An Ontological Approach for the Integration of Life Cycle Assessment into Product Data Management Systems

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Abstract

The consideration of environmental aspects into product design is becoming more and more a key strategic feature of products. However, the inclusion of Life Cycle Assessment (LCA) and Ecodesign aspects in design is still far from being common practice. The complexity of the task, time-consumption and additional workload during design process may be some reasons therefore. There have been some efforts to integrate LCA in CAD systems and Product Data Management systems (PDM) to ease the handling of data and to assist the designer. However, these concepts suffer from inflexible data and database structures which are difficult to maintain and to update, in particular when complex products are designed in collaborative teams. This paper presents an ontological approach to include environmental data in PDM systems. This approach reduces complexity of data structures, eases the use of environmental assessment methods and eases the sharing of product relevant information.

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1. Introduction

PDM systems have become widely established in industry, in particular, when complex products have to be designed and design collaboration between different parties is required. To educate technically skilled employees for industry, technical and vocational schools play an important role in the Austrian market. To advance collaborative design projects among technical and vocational schools, Vienna University of Technology has created and maintains a PDM platform (within a project funded by Austrian federal government) [1]. This platform has been adapted to the specific needs of the technical schools to guarantee a smooth integration into the educational process of design. In a follow up project, the aspect of sustainable product development is further elaborated with the particular aim to integrate environmental considerations into the design education process and to raise an additional value of the established PDM platform.

To proceed in the improvement of the environmental performance of a product, it is necessary to evaluate its environmental performance first. This is however, a complex task, as it involves the handling of a huge amount of data, provoking additional workload in the design process. Design education is already complex; including environmental consideration will make it even more complex. To integrate environmental considerations into the design process, Life Cycle Inventory Data (LCI) is added to the PDM system. This allows the students to focus on the environmental aspects of their design and to reduce the environmental impacts of their design over its entire life cycle. This enhanced PDM solution enables the technical schools to collaborate in design and to evaluate their design as to its environmental impacts. As a proof of concept, four different technical schools jointly designed an environmentally improved cordless drill driver. To ease the process of environmental evaluation, parameters needed for the evaluation are either retrieved from CAD files or manually defined in the PDM system. By using a reporting tool, data is linked to environmental impact indicators to calculate the occurring environmental impacts of a part, a component or a whole assembly. In order to improve the performance of the system, to reduce complexity, to be able to manage data structures, to repeat routines and to further ease the application of environmental evaluation methods, we propose an ontological approach. This paper discusses how ontology was derived in the project and how it was linked to the CAD file structure in the PDM system and the environmental parameters.

2. State of the art

The consideration of environmental aspects is becoming a key issue aspect in product development and product design. Many tools have been developed that help to track and evaluate the environmental impacts of a product over its entire life cycle. In any of the methods for reducing the environmental impacts of a product referred to as Ecodesign, Green Design, Design for Environment (DfE), Life Cycle Design (LCD) or Design for Sustainability (DfS), environmental information is necessary to start the environmental evaluation process. Life Cycle Assessment (LCA) is the most widespread assessment method for this purpose [2-3]. However, there are some barriers that withhold LCA from being a common practice in industry, mainly because of data requirements [4], time-consumption or complexity. LCA requires much data that is constantly changing in the product development process, in particular in the early design stages. The early design stages would allow for the most efficient changes in the design, as they have the greatest potential for any improvement. But data in this stage may be unknown or fuzzy. Later in the development process, more data is available, but the potential for improvement is not so high, a phenomenon commonly known as the "design paradox". Databases such as the Ecoinvent database [5] shorten the time to gain first results of the environmental profile of a product. Ostad-Ahmad-Ghorabi et al. [6] parameterizes the product to extrapolate results for products that have similar features. Some other tools combine environmental databases with quick assessment tools, such as the Ecoindicator [7] or the tool Greenfly Online [8].

There have been some efforts to bring LCA into CAD systems [9]. Most of these approaches suffer from the lack of information in these early design stages. Furthermore, a CAD system is not the major source to gain comprehensive information about product structures and part information. Within the development process, more than one single CAD system may be used and products may contain more items than commonly modeled within CAD. Some approaches try to reduce the amount of parameters that have to be dealt with and try to deliver a good approximation of the pretended environmental impacts. Ostad-Ahmad-Ghorabi and Collado-Ruiz [10] developed a generic model to parameterize the LCA process out of parameters that are known during the initial definition of a product, specifically shown for knuckle-boom cranes. The parametric approach for knuckle-boom cranes enables the inclusion of LCA in early design stages. However, the development of the approach was faced with some drawbacks: first, the approach is much product specific. Second, the database used is difficult to maintain and to update. Third, the generic model cannot be easily transferred to another product. To face these problems, an ontological approach is proposed in this paper.

