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# LCA-oriented semantic representation for the product life cycle

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ABSTRACT

In order to complete a life cycle assessment (LCA) study of the product, each activity interacting with the environment during the product life cycle should be given an explicit description, namely an LCA-oriented representation for the product life cycle should be constructed. A complex functional product usually consists of many parts made of different materials and its LCA-oriented life cycle modeling involves many complex semantic relationships. In this paper, a new LCA-oriented and ontology-based semantic representation model and methodology for the product life cycle are proposed. First, the concepts of processes and flows, and the semantic relationships among processes, and between processes and flows are analyzed in detail. The ontology classes of processes and flows are defined using the Web Ontology Language (OWL). Then, an LCA-oriented semantic concept model for the product life cycle is presented. Based on the proposed semantic representation model, all processes, flows, and the relationships among them can be represented as a Resource Description Framework (RDF) graph in which each node is an instance tagged by an ontology class. A formalization of lifecycle processes on flows is provided, which can be encoded with Semantic Web Rule Language (SWRL) and formed into a knowledge rule base. In addition, a semantic query method for the life cycle inventory of a product is proposed. Finally, an implementation framework and an example of the semantic representation for a ball bearing's life cycle are provided.



## 1. Introduction

Life cycle assessment (LCA) is a comprehensive analysis approach to quantify and assess the consumption of resources and the environmental impacts associated with a product (or service) throughout its life cycle. There are four phases in the life cycle assessment study: i) defining the goal and scope of the study, ii) constructing a life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation (ISO 14040, 2006). The construction of the LCI is the most important phase because in the LCI phase all activities involved in the product life cycle need to be analyzed and modeled, and all of the data relating to environmental impacts needs to be compiled and calculated. The LCI results are the foundation for the subsequent life cycle impact assessment and interpretation phases (Suh and Huppes, 2005).

An LCI analysis mainly involves the LCI data compilation and LCI object modeling. Currently, there are many methods for inventory data compilation (Suh and Huppes, 2005). A number of LCI databases, such as Ecoinvent (Frischknecht and Rebitzer, 2005) and International Reference Life Cycle Database (ILCD) (European Commission, 2010), have been widely used. On the other hand, the LCI data compilation depends on the analysis and modeling of LCI objects. The LCI objects mainly refer to various activities and interactions between the activities and the environment in the product life cycle. How to abstract the LCI objects from realistic products and organize them in a suitable information representation which is also called as the LCI model (Kougoulis, 2008) is very important. Romaniw et al. (2009) proposed a sustainable evaluation model based on activities. Carlson et al. (1998) proposed the concepts of "activity" and "flow", and considered that an activity is a technical system or an aggregate of different processes, and a flow is any substance entering or leaving an activity. Bailey et al. (2004) proposed an input–output based approach for modeling physical flows in the industry that is independent of monetary implications. Currently, the process tree model is widely employed as the LCI model's conceptual model. For example, GaBi 5 establishes an LCI model of a product by describing its plans, processes, and flows (PE International, 2011), and SimaPro 7 by describing the product's components (including its parts and subassemblies) and processes for product usage, recycling, and disposal (PRé Consultants, 2010).

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Currently, there exist a large number of LCA systems and LCI database available. ISO has developed a technical specification for data documentation formats for the life cycle inventory stage entitled "Environmental Management—Life Cycle Assessment-Data Documentation Format" (ISO/TS 14048, 2002). The specification outlines the information that should be recorded during an inventory. While this assures that almost all LCA datasets have the same types of information included, it does not assure that they have the same structure or format. Hence, there are a large number of data formats available for representing LCA data (Moreno et al., 2011), which includes EcoSpold (Frischknecht and Rebitzer, 2005), ILCD, SimaPro data format, Gabi data format, OpenLCA database schema (Ciroth, 2007). The open source EcoSpold data format has been the most widely used data exchange format for LCI data, which is stored as an XML file and promotes the exchange of data between LCI databases.

However, most current LCI modeling systems still employ the declarative modeling, and their modeling results are underutilized, difficult to access, and difficult to understand. In addition, as mentioned above, the LCI information involves various types of activities and interactions between the activity and the environment. Logical and dependency relationships exist among the activities, input materials, emissions, and product assembly objects. Therefore, it is very difficult for the current declarative LCI information representation to cope with following issues (Villa et al., 2009):

(1) Collaborative analysis and modeling.

