Forecasting environmental profiles in the early stages of product development by using an ontological approach

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Abstract

Considering environmental aspects in early product development stages is a complex endeavor. Product life cycle data are fuzzy and subject to changes. Additional workload due to data handling is a common reason why it is withdrawn by engineering designers. Some studies suggest parameterization of products in order to gain a limited set of parameters to handle, some others suggest integration of Life Cycle Assessment into CAD or Product Data Management systems. However, the handling of heterogeneous data from multiple sources is not paid much attention. This paper suggests an ontological approach that allows considering data from multiple sources to set up an environmental profile of the product and allow for adaptations in the product concept.

Keywords: ecodesign, life cycle assessment (LCA), sustainability

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Introduction

The integration of Life Cycle Assessment (LCA) into early stages of product development is an important and efficient way to strive for environmental benign products. However, conducting an LCA in the early design stages is a difficult and complex endeavor: in these early stages, the product is subject to many changes which affect the life cycle of the product and its environmental performance. Later in the development process, more specific data may be available, but the possibility to influence the product decreases; a phenomenon known as the design paradox [1].

Recently, some studies have suggested comparing the environmental performance of a new product being developed with similar products in the market [2]. The so-called Life Cycle Comparison Family (LCP-family) includes products that have similar functional units. Product similarity can therefore be understood as similarity in regard of similar functionalities or similar structures (e.g. similar hierarchy of parts and components, similar platforms, etc…). In this paper, products that fulfill the same or similar requirements are taken to infer the environmental performance of a new product that shares similar requirements.

Design process is already complex, and engineering designers are not necessarily environmental experts. Any approach to integrate LCA into early product development and design stages will fail if it adds to workload or complexity to the process. Engineering designers usually have a good understanding of the product they are developing as well as of the benchmarks and competitors. To implement a methodology for environmental assessment at this phase of data availability, Ostad-Ahmad-Ghorabi and Collado-Ruiz [3] have proposed a methodology that uses only information available and commonly known by engineering designers in the early product development stages; this information is called primary parameters. The methodology asks for technical data, which is usually defined in the list of requirements of the product. This data is then linked to life cycle inventory data to infer environmental performance. This can be compared to similar products, as described above. However, this methodology has been developed for a specific product type, namely cranes. A systematic approach to derive primary parameters is missing.

In this paper, authors are proposing an ontological approach to set up primary parameters systematically for particular product categories. The aim of using an ontological approach is to enable the management and use of heterogeneous data along the product development process [4] [5]. In fact, data defined in the proposition of requirements are taken and processed to set up primary parameters suitable for a specific product category. Further, an ontology can be used to establish a pool of proper products serving as references to compare the environmental performance of the product with as well as to position it within the benchmark.

A case study of hydraulic machines is presented. A proper ontology is developed and suitable primary parameters are derived by considering the requirements of hydraulic machines. A specific product among hydraulic machines serves as case study and with the help of the primary parameters, a forecast for the environmental performance of this product is derived and compared with a suitable benchmark. The paper demonstrates how data from various sources, i.e. data found in the definition of requirements, data considering the functional structure or data from the process structure can be efficiently handled by using the developed ontology approach that links this data with environmental life cycle data and allows for the forecast of an environmental profile and a comparison with similar products. The main goal of the methodology proposed in this paper is to bring together all relevant data for environmental assessment into the early product development stages. At the same time, it is of highest priority to avoid confronting any user with all the detail information and flood of data needed to proceed with a full LCA. However, the assessment shall be representative enough to allow for strategic decisions regarding the preliminary development of the product; may it be the conceptualization of parts and components, material composition, realization of functionalities or else.

State of the art

The start of the product development process is characterized by giving answer what requirements the product has to fulfill. Two types of requirements can be distinguished: general requirement, valid for a product category, and specific requirements, valid for specific products within a category. An example for general requirements is the minimum safety requirements a car has to fulfill in accordance with standards and regulations, e.g. requirements to be fulfilled for frontal-impact test. Specific safety requirements can be defined by a car manufacturer and constitute all additional features (e.g. realization of tiredness sensor for the driver or realization of vehicle-interval radar) which add to safety, but are not demanded by any regulation.
Once requirements are defined, the next step is to think about how the requirements can be realized, which functions have to be realized and what parts and components are needed . Usually, the first approach would be to gather as much information as possible from previous or similar products or to take a deeper look into products from the benchmark. In fact, there are four main source of information that are available and can therefore be handled in the early product development stages:

1. Information that are used to set up requirements
2. Information regarding the realization of functions and processes
3. Information from previous product concepts or variants
4. Information from similar products or benchmarks
5.

