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Integrating ontology into PLM-tools to improve sustainable product development

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ABSTRACT

Sustainability aspects are predominantly considered outside engineering departments by designated organizational units. Some PLM-vendors have already integrated application modules to assess, primarily environmental, sustainability within design environments by giving feedback to engineers but only on predefined options. This paper describes how to combine engineering tools with ontology to enable the identification of multiple viable options covering the functional dimension and all three sustainability dimensions. The approach reduces time consuming trial and error assessment processes and opens up alternative options for sustainable solutions. The proposed solution is demonstrated based on material decisions occurring during the engineering process of a pedelec.

1. Introduction

The decision which products we create and use has effects on resources available for future generations. Sustainable product development attempts to preserve resources and reduce environmental burden while delivering sufficient value to the present generation [1]. Product design determines essential characteristics and properties of a product and correspondingly sets boundary conditions for subsequent lifecycle phases such as manufacturing and product use [2]. The design phase therefore has a large impact on the sustainability performance of a product.

The Nielsen global survey on corporate social responsibility identified that consumers are willing to pay more for environmentally and socially sustainable products [3]. Additionally, legislative requirements drive companies to stringent sustainability considerations as part of their product development, for example, design changes based on European guidelines such as RoHS regulating hazardous substances in electronics. Product engineers often do not have enough knowledge on effects of their decisions on the entire product lifecycle. The most mature method applied in industry to identify sustainability impacts is lifecycle assessment (LCA) [4]. The application of LCA is complex and requires much information. Usually designated teams operating apart from core engineering activities are assigned with the application. Organizational barriers slow down the application and impede direct feedback.

Close-loop feedback can provide improving potentials and additional options directly to engineers. Engineering sustainable products requires companies to address the normative perspective by integrating sustainability goals and respective requirements [5]. Yet, engineers need to know how to work toward these goals and requirements. This paper proposes an ontology based method called OBISO to integrate respective knowledge into engineering environments.

2. Research method and research questions

This research was based on a preliminary fit/gap analysis identifying deficiencies of current product development regarding the engineering of sustainable products. The analysis revealed that sustainability requirements are not adequately integrated into engineering environments. In a further step methods and IT-systems where identified which support the verification of requirements. This paper presents a concept developed based on identified gaps. The paper thus discusses the following questions:

- How can sustainability requirements be reasonably integrated into product engineering, i.e. how can sustainability indicators and associated sustainability boundary conditions drive the design of products?
- How can time-consuming trial and error design processes and concept alternative iterations be avoided by leveraging specified ontology knowledge?

This paper also addresses how ontology can be combined with traditional formula and mathematical model based design systems to provide a mechanism to combine conventional engineering knowledge with sustainability related information.

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3. State of the art in sustainable product engineering

During the last years PLM vendors have increasingly integrated tool support for sustainable product development. They provide especially compliance checking functions: for example, Dassault provides the module Enovia Materials Compliance and Siemens PLM provides Teamcenter Sustainability and Environmental Compliance. Those modules check the compliance, for example, with the RoHS regulation. Few of these tools such as Solid Works Sustainability Pro or Autodesk Eco Materials Advisor also provide a simplified LCA integrated into a CAD system. A simplified LCA only considers a part of the product lifecycle information. Solid Works, for example, bases their LCA results on selected materials and geometry and calculates the impact on, for example, CO_2 emission based on the weight of the component and a selected production process. Transport distances are only considered on a continent basis or must be inserted manually. Recycling processes are per default based on the continent and not on materials. The imprecise results are an obstacle for integrating those tools into the requirements verification process.

LCA tools such as GaBi or Granta Design provide a more mature basis to perform LCA but they are not directly coupled with engineering tools. PLM tools performing a simplified LCA draw data from those LCA databases but they do not allow the LCA model to be modified.

The analyzed tools only provide support on predefined options implicating that the variant has to be fully defined. Solid works provides the option to search for similar materials but there is no support to identify multiple suitable materials based on functional and sustainability requirements, such as minimum elasticity module or CO_2 limit for wrought material production.

The state of the art analysis revealed that a substantial range of information cannot be flexibly integrated into LCA tools embedded into the engineering environment. Options to insert information are either rigid or only limited support is provided on how to calculate LCA indicators.

Scientific approaches to integrate sustainability considerations into the engineering environment are for example proposed by Eigner et al. [6]. They provide a model based systems engineering approach integrating sustainability information and linking information within a PLM model and throughout authoring systems. The idea of a PLM model is highly relevant for engineering sustainable products but, as far as the authors know, no generic but only a specific data model for uncertainties has been published in this context [7]. Several research approaches propose ontology models for integrating heterogeneous data sources [8] or sustainability information [9]. However, those approaches do not consider reasoning based on integrating mathematical formulas.

