ICED13
**INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13**
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

# A CONCEPT FOR AN INTUITIVE AND INTERACTIVE FULLY PLM-INTEGRATED ECO-EFFICIENCY ASSESSMENT IN REAL-TIME

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## ABSTRACT
To be competitive on the global market in a time of an increasing shortage of resources, companies have to develop not only good products but to make them also more sustainable. In the discourse on sustainable development, the potentials of product development are currently inadequately treated. Therefore, a holistic approach is required which accompanies the product from the initial idea, through the development phases and the entire lifecycle, to recycling or reuse. In this paper, a concept for intuitive and interactive eco-efficiency assessment is presented which also can be fully integrated in PLM solutions. It allows a prospective and holistic consideration of environmental factors. Also, this concept enables that the increased complexity due to environmental factors remains manageable and environmental potentials for a product can be identified and influenced early. Furthermore, an intuitive and innovative human-oriented visualization concept for an easy management and control of the appropriate required information is introduced. This new visualization concept makes the information included within today's PLM solutions accessible to a company's management level.

*Keywords: product lifecycle management, visualization, sustainability, engineering network concept, eco-efficiency assessment*

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# 1 INTRODUCTION

The capacity for innovation is of essential importance for industrial companies and also for countries as a business location. The success of an innovation depends on the company's capability to transform innovative ideas into salable products in an efficient and effective way. Moreover, to be competitive on the global market in a time of an increasing shortage of resources, companies have to develop not only good products but to make them also more sustainable.

In the discourse on sustainable development or a sustainable business management, the potentials of product development are currently inadequately treated. Sustainable product development aims at the real goods but also on the assessment of environmental, ecological and social issues over the entire product lifecycle. Therefore, a comprehensive approach is required which accompanies the product from the initial idea, through the development phases and the entire lifecycle, to recycling or reuse. A central problem for those companies interested in sustainable business alignment, however, is to analyze, to optimize and to communicate its product portfolio with as low as possible effort.

The ISO 14040 standardized lifecycle assessment (LCA) and the ISO 14045 eco-efficiency assessment, as parts of a sustainability assessment, provide meaningful methodological frameworks for the economic and ecological dimensions. Nevertheless, in the application of these frameworks it appears that the creation of an LCA or an eco-efficiency assessment is very time-intensive and cost-intensive. This is based on the fact that the practice of both ISO 14040 and ISO 14045 is not yet integrated into current solutions for product lifecycle management (PLM) but still is carried out with special software tools (Eigner et al., 2011). For the future, the intelligent use of existing digital databases (from PLM, ERP[1], MRP[2] systems, etc.) will be of major importance for the extraction of explicit and tacit environmental knowledge from information systems. Efficient delivery and use of this knowledge and the interdisciplinary exchange of knowledge on all phases of the product lifecycle are key factors for a sustainable product development process.

In product development, the ranges of functions and at the same time the scope of complexity of products and processes have increased dramatically. Modern, high-tech products appear to the engineer increasingly more complex and often lead to a feeling of being overwhelmed. A lifecycle-oriented product structure is an overall multi-dimensional network of requirements, functions, behavior, development structures, test structures and production structures about all disciplines involved in the product, across all internal and external development and production sites as well as about all manufacturing and assembly resources related to the product and about the entire product-related documentation. However, for the management and control of such complex structures practically all known visualization and handling technologies fail (Anderl et al., 2012), (Eigner, 2012). These complex interrelationships build the fundament of company-spanning and fitted technical or legal processes such as approval, change management and configuration, and thus are the basis of all product liability-related certifications (CMII[3] and CMMI[4]), which are decisive competitive factors especially with regard to the permanent increase in embedded software and networked systems.

With the integration of environmental factors into the existing systems, other certifications such as EMAS (eco management and audit scheme), TÜV certification PIUS (product-integrated environmental protection), LCA according to ISO 14040 or eco-efficiency assessment according to ISO 14045 are added which require an adaptation of existing business processes. As part of these processes, again and again decision problems arise that can be solved only through creating transparency and corresponding handling of the underlying product information. In particular, decisions in the early phases of product development play a key role in terms of economic-ecological creation of products. According to (Eigner and Stelzer, 2009) up to 70% of the total cost of ownership is set in the early phase of product development. In the same extent according to (Posch and Perl, 2007) the environmental impacts of the final product are determined. As a result, the integration of the requirements for an eco-efficient product in already highly complex product development processes increases complexity once more and brings the today's development processes and tools to their limits.