Most of the available information is either of general nature or, specific to a product but fuzzy and subject to changes and adaptations.
The aim of conducting an environmental assessment of a product in early product development stages may therefore suffer from insufficient data quality. However, Ostad-Ahmad-Ghorabi and Collado-Ruiz have shown that it is possible to conclude to a reliable environmental profile and assessment results by developing a parametric model of the product. Furthermore it is possible to benchmark the environmental profile by setting up a proper family [2,3,6]. However, some existing shortcomes withdraw the concepts to be practicable for daily

use. Firstly, the parametric model was derived for a specific product and no automated process was used to derive the model. Secondly, the concepts of a parametric model and benchmark family are not linked.
What can be taken as an essential module for the development of an ontological approach is the concept of primary parameters, defined as "…the most important design parameters that are defined in the very early conceptual design stages". Also the concept of secondary parameters, through which data in the LCA inventory can be described, is of important need for the methodology being developed in this paper [3].

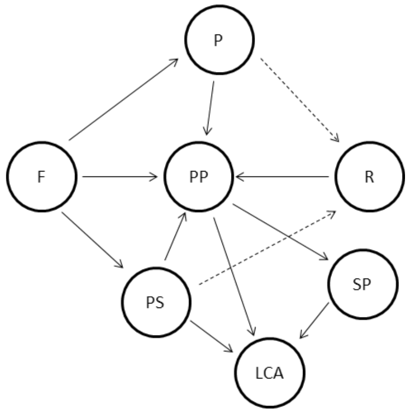
Method and concept

To be able to consider all sources of information, an ontology [7] is developed to enable information handling during early product development stages. In this paper, the method of Noy and McGuinness is used to develop the ontology [8]. Their method premises that the development of an ontology is an iterative approach [9]. Ontology concepts shall consider objects and relations of the domain. Objects are described by nouns and relations by verbs.
According to Noy and McGuiness, seven steps have to be followed to create an ontology:

1. Determining the domain of the ontology: This is done by giving answer to the following questions: What is the ontology going to be used for? What types of questions shall be given answer to by the use of the information contained in the ontology? Who will use and maintain the ontology?
2. Reusing existing ontologies: Existing ontologies may be adapted for the particular domain. Many available ontologies can be accessed through different libraries in the internet, e.g. Ontolingua ontology library [10].
3. Specifying the important terms and listing them: The aim is to create a comprehensive list of terms, without worrying about overlap thoughts. Giving answer to "What are the terms the ontology should talk about?" and "What properties do those terms have?" can help in this endeavor.
4. Defining and creating classes and class hierarchies: They are described using formal (mathematical) descriptions that state precisely the requirements for membership of the class. For example, the class Product would contain all the individuals that are Products in our domain of interest. Classes may be organized into a superclass-subclass hierarchy, which is also known as taxonomy.
5. Determining properties of the classes: To answer the questions defined in step 1, more information is needed, in particular the relation between different items of the class. Formulation such as "has a" or "is part of" can be used. Subclasses inherit all slots from superclasses.
6. Determining the facets of the slots: a slot can have different facets describing: value type, cardinality or permissible values (domain and range). Common value types are: string or number. The slot cardinality defines how many instances a slot can have

7. Creating individual instances in the hierarchy. The approach is as follows: First a class is chosen, second an individual instance for that class is created, and third, the slot values are defined.

Figure 1. Top Level Ontology: R: Requirement, F: Function, P: Process, PS: Product structure, LCA: Life cycle Assessment, PP: Primary Parameter, SP: Secondary Parameter



The ontology serves as a semantic network, which represents and provides information in a structured way [11]. Product functions, product structures and processes are determined by requirements. Product structure refers to information that can be extracted from pervious products and product variants as well as from benchmark products. It implies information about the hierarchical structure of parts and components. Process implies all activities needed to develop a product; including design processes or manufacturing processes. Information processed from the requirements is used to set up primary parameters. Secondary parameters are derived from the LCA model, which can be set up once the product structure, functions and processes are known. LCA inventory data can be assigned to secondary parameters.