By using ontology, a common understanding of different information structures can be achieved, knowledge can be reused and analyzed and general assumptions about a certain field of knowledge can be made [11]. Further, heterogeneous data can be integrated into ontology, which enables complex, semantic database queries. An ontology can therefore be regarded as an interface between databases and their environment.

Ontologies can be developed by using suitable software applications. The tool used in this project is Protégé. It allows the definition of classes and instances, interrelations can be defined and logical rules can be set [12]. Protégé can be used with any operating system.

3. Method

To develop an ontology to be integrated into a PDM system, the METHONTOLGY approach, first developed by Fernandez et al. [13], was followed. The framework enables the development of ontologies at knowledge level. The method includes the identification of the ontology development process, a life cycle based on evolving prototypes, and particular techniques to carry out each activity [14]. The ontology life cycle considers the order in which the activities of the ontology development process should be performed. The METHONTOLOGY approach proposes the evolvement of prototypes for the development of ontologies. For the prototype, terms can be added, changed and removed throughout the evolution of the ontology.

The first step in the method is to define the specifications for the prototype. In parallel, knowledge acquisition is conducted. Once the first prototype has been specified, the construction of the conceptual model is built at the conceptualization phase. Then, the conceptualization, formalization and implementation of the knowledge are carried out. If some lack is detected in the ontology, the specification can be modified.

For the prototype in this paper, the components of the ontology were developed by using the described METHONTOLOGY approach. Protégé is used to develop the ontolgy. The ontology is represented by using Web Ontology Language (OWL).

To proceed with Life Cycle Assessment, the basic approach would be to add environmental data to the CAD files stored in the PDM system. Some of these data can be derived from the CAD system; some have to be defined manually in the PDM interface. The additional data would then be stored somewhere in the databases of the system, which then can be accessed to retrieve an environmental profile.

For the case study of the gearbox, which is discussed in this paper, the complexity of the conventional approach would already grow considerably since it consists of several parts and components, Although having a model at hand, the maintenance and update of this model is a time-consuming task; any change in the original data structure will require the establishment of a new, adapted model.

4. Development of a prototype

To develop the ontology, a two-stage gearbox was taken as a case study. This gearbox has been designed by one of the cooperating vocational schools and is composed of several parts and components. The CAD files were stored in the PDM system.

To overcome the aforementioned obstacles, an ontology is developed for the gearbox, using the METHONTOLOGY approach and Protégé V3.2. The Protégé interface contains a series of Tabs that allow for the ontology to be applied to different areas. The OWLViz Tab, included as a plug-in in Protégé, enables the class hierarchies in an OWL Ontology to be viewed and incrementally navigated, allowing comparison of the asserted class hierarchy and the inferred class hierarchy.

To include Life Cycle Assessment into the ontology, classes (concepts) were defined to be: *Life Cycle* (in order to assign life cycle stages to it), *General Information* (including all design parameters which can not be assigned directly to a particular life cycle of the gearbox), *Materials*, *Manufacture*, *Distribution*, *Use*, *End of Life*. Relations were defined by using terminologies such as: "*consists of*", "*is used for determination*", "*determined by*", *"has effect on calculation"*, *"has action"*, *"influences"* or *"effected by"*. For example, the class Life Cycle *consists of* subclass Materials. Materials *has an action on* the design parameter Quality of Gear Stage (wheel and gear). Quality of Gear Stage *is effected by* Material Selection. Material Selection *has an effect* on Permissible Hertzian Stress which together with the Required Safety Factor *has an effect on calculation* of Existing Hertzian Stress. The Existing Hertzian Stress *is used for the determination* of the Module, which *is used for the determination of* the Dimension (of wheel and gear). Dimensions *influences* Weight. Weight in combination with the selected material can be directly linked to environmental data containing environmental indicator values for materials. This will already allow for the evaluation of the life cycle materials of the wheel and the gear.

