AN ONTOLOGY-BASED APPROACH TO INTEGRATING LIFE CYCLE ANALYSIS AND COMPUTER AIDED DESIGN

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Abstract

One of the principal problems faced by engineering design today is the exchange of product information across different applications and environments. Ontological engineering systems, an evolution of KBE (Knowledge-Based Engineering) systems, seek to facilitate this integration while incorporating additional design information. An ontology, in the engineering domain, can be defined as an explicit specification of a shared conceptualization. **This paper proposes the integration of an ontology with a Computer Aided Design (CAD) program, while also accessing a database of information on environmental impact.** The proposed ontology is based on the AsD (Assembly Design) formalism, which describes spatial relationships and features of CAD models. The use of OWL (Web Ontology Language) and SWRL (Semantic Web Rule Language) ensures machine interpretability and exchange across different environments. **Ultimately, the ontology will be used to represent a CAD model and related information (such as joining methods, materials, tolerances) in formal terms.** Concurrently, a database of information on environmental impact of the materials, processes and transport involved will be accessed to evaluate the model on an environmental level. As a practical illustration, the evaluation of an underwater camera is used as an example.

Keywords: ontology, Knowledge Based Engineering, environmental, Computer Aided Design

1. Introduction

Effective collaboration and information sharing is essential across the various stages of product development. The increasing use of Computer Aided Design (CAD) systems serves as a great aid to this process, however, communication between programs is often difficult if not impossible. This is mainly due the use of proprietary formats and a lack of true integration across different platforms. A parallel issue in the design field is the growing importance given to environmental concerns and impacts generated by products. Both private initiatives and government regulations are placing a great emphasis on reducing contamination and the use of resources.

This paper proposes a method that, with the aid of an ontology, communicates a three-dimensional CAD model of a product with information related to environmental impact data. In the first section, a general background is given of the terms and concepts that the paper is based on. The following section provides a detailed explanation of the proposed method and each of its constituents. In section 4, the results of a practical application of the method itself are given, followed by a section of discussions and conclusions.

2. Background

2.1. KBE Systems and ontologies

The nature of product design as an inherently collaborative process and the increased dependency on computer systems have placed great emphasis on the importance of effective information sharing between designers. As a solution to this need, Knowledge

Based Engineering systems have been created in order to correctly capture, represent and structure product-related information. These systems seek to facilitate the exchange and reuse of design know-how, going beyond the limits of a CAD system to include design intent, objectives and specifications, in addition to geometric models [1]. However, many of these systems lack the ability to efficiently utilize the knowledge itself, and are rarely more than just elaborate information bases. As the successor to knowledge engineering, Ontological engineering seeks to overcome the aforementioned deficiencies by providing methodologies that allow for more effective knowledge use [2].

The definition of an ontology can vary according to the field in which it is applied. Within the engineering and knowledge-sharing disciplines, an ontology can be described as a formal, explicit specification of a conceptualization shared by an agent or group of agents [3]. That is, an ontology facilitates knowledge sharing and reuse by establishing an explicit agreement of objects and relationships within a specific domain of discourse [4]. The use of the term *formal* implies that the ontology is machine-readable, but without being too cryptic for human understanding [3]. By establishing a common language for use and interpretation of information, ontologies allow for efficient and organized exchange and reuse of knowledge.

Within the engineering design domain, one can distinguish between *task* and *domain* ontologies. The first refers to ontologies related to design activities themselves, while the latter deal with the targets of the design process, whether products or manufacturing processes [2].

2.1. Computer Aided Design

From the point of view of knowledge engineering, Computer Aided Design systems provide a basis for representing and sharing a large amount of information related to a products and their components. Within a three-dimensional model, data such as geometry, dimensions, relations, structure and other information can be stored. Current CAD programs are being developed to increasingly include more product-related data, such as CATIA PLM Express or DriveWorks for SolidWorks. These modules allow for product models to contain additional information such as configurations, rules, analysis and cost. However, no true integration of knowledge engineering and CAD has yet been achieved [5]. The use of a CAD model as the core of a knowledge management system allows abstract information to be directly related to the product itself, making use of the system much more visual and effective.