Case study and results

The ontology in this paper is developed for hydraulic machines. This product category contains products such as hydraulic cranes, loaders, pumps or similar. The example of knuckle-boom cranes is further detailed. The ontology shall help to retrieve an environmental profile of the product in early design stages.

To fill the ontology sketched in Fig.1, a list of requirements of hydraulic machines was consulted first. For the example of knuckle-boom cranes, the most important requirement is to lift a certain load over a certain length. At the same time, the dead weight of the crane has to be minimized in order to allow for maximum lifting load. To implement the requirements, certain functions have to be realized. To lift a load, cylinders have to be moved; in fact hydraulic oil has to be pumped into the cylinders. This function on the other hand accounts for further requirements, e.g. those regarding the flow rate of the oil pump. Considering product development processes, more interrelations between the parameters occur. Table 1 opment processes, more interrelations between the parameters occur. Table 1 shows an excerpt of the list of requirements, the functions and processes and how they interlink.

Table 1. Requirements, functions and processes for crane

Requirement	ID	Interlinks with
Total weight of crane	R-1	F-1
Maximum lifting moment	R-2	F-1, F-2
Operating time of crane over lifetime	R-3	F-1, f-2
Function		
Lift load	F-1	
Pump oil	F-2	
Rotate main boom	F-3	
Process		
Determine output power	P-1	F-2
Determine specific fuel consumption	P-2	F-1
Determine necessary oil volume	P-3	F-1

The information above shows what is available in the very early design stages. On the one hand, this information can be taken to generate primary and secondary parameters. The result is taken into account when aiming at conducting an environmental evaluation.

For the aforementioned main requirement of the crane, the primary parameter that maps this requirement is Maximum lifting moment, its unit in meter tons (mt). Accordingly, the parameter that is able to map the requirement of minimum dead weight is Maximum weight of crane, its unit in tons (t). The complete list of primary parameters for the requirements listed in Table 1 is retrieved according to the method in described in [3]. An excerpt is listed in Table 2.

Table 2. Primary parameters for a crane

Parameter	Unit
Maximum lifting moment	meter ton
Total weight of crane	Ton
Estimated weight distribution of each component	Ton
Manufacturing site	-
Weight of packaging	Ton
Flow rate of oil	dm^3/sec
Etc…	

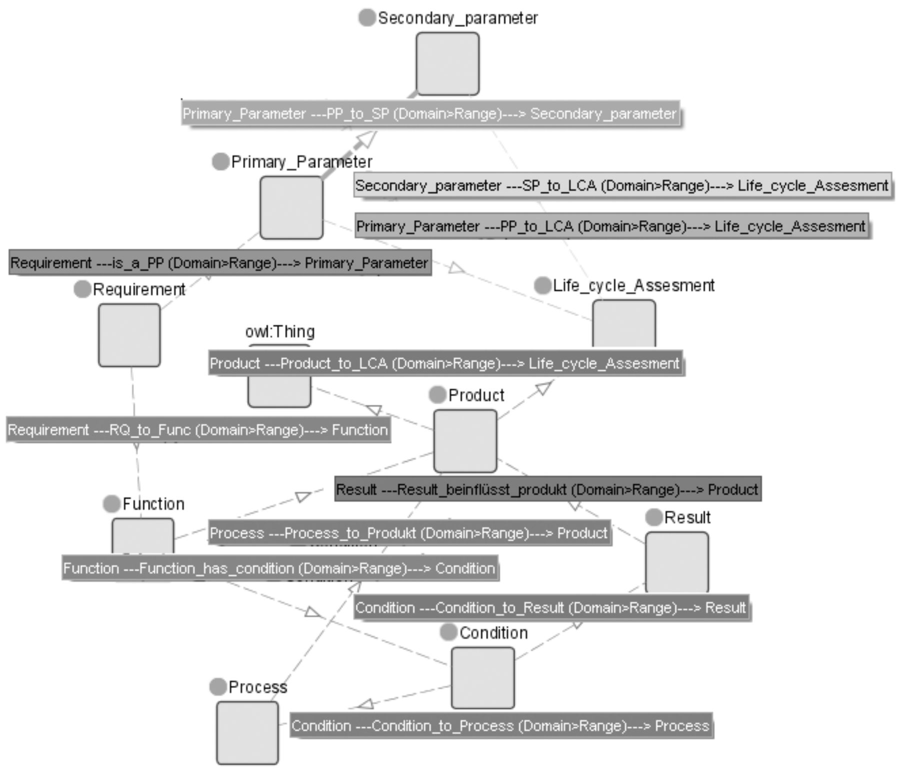
Secondary parameters are derived out of information needed for LCA. This requires the handling of inventory data, usually available through LCA databases. Primary parameters and secondary parameters are linked through either guidelines, physical independencies or statistical data. The latter refers to information from previous product concept and variants or benchmark information.

