A Minimal Ontology Pattern for Life Cycle Assessment Data

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Abstract. Life Cycle Assessment (LCA) is the study of the environmental impact of products taking into account their entire life-span and production chain. This requires gathering data from a variety of heterogeneous sources into a Life Cycle Inventory (LCI). LCI preparation involves the integration of observations and engineering models with reference data and literature results from around the world, from different domains, and at varying levels of granularity. Existing LCA data formats only address syntactic interoperability, thereby often ignoring semantics. This leads to inefficiencies in information collection and management and thus a variety of challenges, e.g., difficulties in reproducing assessments published in the literature. In this work, we present an ontology pattern that specifies key aspects of LCA/LCI data models, i.e., the notions of flows, activities, agents, and products, as well as their properties.

1 Introduction and Motivation

Life Cycle Assessment (LCA) is concerned with analyzing the environmental impact of products, taking into account the complete production chain and the entire life-span of the product. For instance, assessing the impacts of operating a solar array goes beyond the pure manufacturing and assembly of the photovoltaic modules. It also includes the extraction of raw materials, transportation emissions, installation emissions, operation emissions, and the final disposal emissions. Such assessment first requires the gathering of all relevant data from different sources into a so-called Life Cycle Inventory (LCI), followed by the actual assessment of the environmental impacts based on the gathered data, used models, and the literature. Understanding the complex impact of products is crucial for arriving at, and maintaining, a sustainable world where human needs are met while minimizing the harm to the environment and without reducing the ability of future generations to meet their needs. As such, LCA is a highly interdisciplinary field that requires synthesizing information from a variety of discipline-specific studies. This interdisciplinarity can be challenging because the vocabularies often vary between and even within fields of study. This can create significant problems for data sharing in LCA when data from multiple sources are translated, merged, and managed as a single life cycle inventory.

Current LCA models do not facilitate semantic interoperability [5]. While the standardized LCA data formats, e.g., Ecospold and ILCD, do allow for the exchange of data, such formats alone do not guarantee that a dataset from one source can be integrated with another source as there is no consensus on the meaning of central nomenclature for LCA. In other words, the data models are not backed with explicit conceptual models. Ignoring differences in these underlying assumptions, i.e., settling with syntactic interoperability alone, is likely to cause erroneous and unreproducible results.

Many of the significant challenges to data management in LCA practice [10] and interpretation [9, 11] arise from the lack of protocols and mechanisms to ensure mutual comparability and consistency of data sets and results. While Linked Data and ontologies hold great promise for addressing such issues, semantic techniques have only recently been introduced [2, 8] and thus not yet impacted LCA practice. Efforts to develop semantically enriched LCA databases [1] and product models [14] have had limited scope. Given the high interdisciplinarity and granularity within LCA, arriving at a shared monolithic domain model seems like a distant goal. Thus, in this work we introduce a minimal ontology design pattern for LCA data to act as a common core.

2 Competency Questions

Developing an ontology requires use cases that capture recurring domain or cross-domain problems. These uses cases can guide the design of the ontology and help in its evaluation. One approach is co-called *competency questions* [3]. These are (often informal) queries that the ontology should be able to answer and that act as requirements for its axiomatization. To give a simple example, if a typical subject matter expert would make a distinction between two classes B and C of a common subclass A, then an ontology that does not introduce B would not be considered as suitable. The following listing shows examples of competency questions that have been identified by LCA experts.

- Is flow x a reference product (e.g., electricity from a power plant)?
- How long will a flow or activity persist (e.g., the emission of landfill gas)?
- To which compartment does an elementary flow belong to (e.g., soil)?
- What is the location of the agent performing the activity in study x (e.g., where is the coal power plant located for which the emissions of electricity production were assessed in the research study)?

3 The Content Ontology Design Pattern

The proposed ontology design pattern[1] is meant to form a common core for the semantic description of key elements of life cycle inventories. It neither covers the

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[1] OWL file at: `http://descartes-core.org/ontologies/lca/1.0/LCAPattern.owl`

process of carrying out life cycle assessments, e.g., how data is gathered or how system boundaries are defined, nor does it provide the variety of spatial, temporal, and thematic attributes used to scope inventory items, e.g., to express the fact that coal extraction may have varying impacts depending on the geographic region and used technology [13]. Instead, our pattern aims at fostering interoperability between existing data models, specifications, and software, with the intent to act as a joint building block for the rapidly increasing interest in semantics within the broader LCA community. Due to lack of space, we only discuss a few selected axioms here. An overview of the pattern is depicted in Fig. 1.

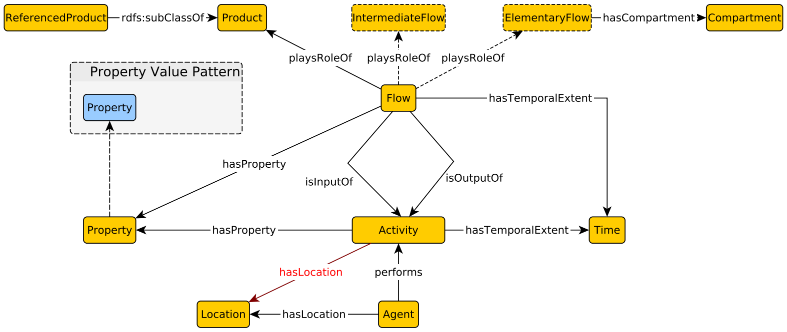

Fig. 1: Concept map for the pattern; core concepts & roles shown by solid lines.

