1.2. Difficulty in identifying improvement opportunities

A LCA usually contains various phases including raw materials acquisition, materials production, manufacturing, usage, and end of life; each life cycle phase is also comprised of numerous activities and events such as machining, joining, painting, and transporting for a typical part manufacturing, and the emissions generated from a life cycle phase could be largely different from one another. These differences are heavily dependent on the characteristics of products being assessed. For example, the life cycle emissions of a vehicle are mainly generated from its use phase (Maclean and Lave, 1998; Schweimer and Levin, 2000), while the life cycle emissions of a solar photovoltaic panel are mostly from its manufacturing phase (Fthenakis et al., 2008; Meijer et al., 2003). In addition, with the technology advancement and innovation, the sources of environmental emissions might shift from one life cycle phase to another (Reap et al., 2008b). For example, replacing conventional vehicles with electric vehicles can reduce environmental emissions from the vehicle use phase but will increase the emissions from the manufacturing and end-of-life phases (Hawkins et al., 2012; Notter et al., 2010). In current LCA practices, when the emissions are aggregated into a total value for each material, the temporal variability of such emissions are completely masked, leading to difficulty in identifying the contaminative sources of the emissions and the associated activities for environmental improvement.

1.3. Inaccuracy in environmental impact assessment

In LCA, the inventory data is used to characterize the environmental impacts of emissions based on their characterization factors, as shown in Eq. (1) (Huijbregts et al., 2001; ISO, 2006; Pennington et al., 2004; Reap et al., 2008b; UNEP, 2003). Following current LCA practice, the amount of the *inventory*$_i$ is mostly an aggregated mass value of an emission material that in fact is a sum of many individual emissions distributed over a product's life cycle.

$$\text{Impact category indicator} = \sum_i (\text{Inventory}_i \times \text{CF}_i) = \sum_i \sum_t \left(\text{Inventory}_{i,t} \times \text{CF}_i\right) \tag{1}$$

where CF is the characterization factor, the subscripts i ($i = 1, 2 \ldots$) and t represents the ith kind of emission inventory and the generation time, respectively.

In current impact assessment, generic (average) values are often used in characterization factors without specifying their temporal differences (Herrchen, 1998; Potting and Hauschild, 2005; Reap et al., 2008b). Although convenient, this simple use of generic values may lead to large uncertainties up to multiple orders of magnitude in the final impact assessment, particularly in the situation of quantifying those time-specific environmental impacts, because the temporal variability of the characterization can be quite large (De Schryver et al., 2011; Potting and Hauschild, 2005; Reap et al., 2008b; Shah and Ries, 2009). For example, Shah and Ries (2009) observed that for the photochemical oxidant impact characterization, the temporal variation of characterization factors for NO_x can be as high as two orders of magnitude.

Intrinsically, the temporal homogeneity issue of conventional LCA lies in its ignorance of the interactions of the emissions with environment during the emission-generating time intervals. In reality, environmental emissions could be released into air, water or soil. An emission material, after released, will be subject to certain fate and transport processes, depending on the physicochemical properties of the material and also the local conditions of the environment (Boethling et al., 2009; Nazaroff and Alvarez-Cohen, 2000). In general, the concentration and amount of an emission released into an environmental medium such as air and water decreases along time, which also decreases its real-time environmental impacts (Gavrilescu, 2005). Nevertheless, these dynamic changes are not considered in the conventional life cycle inventory data aggregation (Hellweg and Frischknecht, 2004; Hellweg et al., 2003; Levine et al., 2007). It has been well recognized that addressing this temporal homogeneity issue has to be through a scientific temporal discounting method (Hellweg et al., 2003; Yuan et al., 2009; Zhai et al., 2010).

2. Perspectives on temporal discounting in LCA

Temporal homogeneity issue commonly exists in economic field in which the timing differences of monetary values are addressed using a temporal discounting approach (Cunningham, 2009; Hellweg et al., 2003; Ludwig et al., 2005; Raineri and Rachlin, 1993). In nature, the general function of economic temporal discounting is to neutralize the temporal influence of monetary flows in regards to a reference time point (usually the present time). Its principle is to project the individual monetary values to the selected reference time by modeling the actual behavior of the monetary flows on the financial market using a representative "discount rate" to calculate the average change of money during that time interval. After temporal discounting, the monetary values from different times are projected to the same time, which can then be aggregated into an equivalent total value. This is meaningful since the discounted values at the same time can be considered as the equivalent amount of monetary values generated at another time.

In principle, the economic temporal discounting consists of four interdependent elements in the discounting mechanism: first, quantifying the temporal scale of the monetary flows; second, specifying the temporal differences of monetary flows by attaching the monetary

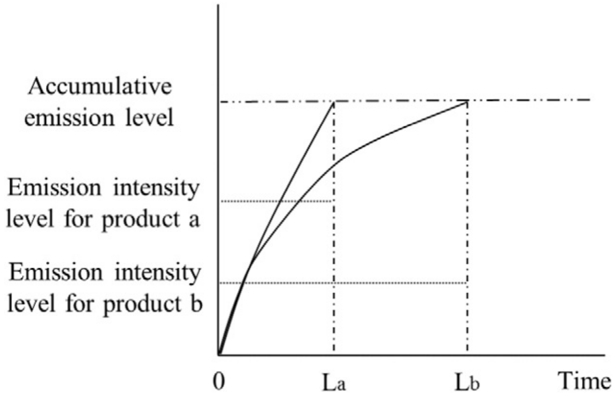

Fig. 2. Two products with the same amount of life cycle emissions but different emission intensities.