An Ontology For Specifying Spatiotemporal Scopes in Life Cycle Assessment

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Abstract. Life Cycle Assessment (LCA) evaluates the environmental impact of a product through its entire life cycle, from material extraction to final disposal or recycling. The environmental impacts of an activity depend on both the activity's direct emissions to the environment as well as indirect emissions caused by activities elsewhere in the supply chain. Both the impacts of direct emissions and the provisioning of supply chain inputs to an activity depend on the activity's *spatiotemporal scope*. When accounting for spatiotemporal dynamics, LCA often faces significant data interoperability challenges. Ontologies and Semantic technologies can foster interoperability between diverse data sets from a variety of domains. Thus, this paper presents an ontology for modeling spatiotemporal scopes, i.e., the contexts in which impact estimates are valid. We discuss selected axioms and illustrate the use of the ontology by providing an example from LCA practice. The ontology enables practitioners to address key competency questions regarding the effect of spatiotemporal scopes on environmental impact estimation.

Keywords: Life cycle assessment; ontology; spatiotemporal scopes.

1 Introduction

Life Cycle Assessment (LCA) is a method for analyzing the environmental impact of a product or a service through all stages of its life cycle [5, 13]. LCA is designed to take into consideration the entire life cycle and product chain, having a holistic viewpoint in dealing with environmental issues. The life cycle of a product or a service normally includes raw material acquisition, manufacturing process, trading process, product usage, recycling process, and waste management. Due to the diverse types of information required to conduct an LCA, knowledge from different domains needs to be gathered and interpreted together. This process is challenging because there is no universal ontology or vocabulary among (or even within) domains of study, creating substantial barriers for information sharing and integration among different data providers.

An important stage of LCA is the creation of a Life Cycle Inventory (LCI), which consists of representing economic activities as a collection of *unit processes* linked together through interdependency relations [3]. A global understanding of these economic activities and the data that comes along require a clear capture of the interdependencies and relationships between the used nomenclatures. Semantic technologies and ontologies are promising methods to support interoperability in LCA. They foster semantic interoperability without the need to enforce a single domain schema.

Researchers have long been considering the significance of a spatial perspective in LCA [11, 2, 6]. Because environmental impacts in LCA are driven by the emission of substances into the environment, site-specific assessments are often necessary to deal with spatial variation, which refers to differences in geology, topography, land cover, and so forth [12]. The geographic location of a process can also be important in determining the impacts of activities that occur elsewhere in the supply chain, such as freight transport. Likewise, a number of studies have argued that a dynamic approach is necessary to account for temporal variations in activities or impacts [9, 14]. These investigations show that the *spatiotemporal scope* of assessed activities is important to LCA. While recent studies [3, 18] have used semantic technologies for LCA, most of them are too general and have not taken scoping into account. Here, we introduce a compact ontology that formalizes the spatiotemporal scope of activities in LCA and integrates well with previously published LCA-related ontology design patterns [8, 15].

While our work is concerned with LCA as a diverse field that will benefit from the ontological modeling of its data and workflows, spatiotemporal scopes are relevant for a multitude of other domains. Thus, the core part of our ontology can be regarded as an ontology design pattern (ODP).

2 Competency Questions

Designing an ontology requires generic use cases to capture the recurring problems in one or multiple domains. *Competency questions* have been recognized as an effective approach to identify such use cases. Competency questions are frequent queries that subject matter experts would like to submit to a knowledge base to find answers. The following listing shows examples of competency questions that have been identified by international LCA experts during the GeoVoCamp Santa Barbara 2015:

- **Question 1**: "What is the emission of activity a at place p at time t?"
- **Question 2**: "What are the supply chain requirements of activity a when it happens at place p_1 and time t_1?"
- **Question 3**: "What is the difference of activity a at places p_1 and p_2 at the same time t?"
- **Question 4**: "What is the difference of activity a at times t_1 and t_2 at the same place p?"

As can be seen, answering the four competency questions requires four main concepts: *Activity*, *Flow*, *Place*, and *Time*. An activity in LCA may have *Requirement* (Question 2) and *Outcome* (e.g., emission) (Question 1), which collectively make up flows. To effectively link these concepts, proper relations have also been specified.