The usefulness of combining tools verifying functional requirements with methods analyzing sustainability impact has been revealed, for example, by Russo [10] who performed case studies to highlight the benefits of linking CAE tools with an LCA approach.

4. Improving sustainable product engineering with OBISO

Information to assess the sustainability of a product more is distributed in different IT-systems. The geometry, for example, is created in a CAD system, information on suppliers, for example the distance, is located in ERP systems, information on the use scenario is stored in PDM or requirements management systems. Sustainability related data such as CO_2 emission for wrought material production is stored in designated databases such as GaBi or EcoInvent.

A model providing the relation between product parameters and sustainability impact factors and necessary data can provide a basis to identify options jointly fulfilling functional and sustainability requirements. In the collaborative research center SFB 1026 the suitability of an ontological approach to integrate dispersed information and identify viable options is examined.

Table 1
Ontology levels.

Ontology level	Content	Characteristic
General ontology	Concepts and relations, possible IT-Interfaces, relevant parameters, formulas	General, exchangeable among companies
Company-specific ontology	Instantiated ontology for product or component and company IT-landscape	Company (e.g., IT-interface) or product specific characteristics

A method is developed called OBISO (*Ontology based identification of sustainable options*) based on an ontology to integrate and process sustainability related information along the product development process.

The ontology links product properties and corresponding sustainability impact factors to product parameters, databases, and IT functions and provides knowledge on which information is required to consider a requirement on a specific property, where to access this information or how to generate the required information. The information basis of OBISO comprises two layers described in Table 1.

The general OBISO ontology provides a meta model (based on classes). A company-specific ontology is an instantiated version for a company for one or more products or components (based on individuals). An engineer works with the company-specific ontology (OBISO knowledge base). Based on the two information layers the method comprises two steps.

1) Build OBISO knowledge base

The general ontology provides relevant concepts and relations including relevant IT-interfaces, relevant parameters, properties, and formulas. A guideline for implementing a company specific ontology assists in creating a specific company, product or component ontology. A part of the general ontology is depicted in Fig. 1.

2) Query OBISO knowledge base

This step is the actual application of the OBISO method. An OBISO software tool extracts relations between a product property and validating IT-functions and relevant data.

A requirement set during product development usually addresses a property of the product (e.g., fuel consumption). Sustainability aspects can be integrated by addressing a requirement on a respective property (e.g., CO_2 emission). Consequently, the central concept of the ontology is "Property." Product properties are either determined by further properties (e.g., fuel consumption by weight and air contact surface) or by characteristics (e.g., the volume of a tube is determined by its radius and its

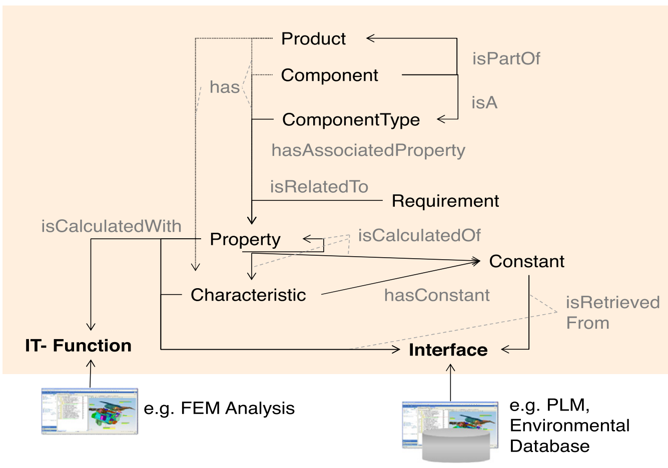

Fig. 1. Basic part of general ontology.

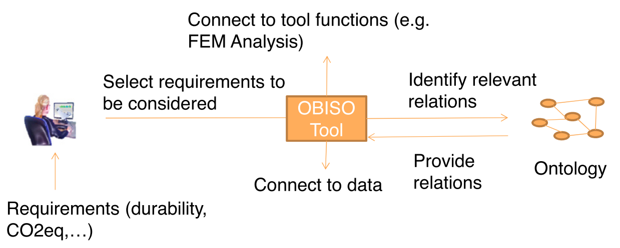

Fig. 2. Application of OBISO.

length). Characteristics are all aspects which a product engineer has to decide on, for example, geometric parameters, material, tolerances and a specific product technology. Manufacturing and end of life processes can be considered as characteristics which can be integrated by respective constants, for example, CO_2 emission per cm welding seam.