Information at hand is different in quality and heterogeneous in their sources. To be able to handle the information properly, an ontology is developed by following the seven step approach discussed earlier in the paper:

- Step 1: Domain: Life Cycle Assessment in early stages of product development.
- Step 2: Does not apply to this case study, since there is no ontology available that can be reused, adapted or extended.
- Step 3: Important terms: LCA, Part, Primary Parameters, Environmental Performance, Requirements, Engineering
- Step 4: Classes and class hierarchies: Classes: Function, Condition, Life Cycle Assessment, Primary Parameter, Process, Product, Requirement, Result, Secondary Parameter; Class hierarchies: Relations: e.g. Condition to Process, Function to Product, Process to Product, Requirement to Function etc.
- Step 5: Properties of the product classes: has amount, has ID-number, has Material, is Part of, has Weight, has Version etc.
- Step 6: Determining the facets of the slots: Value types for Life Cycle Assessment class: Potential for global warming indicator, expressed in g-CO2-eq, for all life cycle stages (Raw materials, manufacturing, distribution, use and end of life)
- Step 7: Instances: Product: Crane_20LM

The result is partly shown in Fig. 2.

Figure 2. Protégé [12] screenshot of the ontology) with Protegé Jambalaja Plugin [13]

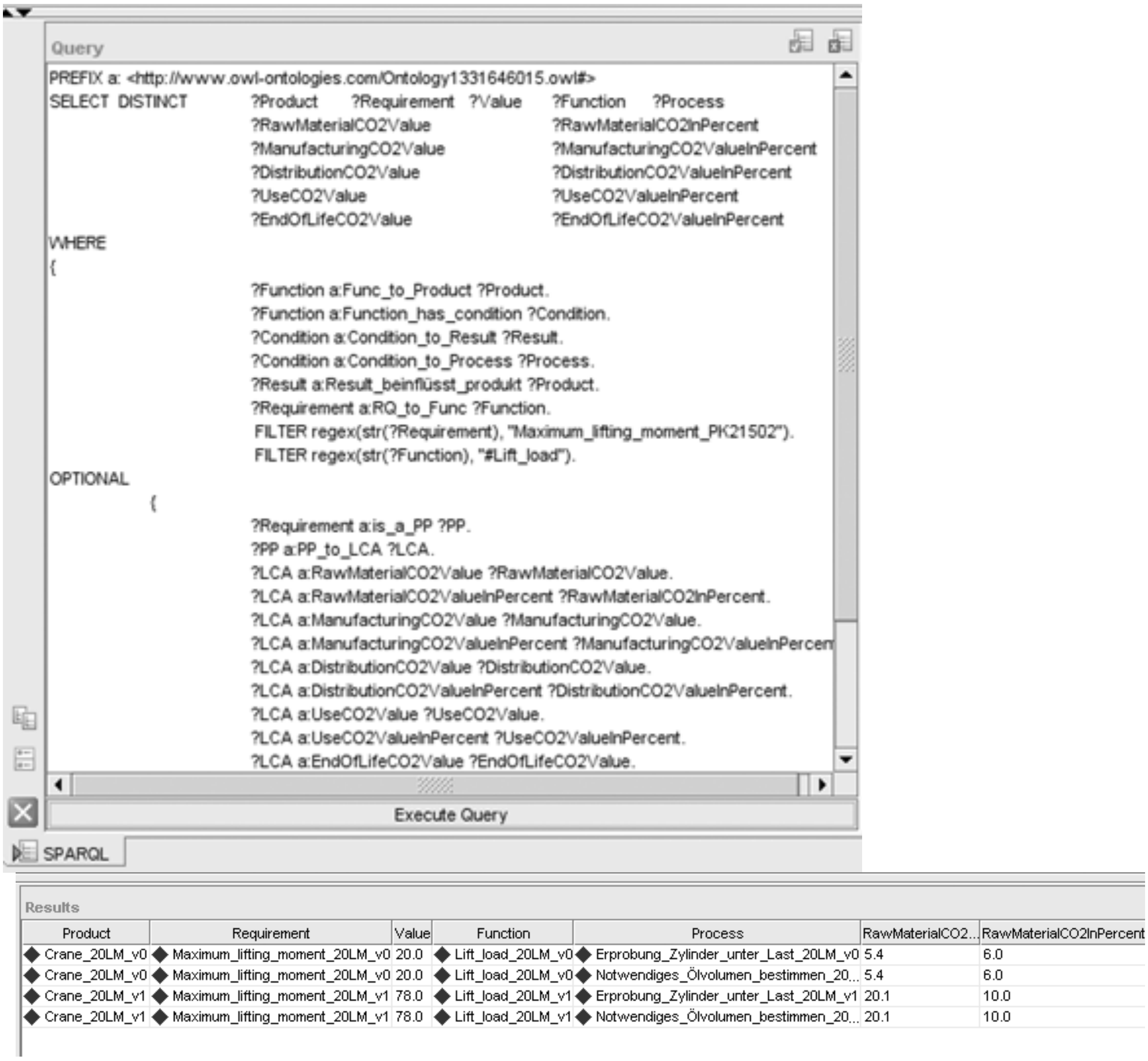


To demonstrate the usage of the ontology, first a reference crane is considered. The reference crane has a maximum lifting moment of 20mt. Since maximum lifting moment is the most important design parameter for a crane, it is assumed that for a new model of the crane, this parameter is changed from 20mt to 78mt. This results in a bigger crane that has to fulfill different requirements, may have additional functionalities or asks for different processes in the development process. All these changes influence the environmental performance of the product.

With the help of the ontology, it is now possible to track how the change in the parameter maximum lifting moment will finally influence the environmental evaluation results.