2.3. Environmental impact assessment

Another area that is currently of great interest within the engineering design community, and the world at large, is the environmental impact created by products and processes. Environmental criteria are being increasingly integrated into the design process at earlier phases, along with the development of strategies for end of life management. Taking these criteria into consideration at earlier stages in the design process reduces the need to make costly changes at a later stage. While some of these changes can refer to material use, processes and transport, others may relate to the geometry of the product itself.

One method for evaluating the environmental impact of a product is Life Cycle Assessment (LCA) which assesses the impact generated by the product throughout the various stages of its life cycle [6]. This process consists of four main stages: definition of goal and scope, inventory analysis, impact assessment and interpretation [7]. In order to carry out an LCA it is necessary to define, among other things, the material and process flows that occur during the life cycle of the product. For example, for a product that can be broken down into components, the amount of material used for each component and the process used to manufacture it must be defined. The impact is then calculated for each step of the product’s life: obtaining the raw material, intermediate and final processes, disposal, and so on.

Several existing software tools, which incorporate large material and process databases, can be used to facilitate carrying out an LCA [6]. Even though many assumptions and estimations are made, these tools help give a general idea of the main sources of impact generated by a product and at which stage they occur. An LCA software tool of extended use is SimaPro, developed by PRé Consultants. SimaPro contains a variety of databases and methods for impact assessment, such as Eco-indicator 95 and EPS 2000.

At the present time, several tools exist to directly evaluate a product design from an environmental perspective using different methods, among which is the LCA. These tools include Green Design Advisor [8], ECoDe [9], LASeR [10], DFD/E [11], and RecyKon [12]. These analytical tools exist as stand-alone programs. That is, much like most of the software used by product designers, they only deal with the evaluation itself and do not offer integration with other environments or programs. Not only is it necessary to develop an automatic and efficient way to evaluate a product from an environmental perspective, it is fundamental to be able to integrate this method with other areas of product design.

3. Methods

3.1 CAD model

The first step of the proposed method consists of creating a three-dimensional model of each part of the product that will be evaluated. It is fundamental to create models that precisely represent each component, given that they will later be used for evaluation. For this step, the authors have used SolidWorks 3D CAD software. Once each part is modeled, sub-assemblies and an assembly of the entire product are created. Within each part file, a material is specified and its properties (such as density, conductivity, Poisson's ratio, etc.) are applied to the part. In SolidWorks, materials can be chosen either from the standard database or a user-defined set of materials. Upon completion of this stage, an accurate representation of the product geometry and material is obtained.

3.2 Environmental impact assessment data

As previously mentioned, SimaPro software is a tool to assist in carrying out Life Cycle Analysis. For this work, the Eco-Indicator 95, a versatile and comprehensive method, was applied. Eco-95, developed by PRé Consultants for the Dutch government, groups impacts into three categories: human health, ecosystem health and resources [6]. Single score results are given in Eco-Indicator points (Pt) where 1Pt is representative of one thousandth of the yearly environmental load of one average European inhabitant [13]. In order to analyze the impact of a material or process, an amount must be specified, such as mass, surface area or length. At this phase of the method, only an analysis based on mass is carried out. For each unit of mass, the material required and the relevant manufacturing process is analyzed. In order to do so, a separate impact assessment of one kilogram of each of the materials specified in SolidWorks was completed. Single Score results are used, in order to facilitate comparison between different parts and materials. As a result, the outcome of the LCA of each material is exported to an Excel spreadsheet.

Impact evaluation macro

At the present time, the link established between the CAD model and the results of the LCA is carried out by a macro developed in Microsoft Excel. This software was chosen because of the possibility of creating a macro that could easily be executed by a user with little or no knowledge of either CAD or LCA. The macro was written in Visual Basic, a language supported by the SolidWorks Application Programming Interface (API). In the Excel file that contains the macro are two buttons that execute different commands when selected by the user. The button labeled “Get Component Properties” lists the components of the CAD assembly model, the material assigned to each one and its mass in kilograms. If no mass property is available for a component, the returned value is "-". The command button labeled "Evaluate Component Impact" calculates the environmental impact of each component and returns a numeric value in Pt. In the case of a sub-assembly within an assembly, a nil value is returned. This calculation is based on the LCA data previously exported from SimaPro for each material. The result of this simple and automated step is a concise evaluation of the impact generated by each component, giving the designer a clear picture of the product's environmental impact.