Estimating the environmental impact of a certain product requires an understanding of all impacts accumulated during its creation, lifetime, and decommissioning. With respect to the solar panel example introduced before, the creation of the solar arrays requires multiple activities such as the transportation of resources, the generation of electric power by a coal power plant necessary to manufacture certain parts of the panels, or the disposal of polluted sludge accumulated during the production. In other words, the Eco-efficiency of solar panels depends on the activities involved in all stages of their life-cycle. Each activity is performed by at least one agent such as an coal power plant that performs the generation of electricity (Eq. 1). An activity is located via the location of the agent performing it (Eq. 2). Activities also have a temporal extent and can have a variety of properties such as the electricity generated per year, and so forth.

$$Activity \sqsubseteq \forall performs^{-} Agent \sqcap \exists performs^{-} Agent \tag{1}$$

$$performs^{-} \circ hasLocation \sqsubseteq hasLocation \tag{2}$$

Flows are streams of material or energy that can act as the inputs and outputs of activities. Flows can also be purely monetary or represent social pressures, e.g. insecurity or psychological stress. In our running example, coal is an input to the activity of electric power generation, while CO_2 emissions are an output. Typically, emissions are an undesired product of power generation, and, thus, can be distinguished from reference products (Eq. 3) such as the produced electricity, which is also an outcome of the activity. Note that while flows and their activities both have temporal extents, these extents can differ substantially. An activity such as waste disposal may take hours, while the resulting emissions may continue for years.

$$ReferenceProduct \sqsubseteq Product \tag{3}$$

Besides their role as products, flows can optionally be categorized into elementary flows or intermediate flows (Eq. 4, 5). The first case describes flows that are entering the system from the environment without any previous transformation by humans or are leaving the system by being released into the environment without further human transformation (Eq. 7) [6]. The environment is typically described in terms of compartments such as air, water, or soil (Eq. 6). In contrast, intermediate flows occur between processes of the studied system.

$$IntermediateFlow \sqcap ElementaryFlow \sqsubseteq \bot \tag{4}$$

$$ElementaryFlow \sqcap ReferenceProduct \sqsubseteq \bot \tag{5}$$

$$\{\texttt{air}, \texttt{water}, \texttt{soil}\} \sqsubseteq Compartment \tag{6}$$

$$Flow \sqcap \exists hasCompartment.\{\texttt{air}, \texttt{water}, \texttt{soil}\} \sqsubseteq ElementaryFlow \tag{7}$$

Guarded domain and range restriction (see Eq. 8, 9 for examples) enable us to infer additional facts about agents, activities, flows, locations, and so forth.

$$\exists isInputOf.Activity \sqsubseteq Flow \tag{8}$$

$$Flow \sqsubseteq \forall isInputOf.Activity \tag{9}$$

4 Relation to Other Patterns and Ontologies

The pattern can be related to a number of other ontologies and ontology design patterns. Details about properties and their values can be modeled via alignments to the GeoLink property pattern [7]. The location of an agent can be expressed using GeoSPARQL, e.g., to represent the spatial footprint of a region. The temporal extent can be modeled via OWL:Time. As discussed before, the pattern models activities and flows, e.g., by describing their duration, inputs, outputs, roles, and so forth. Equally relevant for LCA is the temporal and spatial extent that scopes the impact assessments, e.g., to state that a certain level of emissions was representative of Western Europe during the 1980s. This can be modeled using the LCA scope ontology [13]. Our pattern and the scope ontology can be aligned using their common *Flow* class. The pattern can further be aligned to the material transformation pattern [12] that deals with products as outcomes of transformations. Units are handled using the QUDT ontology [4].

5 Coal Power Plant Example

Here, we outline an example for emissions from a coal power plant to show how the pattern answers the competency questions. In this case, CO_2 emission is a *Flow* as is the used coal. Electric power generation is modeled as an *Activity*, the CO_2 emission as its output (*isOutputOf*), and coal as its input (*isInputOf*). The power plant generating (*performs*) said electricity is of type *Agent* and has a certain location. Thereby the activity can be located as well. The CO_2 emission is an *ElementaryFlow* with *air* as its compartment. In contrast, electric power (which is also an output of the power generation activity) is the *ReferenceProduct*. The activity and the flows can have a temporal extent (*hasTemporalExtent*).

6 Conclusion and Future Work

In this work, we briefly outlined the motivation behind developing a pattern as common building block for LCA/LCI. We presented a few of the used axioms and gave examples from the domain of power generation. The described work is the joint result of a VoCamp on LCA that brought together leading international domain experts with ontology engineers in March of 2015 at UCSB. Future work will focus on introducing the pattern to a larger audience and integrating it with the ongoing ontology projects at the US Environmental Protection Agency.

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