Using SPARQL [14] as ontology querying language, all information interlinked with the parameter maximum lifting moment will be listed. The query indicates that the primary parameter maximum lifting moment is interlinked with the functions *lift_load, move_cylinder, move out crane, pick_load, transmit_torque, pump_oil or operate_hydraulich_pump*. These functions on the other hand, are linked to processes such as testing cylinder with load, determine oil volume, or determine output power of oil pump. Some of these processes are already linked to LCA inventory data, for example oil volume is linked to LCA inventory data of oil, and CO2 value for oil can directly be linked to its volume.

Figure 3. SPARQL query [15] and results



The results further indicate that 89% of the total environmental impacts of the crane occur in its use phase. The impact sin the use stage are dominated by the fuel consumption for crane operation. Improvements can be achieved by installing affective oil pumping systems (e.g. variable displacement pumps rather than fixed ones) or thinking of alternative power supply for the crane (e.g. electric power supply on construction sites and whenever possible). The impacts in the other life cycle stages are negligible compared to the use phase (materials 6%, manufacturing 7%, distribution negligible, end of life -2%, due to recycling processes).

Summary

In the early stages of product development a mixture of qualitative and quantitative data is available. This data can be taken to forecast the environmental profile of the product. To avoid additional workload for engineering designers for handling data and providing relevant data at any step of the product development process, it is important to extract as much information automatically as possible. The interrelations of information from different sources are an important aspect in this process. The ontology described in this paper shows how different data found in the list of requirements, in the qualitative description of functions and processes can be interlinked. The SPARQL query provides a platform where the query asks for the relevant information and where the user can input as much information as is known at a particular time. The ontology links the data with primary and secondary parameters; the latter itself is linked to LCA inventory data. The LCA inventory data can then be used to set up o first environmental profile of the product.

In future research steps, more ontologies will be developed for the same purpose for different product types. The aim is to provide suitable ontology elements for as many product types and categories as possible.

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