3.3. The ontology

An ontology consists of three main elements: classes, properties and individuals. The ontology developed for this work is based on the program Protégé 3.2 and is represented using OWL (Web Ontology Language). As part of the Semantic Web, the use of OWL as a common vocabulary for ontology representation ensures data sharing and re-use across different environments [14, 15]. In order to develop the OWL code in a more intuitive way, the aforementioned program is divided according to the classification of an OWL ontology. Afterwards, the tools employed will also be explained.

Classes:

OWL classes are interpreted as sets that contain individuals. They are described using formal (mathematical) descriptions that state precisely the requirements for membership of the class. The structure of the ontology, based on the Assembly Design (AsD) ontology [16], consists of the following classes. Each class is defined by the indicated properties:

Structure: Elements with a spatial location and a degree of topological connection between them. This class defines the physical elements that constitute a design.

Assembly: Elements that are a part of the structure of an object and consist of at least 2 parts.

Part: Elements that are part of the structure and may have a topological connection with other parts in order to form an assembly.

Material: This class indicates the materials of which parts of a structure may be made. It is essentially related to data properties, in order to completely define physical properties.

Topological Connectness*:* This class is based on the spatial relationships originally put forward in 1975 by Ambler and Popplestone [17]. It indicates the type of connection that exists between two parts and is subdivided in the following classes:

- Against: the mating surfaces touch at some point. This relationship is the most basic spatial relationship and applies to any assembly. Any combination of two parts can possess this property.
- Aligned: two features are aligned if their centerlines are collinear.
- IncludeAngle: the inclination relation holds for an include angle between two planar faces in their positive normal direction. The rotation is clockwise with respect to a normal of a picking face. The rotational axis has to be parallel to the normals of above two planar faces.
- ParallelOffset: the parallel relation holds between planar faces, cylindrical and spherical features. In the case of two parallel planar faces, the outward normals are pointing in the same direction. This relationship exists without physical contact of two features with an offset distance.

- ParaxOffset: this relationship is similar to parallel-offset but the outward normals of the parallel planar faces are in opposite directions.

<u>Properties:</u>

Properties are binary relations on individuals - i.e. properties link two individuals together.

Object Properties:

These properties essentially exist in order to establish the necessary logical rules between elements of a structure. The types are: has_Spatial_Location; isPartof; isAssembledBy; and hasMaterial.

Datatype Properties:

The properties that are applicable to classes can be divided into the following two areas:

- Physical properties, which are applied to the structure area. This information is obtained from the macro that links SolidWorks to a spreadsheet. For example: density.
- Environmental impact of the materials, applied to the information extracted from SimaPro.

The Protégé interface contains a series of Tabs that allow for the ontology to be applied to different areas. Below is a brief explanation of the Tabs that have been applied in order to develop this work:

<u>DataMaster Tab</u> – DataMaster is a Protégé plug-in for importing schema structure and data from relational databases into Protégé [18]. It allows for information from the macro to be linked to the ontology.

<u>TGViz Tab</u> – TGViz Tab is a plug-in for Protégé which allows visualizing ontologies using the TouchGraph library. TouchGraph provides a java library for rendering networks as interactive graphs. This library has been modified and integrated with Protégé as a tab plug-in [19]. It allows for the different relations that exist between components of an object to be defined.

<u>OWLViz Tab</u> – OWLViz is designed to be used with the Protégé OWL plug-in. It 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. OWLViz integrates with the Protégé-OWL plug-in, using the same color scheme so that primitive and defined classes can be distinguished, computed changes to the class hierarchy may be clearly seen, and inconsistent concepts are highlighted in red. OWLViz has the facility to save both the asserted and inferred views of the class hierarchy to various concrete graphics formats including png, jpeg and svg [20].

Individuals

Individuals represent objects in the domain that we are interested in. Individuals are also known as instances. Individuals can be referred to as being ‘instances of classes’. In each of the previously mentioned classes, the relevant instances are represented in order to organize the available knowledge.

The ontology allows for the available knowledge to be organized according to the information provided by the macro, and makes it possible to infer new knowledge and search the existing one. This capability is provided for by the use of the Semantic Web Rule Language (SWRL). In this way, the ontology achieves the integration of the structural information and the environmental impact data.