3 Spatiotemporal Scoping Ontology

The ontology for spatiotemporal scopes[5] is developed based on the existing Activity ODP, [1] which also includes concepts such as *Activity*, *Requirement*, and *Outcome*. Since the Activity ODP focuses on human activities, we modify and extend it to fit

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[5] `http://descartes-core.org/ontologies/lca/1.0/stscope.owl`

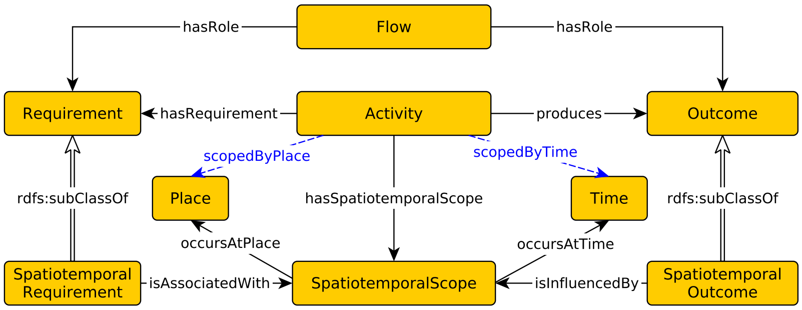

Fig. 1. An overview of the *spatiotemporal scope* ontology.

the activities in the domain of LCA and add the scoping on top of the resulting model. Figure 1 provides an overview of the spatiotemporal scoping ontology. In the following, we describe the classes and relations by showing selected description logics axioms.

SpatiotemporalScope: This class represents the spatial and temporal context under which an LCA activity occurs. We define this class instead of directly using *Place* and *Time*, because many requirements and outcomes are associated with the spatiotemporal contexts rather than places and time (intervals) alone. *SpatiotemporalScope* is associated with the classes *Place* and *Time* through the relations *occursAtPlace* and *occursAtTime*. *Time* should be an interval because an LCA activity generally represents the performance of a typical facility or a set of facilities over a time period, rather than at a specific moment. A place is some, typically named, extent in geographic space, e.g., a country or region. We do not specify both classes here and refer to OWL-Time and GeoSPARQL for details (which implies that geometry types such as multi-part polgyons can be used as spatial footprints of places). We assert that each spatiotemporal scope has at least one place and time (see Eq. 1).

$$\begin{aligned} SpatiotemporalScope \sqsubseteq\ & \exists occursAtPlace.Place \sqcap \exists occursAtTime.Time \\ & \sqcap\ \exists hasSpatiotemporalScope^{-}.Activity \end{aligned} \tag{1}$$

Note that we also provide role chains in the ontology (see Eq. 2 as example) but do not discuss them here for lack of space.

$$hasSpatiotemporalScope \circ occursAtPlace \sqsubseteq scopedByPlace \tag{2}$$

$$hasSpatiotemporalScope \circ occursAtTime \sqsubseteq scopedByTime \tag{3}$$

Activity: The *Activity* class represents activities in the LCA sense and thereby differs from other conceptualizations of activities. An activity roughly corresponds to a *unit process* as defined in the ISO 14044 standard [7], but may also indicate a reservoir, stock, or natural process such as dissolution into fresh water. An activity always occurs at a certain place (e.g. in a particular factory or river) in a particular time span. We link *Activity* to *SpatiotemporalScope* through the relation *hasSpatiotemporalScope*. An activity in LCA also has *Requirement* and *Outcome*.

$$\begin{aligned} Activity \sqsubseteq\ & \exists hasRequirement.Requirement \sqcap \exists produces.Outcome \\ & \sqcap\ \exists hasSpatiotemporalScope.SpatiotemporalScope \ldots \end{aligned} \tag{4}$$

Flow: A *Flow* is a highly generic concept in LCA mainly defined as a counterpart to an activity. A flow may represent the transfer of matter, such as an emission of combustion gases, or an exchange of services, such as transporting a good. A flow is exchanged between an activity and another activity. Although flows are the products of processes, many flows can exist independently of any process, can be accumulated in reservoirs, and can have properties, such as economic value. A flow can play a role in both the *Requirement* of one activity and *Outcome* of another, and thus, we define the relation of *hasRole*. If the two activities in the exchange are industrial unit processes, the flow is referred to as an *intermediate flow*. The two activities can be described as "partners" to the exchange. A flow exchanged with the natural environment is called an *elementary flow*. We formalize the class of *Flow* as below:

$$Flow \sqsubseteq \exists hasRole.(Requirement \sqcup Outcome) \tag{5}$$

An ontology for flows has recently been developed and formally specifies the distinctions made above [8].

