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Systemic boundaries in industrial systems: A new concept defined to improve LCA for metallurgical and manufacturing systems

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ABSTRACT

Life cycle assessment (LCA) is a conventional approach of analyzing and assessing the environmental impacts caused by industrial products during their full life cycles. It establishes inventory records of metabolic behaviors of materials and energy (ME) depending on the processing unit. However, more accurate estimations on metabolic behaviors of ME not only depend on the cascades of processes but also involve the equipments and the corresponding productions. The conventional LCA actually encounters challenges while both the product and the relevant production system are taken into account for the inventory analysis on metabolic behaviors of ME. For overall considerations, both the processing system relevant to products and the industrial system relevant to equipments shall be regarded as an integrated system in order to develop a more quantitative approach to LCA. Based on this point of view, a generic morphologic model of industrial system based on the concept of systemic boundary is employed to improve the LCA approach for more definite analysis on the inventory data of ME and more accurate estimation on the environmental impacts. Two case studies are provided to demonstrate the positive effects of the improved LCA on the metallurgical industrial system and the mechanical manufacturing system. Both case studies show the improved LCA approach based on the concept of systemic boundary is feasible, quantitative and efficient to conduct the inventory analysis on ME consumptions and the assessment on environmental impacts, not only for the continuous industrial system but also the discrete manufacturing system.

1. Introduction

Life cycle analysis (LCA) is usually used to analyze how the energy and materials are operated and give a proper assessment on the environmental impacts during the life cycle of an industrial product. Many institutes around the world applied LCA for the research on environmental friendly industries. Canada Windsor University set up an ECDM (Environmentally Conscious Design and Manufacturing) Lab and an EC (Environmental Consciousness) information database based on the open networks and developed a software system EDIT (Environmental Design Industrial Template) to implement the environmental consciousness design and manufacturing with LCA. In China the Zhizhuo Research Centre for Green Manufacturing at Tsinghua University has been engaged in LCA, green design and recycling process for circuit boards and other electronic products since 2001.

Originally Graedel illustrated the streamlined LCA as a technique framework which is widely used for the assessment and analysis on resource consumptions and environmental impacts in various industries and scientific fields today (Graedel, 1998). Many industrial products such as aircrafts, automobiles, machine tools, electric appliances, even architecture buildings are analyzed and assessed in the aspects of energy consumptions and environmental impacts with using LCA (Lundie and Huppes, 1999; Airbus et al., 2008; Kofoworola and Gheewala, 2008). The conventional LCA is usually used to analyze and assess a type of material like a certain industrial product depending on its processes and productions. Ferreira's research examined the use of LCA methodology to evaluate the environmental impact of alumina/ZnO2 and MgO/ZnO2 as reinforced refractory for two different end-of-life scenarios, i.e.

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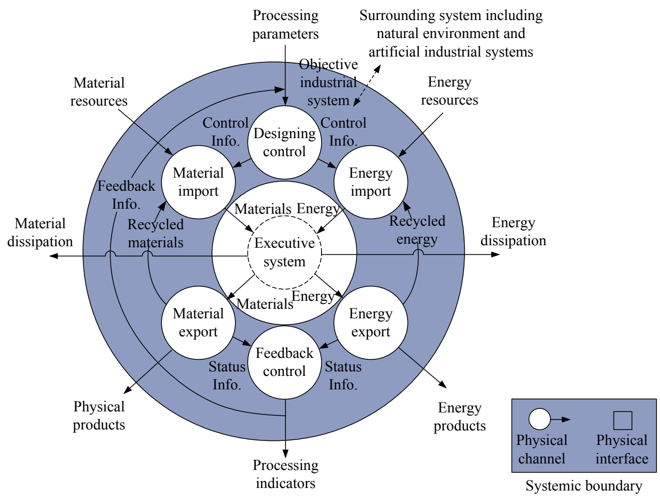

Fig. 1. A generic morphologic model of the systemic boundary for the industrial system.

landfills and recycling (Ferreira et al., 2014). Madival used the LCA methodology to assess the environmental profile of PLA, PET and PS clamshell containers (Madival et al., 2009).

In these scenarios each process during the life cycle is analyzed as a unit of inventory analysis on the amount of consumptions and emissions of materials and energy (ME). If the processes of a component is cascade and streamlined and one machine tool only handles one type of components at a time, the ME amount in the unit of process for LCA is considered equal to the tested data of ME directly from the machine tool averaged by quantity of components. That is a simply ideal scenario since the amount of ME consumed by the machine tool is apt to be directly sensed. Therefore the exact ME amount in each process can be definitely obtained when conducting the inventory analysis for the conventional LCA.