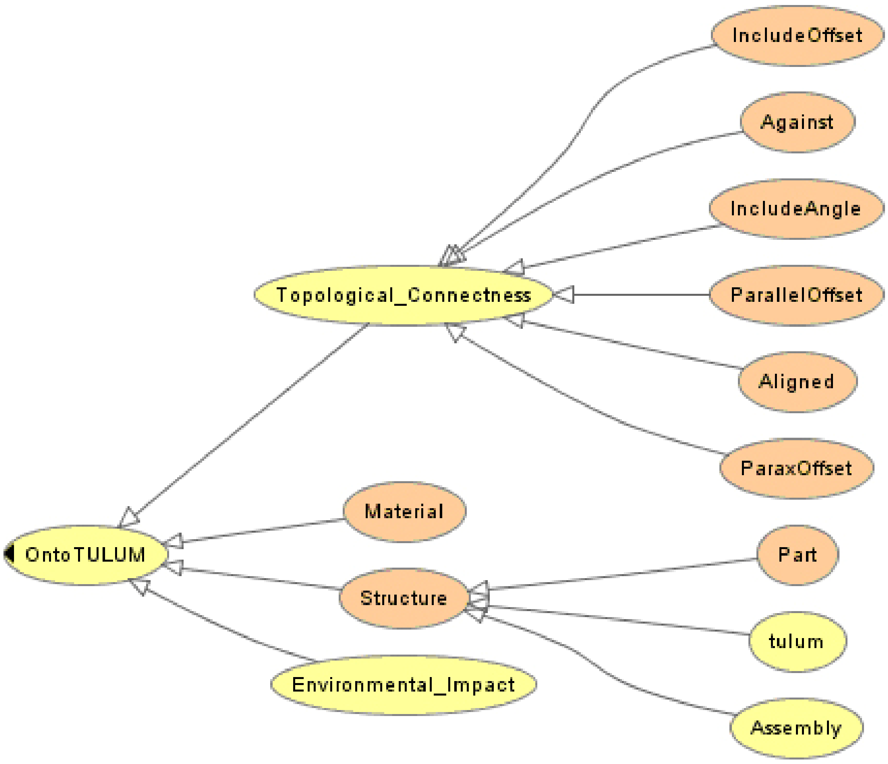


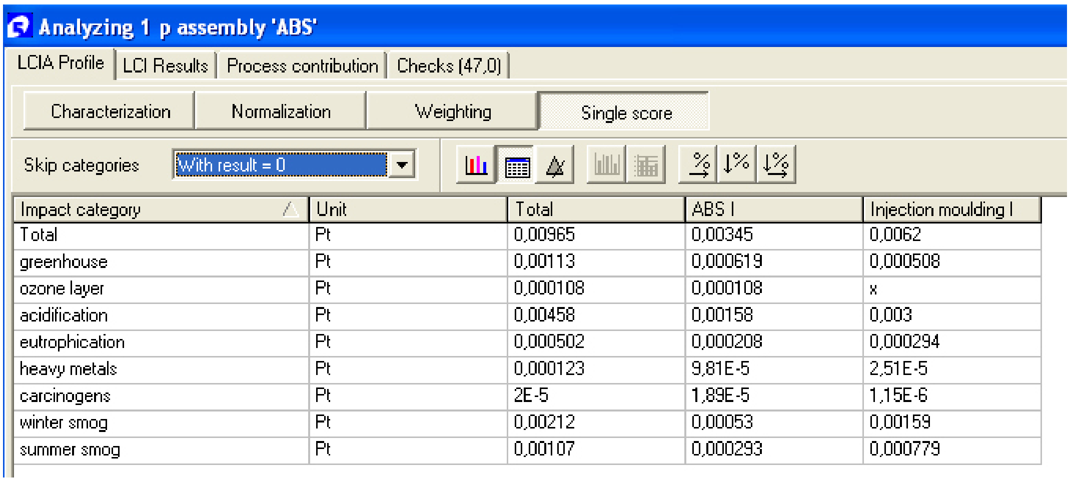
Figure 1. The ontology

4. Practical application and results

In order to illustrate the proposed method, the previously described steps have been applied to an assembly of an underwater camera. This particular assembly consists of 9 parts manufactured with different materials and processes, and held together by standard fasteners. An image of the three-dimensional model of the assembly is shown below. A new database of materials was created in SolidWorks, containing ABS, Spring Steel, Cast Stainless Steel and Aluminum 6061 Alloy. Within each part file, a material was selected from this database.