The same logic is followed for all design parameters of the gearbox to retrieve those parameters, which according to the definition by Ostad-Ahmad-Ghorabi and Collado-Ruiz [10], are primary parameters. These are parameters that can be defined in the very early conceptual design stages and have a considerable influence on the environmental performance of the product. These parameters are shown in Table 1 for the case study of the gearbox.

Table 1.- Primary parameters for the gearbox and their influence on other parameters in accordance to definition in [38]

Life Cycle	Primary parameter	Has a link to/ influences
General	Input power	E.g. Torque & weight of gear, weight of wheel, total weight of gearbox, etc…
	Revolution per minute input	E.g. Module
	Revolution per minute output	E.g. Forces on shaft
	Impact coefficient	E.g. Module
	Dynamic factor	E.g. Existing safety factor for wheel/ gear
Materials	Quality of gear stage	E.g. Total weight of gearbox, Module, material selection, power dissipation, forces on shaft…
	Safety factor	E.g. Module
Manufacturing	Manufacturing sites	E.g. Consumption of resources for manufacturing, transportation distance, etc…
Distribution	Type and weight of packaging	E.g. Total weight of component for distribution
	Transportation mode and distance	
Use	Amount of oil	E.g. Dimensions and total weight of gearbox,
End of Life	End of life processes	E.g. Resource consumption for end of life treatment

Part of the final ontology is shown in Figure 1.

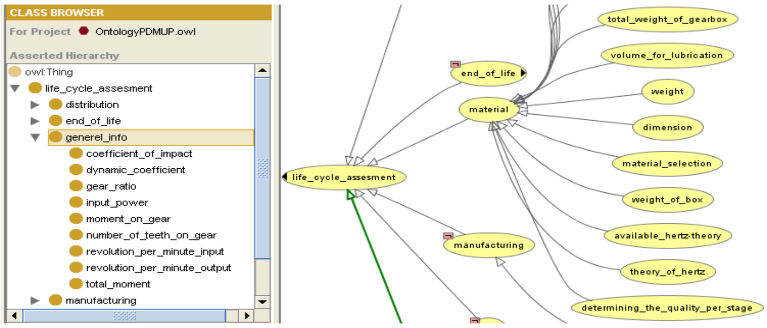

Figure 1 Screenshot of part of the ontology derived with OWLViz plug-in

5. Conclusion and outlook

With the ontology derived in this paper, environmental data can be integrated in early design stages and LCA is enabled. Design parameters can be retrieved from PDM systems and be interlinked with environmental indicators.

The ontology, however, has to be considered as a prototype with the intention to interlink technical design parameters known in early design stages with environmental data to establish an environmental profile of the product. Any change of a particular design parameter can easily be tracked as to its influence on the environmental profile. Of course, there are other approaches that may facilitate a similar output. The outcomes of this paper can be understood as an intermediate step in a long-term research project. Although the ontology developed in this paper is still specific to a particular product, it allows bringing together design and environmental considerations in a systematic way. To us, this approach is considered to be an efficient one that brings LCA and PDM together in a user and administrator-friendly way.

The systematic approach will be used in our next research step to retrieve standardized ontology elements that can be merged together based on the characteristics of the product being analyzed. Collado-Ruiz and Ostad-Ahmad-Ghorabi have come up with definitions of similar or equivalent products in the scope of their LCP families [15]. In particular, they introduce a systematic approach to compare the environmental performances of products within the same family. A premise for their work is to have LCA results at hand, which may require an additional process of environmental evaluation. With the help of standardized ontology elements together with the LCP family approach, ontologies may be set up for similar products in a systematic and automatic way and environmental impacts of each life cycle stage of the product can be calculated out of this process.

This paper showed that LCA and PDM can be brought together by using an ontological approach. Data from a PDM system was retrieved and different CAD systems were handled. The complexity of data structures was considerably reduced in comparison to conventional database relations. Also, it was able to visualize results in a convenient way. All these aspects are important when it comes to successful implementation of environmental considerations in early design stages. Next steps in the research line include mapping of data in the PDM system with the ontology derived. This will help to derive a final list of independent and general (not product-specific) parameters and probably to optimize the amount of parameters involved. Further, the concept has to be optimized in order to allow starting the environmental evaluation process at any point in the ontology. The ontology shall automatically ask for all necessary information to calculate the environmental profile and give feedback to the engineering designer. Also, the acceptance of LCA with PDM systems in design education and also from an industrial point of view needs to be elaborated.

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