Properties can often be calculated with specific CAx and PLM IT-tools. The volume, for example, can be easily calculated by a CAD system. The calculation of sustainability related properties often requires access to dedicated databases such as GaBi or ELCD, for example, to determine the CO_2 emission of a material wrought process based on the mass of a component. The ontology must therefore capture relations between relevant properties and IT-functions calculating the properties and to databases storing relevant data. Fig. 1 depicts the core ontology. If the knowledge base is build based on the OBISO ontology the OBISO tool can interpret relations, and if interfaces are set correctly, automatically calculate if requirements are fulfilled.

Fig. 2 describes the process of querying the OBISO knowledge base.

The application of the OBISO method requires the specification of characteristics and the availability of certain data, for example, a FEM model, to calculate the durability of a component. Thus, the method is primarily relevant for product improvement or redesign. However, the method can also be applied to new product development if characteristics are outlined or only properties are considered which do not require a complex calculation or underlying data model. The method is especially suitable to identify viable options for characteristics with a limited, discrete amount of options. Currently the OBISO method does not explicitly distinguish between component level and assembly and/or product system level. This extension will be considered once further application scenarios (e.g., identification of suitable production processes) require distinction. The distinction can be made by specifying a respective component type. The next section describes how the method can be applied to identify viable options for a material when having a defined geometry.

5. Integrating the ontology approach in the design process of a pedelec

In the SFB 1026 a Smart Urban Wheeler in form of a pedelec called Tripelec has been developed as a demonstrator. The selection of a material for the frame shall serve as an exemplary case to demonstrate the OBISO application (Fig. 3). The material choice is dependent, for example, on the geometric design and durability requirements. Additionally, the CO_2 emission for wrought material production shall be integrated into decision making. Fig. 3 displays the procedure of working with the OBISO tool. First a component is selected, in this case the pedelec frame. A component type is assigned if no component type has been assigned before, in this case the component type is "carrying part." Based on the component type properties on which the user can set requirements such as stiffness, durability and CO_2eq are proposed. All data relevant for properties which are selected must be available in respective data bases. The mass is required to calculate the CO_2 emission. A FEM model is required to calculate the

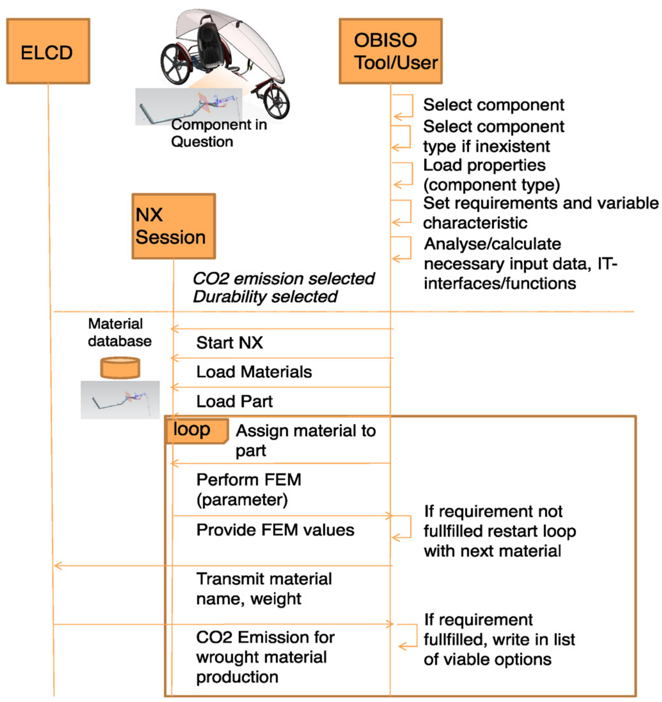

Fig. 3. Viable material identification.

durability. In the example, the mass is stored in the PDM system Teamcenter. The mass was originally calculated by the CAD system NX and automatically stored based on adapted settings. The FEM model is stored in NX. Teamcenter can be accessed via a SOA interface and NX via an Application Programming Interface (API) provided by NX Open.

Once the component to be analyzed has been selected, requirements can be set based on relevant properties and the variable characteristic can be defined. In the current implementation only the material is set as a variable characteristic but in future versions, further characteristics will be set as variable (e.g., geometric parameters). The OBISO tool analyses the "calculatedOf" relationships for the property CO_2 emission and durability and successively substitutes properties with required input properties or with respective data once a "retrievedOf" or "calculatedWith" relationship is reached. The CO_2 emission, for example, is calculated by the property "mass" which is in this case accessed via a PDM system and by the constant 'CO_2 per kg' of the material which is drawn from an environmental database. The formula "mass $\times$ CO_2 per kg" is stored as a string. The OBISO tool interprets the string, searches for the relevant concepts via "calculatedOf" relations and finally substitutes mass and the constant by their values.