Figure 2. CAD model of underwater camera assembly

The next step is to carry out an LCA of each of the above materials (and their relevant manufacturing processes) in SimaPro and export the results to an Excel spreadsheet. Below is an example of the results of analyzing one kilogram of ABS with the Eco-Indicator 95 method.



Impact category	Unit	Total	ABS I	Injection moulding I
Total	Pt	0,00965	0,00345	0,0062
greenhouse	Pt	0,00113	0,000619	0,000508
ozone layer	Pt	0,000108	0,000108	x
acidification	Pt	0,00458	0,00158	0,003
eutrophication	Pt	0,000502	0,000208	0,000294
heavy metals	Pt	0,000123	9,81E-5	2,51E-5
carcinogens	Pt	2E-5	1,89E-5	1,15E-6
winter smog	Pt	0,00212	0,00053	0,00159
summer smog	Pt	0,00107	0,000293	0,000779

Figure 3. Screenshot of LCA of ABS

Once the CAD model and LCA are completed, the first part of the macro is executed in order to obtain the mass properties for each component of the assembly. Next, the second command button is selected, and the environmental impact of each component is obtained.

	A	B	C	D	E	F	G	H
1	Level	Component Name	Mass in kg	Material	Impact			
2	1		?					
3	2	Static brake assembly-1	0,232705247	-	-			
4	3	Static brake assembly-1/M3x20 flat head-1	0,00120703	X10Cr13 (mart 410)	1,07433E-05			
5	3	Static brake assembly-1/Spring 5mm-2	0,167443985	50CrV4	0,002045831			
6	3	Static brake assembly-1/Static cogged brake-3	0,064054233	ABS I	0,001236439			
7	2	Camera housing assembly-1	0,376119949	-	-			
8	3	Camera housing assembly-1/Cogged housing right-1	0,062633518	ABS I	0,001209015			
9	3	Camera housing assembly-1/Accessory holder-1	0,039339876	ABS I	0,000759378			
10	3	Camera housing assembly-1/TV camera-1	0,126442902	6061 Alloy	0,009624695			
11	3	Camera housing assembly-1/Tightening screw assembly-2	0,038305469	-	-			
12	4	Camera housing assembly-1/Tightening screw assembly-2/Tightening sc	0,017634202	ABS I	0,000340393			
13	4	Camera housing assembly-1/Tightening screw assembly-2/Tightening sc	0,020671268	X10Cr13 (mart 410)	0,000183986			
14	3	Camera housing assembly-1/Cogged brake-2	0,010094577	ABS I	0,000194856			
15	3	Camera housing assembly-1/Cogged housing left-1	0,063344923	ABS I	0,001222747			
16	3	Camera housing assembly-1/Cogged brake-1	0,010094577	ABS I	0,000194856			
17	3	Camera housing assembly-1/M4x20-1	0,002553453	X10Cr13 (mart 410)	2,27272E-05			
18	3	Camera housing assembly-1/M4x16-2	0,002166409	X10Cr13 (mart 410)	1,92823E-05			
19	3	Camera housing assembly-1/M4x16-1	0,002166409	X10Cr13 (mart 410)	1,92823E-05			
20	3	Camera housing assembly-1/M4x54-1	0,005843329	X10Cr13 (mart 410)	5,20091E-05			
21	3	Camera housing assembly-1/M4x54-2	0,005843329	X10Cr13 (mart 410)	5,20091E-05			
22	3	Camera housing assembly-1/Nut 7mm-4	0,00081697	X10Cr13 (mart 410)	7,27151E-06			
23	3	Camera housing assembly-1/Nut 7mm-3	0,00081697	X10Cr13 (mart 410)	7,27151E-06			
24	3	Camera housing assembly-1/Nut 7mm-2	0,00081697	X10Cr13 (mart 410)	7,27151E-06			
25	3	Camera housing assembly-1/Nut 7mm-1	0,00081697	X10Cr13 (mart 410)	7,27151E-06			
26	3	Camera housing assembly-1/Nut 13mm-1	0,004983769	X10Cr13 (mart 410)	4,43585E-05			
27	3	Camera housing assembly-1/Nut 7mm-5	0,00081697	X10Cr13 (mart 410)	7,27151E-06			
28								
29								
30								