However the life cycle of an assembled product is not always streamlined. In most cases of physical productions, a machine tool processes various components with using a diversity of ME resources. These components might belong to different products. Thus the amount of ME consumed during each process is usually hard to be directly tested due to the diversity of components that flow through the machine tool. For computing the exact amount of ME in each process for LCA, the tested data of ME directly from the machine tool needs to be deconstructed and distributed to different components and the corresponding processes. The distribution proportion of ME for each process of each component depends on the actual machining hour of each component and the quantity and types of components handled on a machine tool. Although, the quantity and types of components handled on a machine tool always are uncertain due to the changes of production tasks and schedules. The machining hour is also uncertain due to the changes on machining parameters. All these makes the scope of processes for an industrial product is unable to be exactly defined and the conventional LCA falls into troubles.

In conventional LCA, the industrial products and their processes are used to serve as the unit for the inventory analysis of the consumptions and emissions of ME during their life cycles. However, LCA is not always dependent on the processing unit of the product but also used for assessing and analyzing the industrial system as well as for the product. More scholars consider that LCA methodology based on the industrial system rather than processes or products needs to be developed for more definite and accurate analysis on the environmental impacts and the ME flows. Bidstrup proposed a LCA procedure which was adopted in SEA (Strategic Environmental Assessments) for various types of process planning (Bidstrup et al., 2014). Renzulli illustrated the results of a LCA approach implemented for the improvement of existing performance and sustainability of a specific industrial reverse osmosis concentration system used in a southern Italian winery (Tassielli et al., 2014). Not only in the discrete manufacturing industry but also the continuous industrial system such as the metallurgical industry, LCA is widely applied to discover the implications of ME and environmental impacts. As early as 2002, Cai joint with CAE (Chinese Academy of Engineering) member Lu introduced LCA to assess the environmental loads and impacts produced by the typical iron and steel-making processes (Cai et al., 2002). Iosif provided an integrated modeling approach based on LCA and made an inventory analysis for the sintering processes under a ULCOS (Ultra Low CO2 Steel-making) technical framework (Iosif et al., 2008). The same weakness of the conventional LCA exists in the continuous industrial system. The confused scope of process system and the diversified origins of ME data also limit the LCA application in the continuous process system. Iosif was aware that ME data came from both aspects of the cascade of processes and the parallel of equipments. Consequently he established an integrated model which considered the process and the corresponding equipment as an integrated system for LCA on steelmaking processes (Iosif et al., 2008).

For further improving the performance of LCA, scholars introduced some new methods to overcome the weaknesses of the conventional LCA. Avadí used the LCA and DEA (Data Envelopment Analysis) framework to assess the eco-efficiency of Peruvian anchoveta steel and wooden fleets. DEA is sufficient to be integrated into the LCA framework for the assessment on the eco-

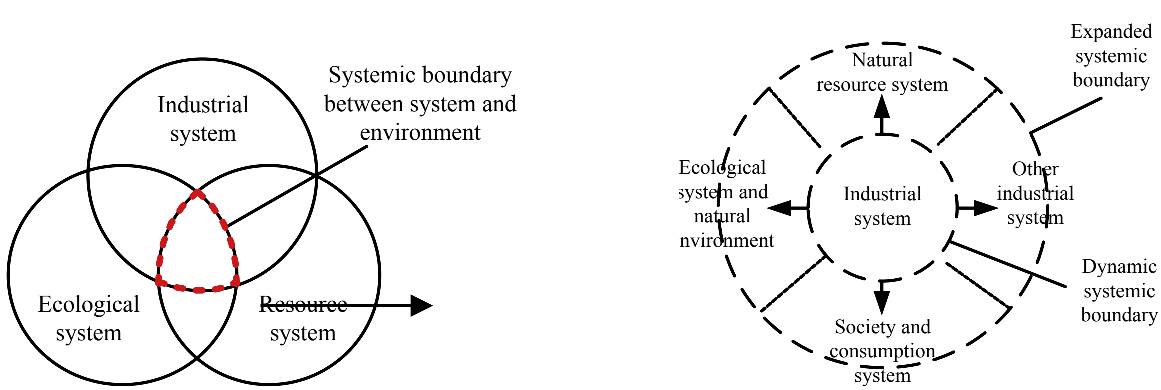

Fig. 2. Dynamic attributes of the systemic boundary in the industrial system.