If interfaces are set correctly within the company-specific ontology, a connection to relevant IT-systems is established and necessary data is transmitted. In a first step, materials are loaded from the materials data base linked within the company-specific ontology (in this case the NX database to ensure all FEM relevant material parameters are available). Then the FEM model is accessed and a material is assigned to the frame. If the calculated FEM values meet the durability requirement, the material is checked for the CO_2 requirement. If not, the next material is assigned.

If both requirements are met, the material is assigned to a list of viable materials and the next material is assigned to the frame until all materials have been checked.

A more detailed process of analyzing the knowledge stored within the ontology for the requirements stiffness and CO_2 emission was presented in [11]. In the previous publication only a specific cross section of the frame was considered and the stiffness for this section was calculated by the OBISO tool based on integrated formulas. The radius and wall thickness were retrieved from the PDM System Teamcenter. Integrating a FEM tool enables the analysis of the entire frame.

The analysis of suitable materials in the exemplary case can only serve as a design direction. However, engineers will have a proposition for materials based on the entire material database. A manual trial and error process to check requirements is time consuming. Consequently, engineers are likely to integrate materials into consideration which they are not familiarized to, but which are more sustainable. Yet, at this point, an exact design must further be performed with a CAD system combined with a FEM functionality as it provides more visualization and direct adaption possibilities.

In a next step, manufacturing processes will be integrated into the case of material selection. The CO_2 emissions are therefore composed of wrought material production and subsequent manufacturing processes. Potential manufacturing processes for the frame are bending (single component) and welding (assembly). Input parameters would be the length of the welding seam for welding and bending angle, radius, wall thickness and length of frame parts for bending.

6. Discussion and outlook

The OBISO method provides a basis to model and interpret knowledge on sustainability related product properties and necessary knowledge to calculate their values. The OBISO method was especially designed to integrate sustainability related knowledge including the environmental, the economic, and the social perspective into engineering environments. It was designed to overcome limits of current engineering support and provide a flexible method and a corresponding tool to adapt the underlying knowledge model. New properties or data sources can be flexibly inserted into the general ontology and interpreted by the OBISO tool mitigating the rigidity of conventional support. The implementation of an ontology-based approach supports the reusability among different companies. The general ontology can be constantly extended with general knowledge, for example, relevant sustainability databases, while the company specific instantiated ontology embraces additional company specific knowledge which is in general not transferable.

In the exemplary case only materials registered in the ELCD database were considered. ELCD datasets are freely available but the amount of datasets is only limited. The lifecycle data network (http://eplca.jrc.ec.europa.eu) based on the Soda4LCA application offers flexible and automatic access to lifecycle data offered in a network of multiple data providers [12]. The integration of this solution as an access point for lifecycle assessment data seems promising.

At the moment the OBISO general ontology is only filled with limited knowledge. Only the environmental perspective is addressed and only one component type is considered. Further work must classify components with relevant properties to provide a feasible selection of relevant properties.

Production and EOL processes are currently only considered by integrating these processes by their constants. If company specific data shall be considered, for example, based on a digital factory tool, the ontology can be extended to also consider relations between process variables and output.

Only quantifiable properties are considered right now. To establish a comprehensive knowledge base also non-quantifiable parameters can be integrated but not linked to a verifying IT-function. They can be kept for transparency reasons.

A large part of the general ontology can prospectively be automatically instantiated into a company specific ontology. The instantiation can be partially automated by analyzing product structures such as in PDM or CAD systems [13]. Reasoning could allow an automatic identification of component types and thus instantiate relevant properties. This reduces the effort to create the OBISO knowledge base. However, IT-interfaces must always be customized to some extent based on APIs and server location.

Formulas are now only stored as strings. This could lead to interpretation errors if the ontology is used with another interpreting program or careless mistakes when inserting a formula. For the discussed purpose and in combination with the OBISO tool storing the formulas as strings is sufficient but further research can examine the use of design patterns for storing formula concepts in ontologies.

In the case study, all materials from the materials database which are available in the ELCD database are analyzed. If further environmental databases are used, the material database is large, and there are requirements on performance, further criteria should be defined to exclude materials from consideration. Additionally an entire lifecycle model, integrating all relevant product lifecycle processes or process constants, for example, to determine the value for the entire CO_2eq emission must be integrated.

7. Summary and next steps

The paper proposed an ontology-based method called OBISO to overcome limits of current support for sustainable engineering. The method is based on a general ontology, a company-specific ontology and a software tool to interpret knowledge stored within the company specific ontology (OBISO knowledge base). A case study presented the general potentials of the approach. In future work the general ontology must be extended and more mechanisms to automatically instantiate the company specific ontology must be provided to offer sufficient functionality. Also design experiments are planned with different type of designers and analysts to analyze the degree of methodological maturity of the OBISO method.

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