Get Component Properties

Evaluate Component Impact

Figure 4. Excel spreadsheet of assembly

The final result is a clearly visible analysis of the environmental impact generated by the assembly. Due to the fact that each component is analyzed separately, the designer is able to clearly identify which component has a greater impact in relation to its mass. In this case, it is evident that the component “TV Camera” generates the greatest environmental impact. If changes are made to the assembly, the macro is newly executed and any improvements in the impact are instantly visible.

Once all of the available information has been gathered, it is incorporated into the ontology. As a result, the existing relations between the components are specified in the terms used by the ontology, and the information related to each component is displayed. The figure below is a part of the graphic representation of the ontology as applied to the camera assembly (the entire image is too large). By structuring the available knowledge in an ontology, it is now possible to carry out searches or even infer new knowledge.

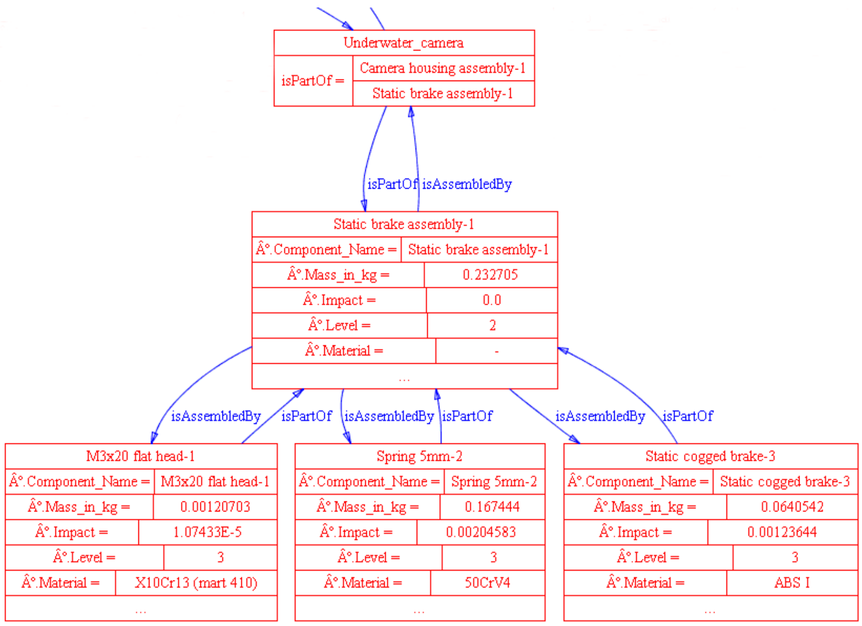


Figure 5. Ontology representation of a sub-assembly of the camera

5. Conclusions and discussion

Despite being an initial exploration, this work is an important step in a new direction that explores the possibilities of integrating three-dimensional CAD models with Life Cycle Analysis by means of an ontology. The growing importance of environmental criteria and the competitiveness of product design today create the need for an effective way to incorporate LCA into early design phases. Following a notable trend in engineering design, the use of an ontology allows for the incorporation of additional knowledge and possible integration with other programs. The developed ontology could be expanded to include cost analysis, manufacturing, product functions and many of the other areas that product design encompasses. Rather than a solution in itself, the research carried out demonstrates the feasibility of incorporating environmental criteria into design without the use of specialized software. The fact that this analysis is almost entirely automatic implies that tedious and manual analyses can be avoided, and the effects of improvements on a design are instantly visible. Using a three dimensional model as a central part of a knowledge management system gives users a much more visual and effective way to interact with the system and the abstract data it contains.

In the future, the proposed method could be expanded to include a more complete environmental analysis, such as alternative evaluation methods and data libraries. Impact could also be calculated based on surface area and length as well as mass, depending on the material and process chosen. Another possibility would be to develop the macro into an independent User Interface, which would allow for more flexibility and the inclusion of additional environmental criteria.

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