LCI analysis and modeling of a complex product is a very tedious and time-consuming work. It is best to have many analysts in the different environment collaboratively work together through Web for LCI analysis and modeling.

(2) Analysis and modeling for products in the supply chain.

With the globalization of the economy, in a complex product there are many parts or components which are provided through the supply chain. It is difficult to implement LCI analysis and to model this kind of products because they can only provide the limited product life cycle information.

(3) Sharing the LCI information for the application of different disciplines.

An LCI provides the quantized impact data on the environment of a product life cycle, so the LCI information is crucial for the some applications, such as LCIA, eco-design of a product, and the process design of a product lifecycle. In general, the applications of various disciplines are carried out in different system platforms, so it is required to share and exchange the LCI information.

(4) Having the domain knowledge representation capability.

Currently, the declarative LCI modeling lacks the supports of the knowledge representation so that an LCA study heavily depends on the domain knowledge of the practitioners. In fact, the product process analysis, the allocation of the quantitative data and environmental impact analysis need much domain knowledge. It is necessary for a new generation LCI modeling system to have the ability for the domain knowledge representation.

From the issue analysis mentioned above, it is evident that it is very necessary to research and develop new semantic representation for LCI modeling so as to make the LCI information be open, shared, understandable, and exchangeable.

An open, shared, and formally and explicitly defined concept system is the foundation for information understanding. In addition, it is also important to organize and store the concept information in a human-readable and machine-readable format. The ontology-based semantic Web technologies are capable of providing this means and have much more advantages than other concept modeling technology in the classification, sharing and formalization.

Recently, the ontology-based semantic Web technologies have been widely applied into many research fields. In the life cycle management of products, the ontology-based semantic technology attracts much research. Harms et al. (2010) analyzed the life cycle management challenges and potential for semantic Web technologies, and proposed a technical framework based on the knowledge and the semantic Web for product life cycle management. Despeisse et al. (2012) analyzed environmental principles and industrial practices in order to develop a conceptual manufacturing ecosystem model as a foundation to improve environmental performance. Hai et al. (2011) presented an ontology based approach for operational process modeling. Matsokis and Kiritsis (2010) developed an ontology model of a product data and knowledge management semantic object model for PLM. Garcia-Crespo et al. (2010) presented a conceptual model based on ontology for semantic representation of industrial manufacturing processes, which mainly focused on the process management. Moreno et al. (2011) gave a review on the application of product data technology standards to LCA data, and considered that semantic Web technology provides an opportunity for storing, sharing and exchanging LCA data.

In the meantime, more and more LCI modeling attentions are being directed at semantic and ontology applications. Bertin et al. (2012) proposed a semantic approach for modeling life cycle inventory databases. They recognized that an LCI database may contain thousands of interconnected processes, thus making it difficult to understand an LCI model. In addition, the semantic similarity is particularly noticeable. Therefore, semantic information should be added to the LCI model, and the processes may be regrouped by establishing a two-layer model. Davis et al. (2009) presented an approach where the LCA is integrated into an agent-based model (ABM), which is a simulation tool that allows many entities (or agents) to make simple decisions and interact with one another and the virtual world around them. Villa et al. (2009) considered that semantically aware environmental modeling is a way of designing, implementing and deploying environmental datasets and models, and gave a review of emerging semantic approaches to environmental modeling. The Earthster Core Ontology (ECO) is a core domain ontology for LCA, which was developed as part of the Earthster project to facilitate the open publication and sharing of LCA data on the web and the sharing of information between different organizations in the supply chain (Epimorphics Ltd, 2010). ECO has defined some preliminary and core ontologies, such as the temporal concept, elementary flow and relationships between concepts. However, from the public literature, ECO still lacks the systematic research on the semantic representation of LCI information. For example, so far we have not found reports on how to use the established ontologies to describe a specific product life cycle and implement information processing.

With this in mind, this paper analyzes the essential nature of various activities that interact with the environment during the product life cycle in detail, and presents a new ontology-based semantic representation model and framework for the LCI modeling. In the proposed semantic representation, the various activities and flows during a product life cycle are represented as a set of instances of the process ontology and flow ontology respectively. The process instances and flow instances are linked to each