Requirement and Outcome: Any activity in LCA has required inputs and resulting outputs. These inputs and outputs are formalized as *Requirement* and *Outcome* in our ontology. The provision of *Requirements* and the disposition of *Outcomes* depend on the specific place and time that an activity takes place. Thus, we define *SpatiotemporalRequirement* as a subclass of *Requirement*, and associate it to the *SpatiotemporalScope* using the relation *isAssociatedWith*. Similarly, we define *SpatiotemporalOutcome* as a subclass of *Outcome*, and use *isInfluencedBy* to link it with *SpatiotemporalScope*.

$$\begin{aligned} SpatiotemporalRequirement &\sqsubseteq Requirement && (6)\\ SpatiotemporalOutcome &\sqsubseteq Outcome && (7)\\ SpatiotemporalRequirement &\sqsubseteq \exists isAssociatedWith.SpatiotemporalScope && (8)\\ SpatiotemporalOutcome &\sqsubseteq \exists isInfluencedBy.SpatiotemporalScope && (9) \end{aligned}$$

Domain & Range Restrictions and Class Disjointness: In addition to the above axioms, the pattern also defines a set of *guarded* domain and range restrictions. Specifically, for each object property P pointing from the class A to the class B in Figure 1, we define $\exists P.B \sqsubseteq A$ as the guarded domain restriction and $A \sqsubseteq \forall P.B$ as the guarded range restriction, which also acts as a local closure of P. For example, for $occursAtPlace$ property, we have:

$$\begin{aligned} \exists occursAtPlace.Place &\sqsubseteq SpatioTemporalScope && (10)\\ SpatioTemporalScope &\sqsubseteq \forall occursAtPlace.Place && (11) \end{aligned}$$

Specific for $hasRole$ property, we have:

$$\begin{aligned} \exists hasRole.Requirement \sqcup \exists hasRole.Outcome &\sqsubseteq Flow && (12)\\ Flow &\sqsubseteq \forall hasRole.(Requirement \sqcup Outcome) && (13) \end{aligned}$$

Finally, we assert class disjointness for every pair of classes in Figure 1, except when the pair of classes are connected via rdfs:subClassOf.

4 Use Case

A use case was created by selecting a unit process from the US Life Cycle Inventory database, in this case "Conditioned log, at plywood plant, US SE," [10] depicted in Figure 2. The data set was obtained from OpenLCA software in ILCD format [4, 17]. Conditioning is an intermediate step in the preparation of logs for the production of plywood [16]. The activity's requirements are its input flows: hogfuel biomass, electricity from the grid, heat from the combustion of liquefied petroleum gas (e.g. propane), water, and the debarked wood itself. Its outcome is its sole output flow, the conditioned logs.

The scope of the activity is a plywood plant in the southeastern United States during the year 2000. The mix of process energy reported is an averaged result of several facilities within the scope. To use the data for LCA, each requirement would need to be linked with an exchange partner that produced it as an outcome. Similarly, this activity's outcome could be exchanged with another partner activity that requires the logs as input.

The competency questions presented above can be addressed through the selection of *exchange partners*. A database can be constructed that accepts an activity specification and a spatiotemporal scope and returns a list of exchange partners. The logistical requirements associated with performing the exchange are implicit in the spatiotemporal scopes of the partners. Differences in emissions resulting from the same activity in a different scopes can be inferred through the differences in exchange partners.

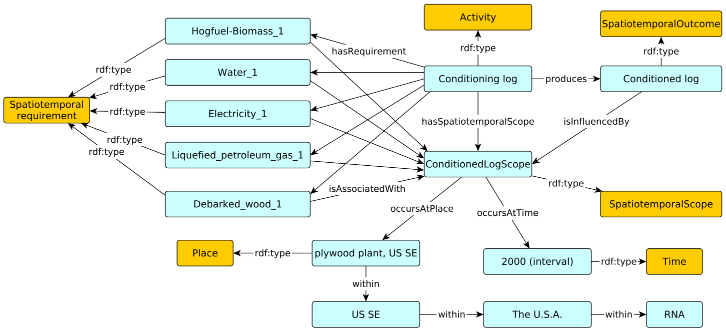

Fig. 2. An example to populate LCA Activity pattern using *Conditioning Log Activity*.

5 Conclusions and Further Work

This paper proposed a compact ontology to capture the spatiotemporal scope of activities referred to in LCA inventory models. The pattern enables key competency questions to be addressed by querying a spatiotemporally-explicit data resource. The pattern can be used as a bridge between sets of activity and flow definitions and spatial modeling ontologies. Future work will focus on integrating this ontology with other LCA ontologies and ontology design patterns (such as [8]) in order to further enhance semantic interoperability in LCA and improve the reproducibility of published LCA studies.

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