[1] Enterprise resource planning
[2] Manufacturing resource planning
[3] Configuration Management II
[4] Capability Maturity Model Integration

In order to be able to develop eco-efficient products and to control the rising amount of product and process information with the help of different application systems (PLM, ERP, MRP, CRM[5] and SCM[6]) in the future, an acute need for action exists. However, since the current systems - because of their outdated user interfaces which no longer satisfy today's customer demands and needs - already make currently existing complex data insufficiently accessible, a simple upgrade and expansion of these systems by environmental factors falls short. If one looks at today's common user interfaces, the information is accessed with standard input devices (mouse, keyboard, etc.) - also through the internet - and visualized with graphical standard components (table, text box, button, etc.). Nevertheless, these interfaces (input and output) are not "natural" human-oriented user interfaces ("native user interfaces (NUI)"). But, in several studies (Brodie and Perry, 2002), (Gidel et al., 2011), (Ryall et al., 2004), (Stark et al., 2012) it could be shown that the use of modern multi-touch multi-user input devices which allow a more human-oriented way of working improves the results of a decision-making situation, such as in a LCA or in an eco-efficiency assessment, significantly.
In the following, the ideas of a new and innovative approach are presented which targets problems of LCA, eco-efficiency assessment and corresponding complexity in order to find new solutions which allow the holistic consideration of environmental factors in a PLM concept in the context of a prospective lifecycle assessment, so that, coupled with an intuitive and innovative human-oriented visualization of the required data or information, the increased complexity due to environmental factors remains manageable and environmental potentials for a product can be identified and influenced early.

## 2 FROM LIFECYCLE ASSESSMENT TO ECO-EFFICIENCY ASSESSMENT

Whether a new product is to be designed or an existing one is to be improved, the process of creating distinctly more eco-efficient products needs to be monitored and managed. In order to address such an engineering design process, appropriate methods and tools are required. An internationally standardized tool to serve the ecological dimension of sustainability does already exist – lifecycle assessment (LCA, ISO 14040). Basic principles of any lifecycle assessment are the "cradle to grave" analysis and the use of a functional unit to which all mass and energy flows, resource and land use, and even the potential impacts and probable interventions are set in relation as a quantitative measure in order to evaluate the environmental aspect of a product system. LCA can assist decision-makers in industry by identifying opportunities for improving the environmental performance of a product and can also help governments and non-government organizations by the implementation of eco-labeling and environmental product declarations. For this purpose several software solutions do already exist:

- GaBi Software: Stand-alone software solution LCA at the product level.
- SimaPro Software: Stand-alone software solution LCA at the product level.
- Dassault Systèmes Sustainability Pro: Software solution embedded into the CAD of SolidWorks
- Siemens Teamcenter Sustainability: Semi-integrated in PLM solution.
- PTC Windchill Product Analytics: Stand-alone software solution but in practice mainly semi-integrated in PLM solution.

This paper considers PLM as one key concept for the establishment of eco-efficiency engineering design processes. PLM as the overall engineering concept is based on the idea of connecting knowledge. It represents a concept rather than a monolithic IT-system. It achieves efficiency by using a shared information core system that helps business to efficiently manage complexity in the product lifecycle from design to end-of-life. It offers a solution to systemize the various operational tasks in design and production, so that processes are rationalized and optimized. With the increasing importance of design for environment due to the scarcity of resources and stricter requirements on the products, a close collaboration between design and environmental engineers is needed.
In order to fulfill this problem the research project ERMA – energy- and resource-efficient mobile working machines – was initiated (Eigner et al., 2011). The scarcity of fossil resources and raw materials as well as the rising energy costs in the last years has brought the industry to a massive rethinking, so that the number of applications of eco-efficiency assessments in the sector of commercial vehicles is very high. Reduction of energy consumption and successive use of renewable energy are one of the most important innovation topics in this industry branch. In order to fulfill the high

[5] Customer relationship management
[6] Supply chain management

energy requirements in the near future, extensive concepts, new structures and innovative technical approaches increasing the total energy efficiency of the machines are needed. Looking at the lifecycle of a mobile working machine (Eigner et al., 2011) or an agricultural machine (Pickel and Eigner, 2012) for example, an eco-efficiency assessment helps to identify environmental key factors and cost drivers within the use phase where $CO_2$ emissions, resulting from fuel consumption, are very high. Thereby, the existing PLM concept used in ERMA will be extended by enabling the monitoring of a product lifecycle already in the early phases of an engineering design process. The first step towards an integrated sustainability assessment by the link between economic and ecological issues is realized in ERMA as it is claimed in the new international standard ISO 14045 – Eco-Efficiency Assessment of product systems: principles, requirements and guidelines – adopted in 2012.
The general principles of eco-efficiency are combined with the lifecycle thinking and translated into certain goals (Baroulaki and Veshagh, 2007):

- Minimize energy intensity.
- Minimize the material intensity of goods and services.
- Maximize the use of renewable resources.
- Minimize toxic dispersion.
- Extend product durability.
- Increase product efficiency.
- Promote recycling.

Objective of eco-efficiency assessment is to support the evaluation of different optimization solutions by providing an overall lifecycle view. The concept shown in Figure 1 refers to such a kind of eco-efficiency assessment and is linked to PLM (Eigner et al., 2013). It extends both product model and process model by technical-economical attention of ecological parameters, thus it allows an aggregated evaluation of energy and resource efficiency of the product over the product lifecycle. Energetically improved technical products will assert themselves in enterprise practice only if they are advantageous in economic regard. Hence, the deliberate design of eco-efficiency products is as important as both economic balance and lifecycle assessment. The concept deals with both and is outlined in a way that it corresponds to a multi-dimensional, interdisciplinary and federated lifecycle management.

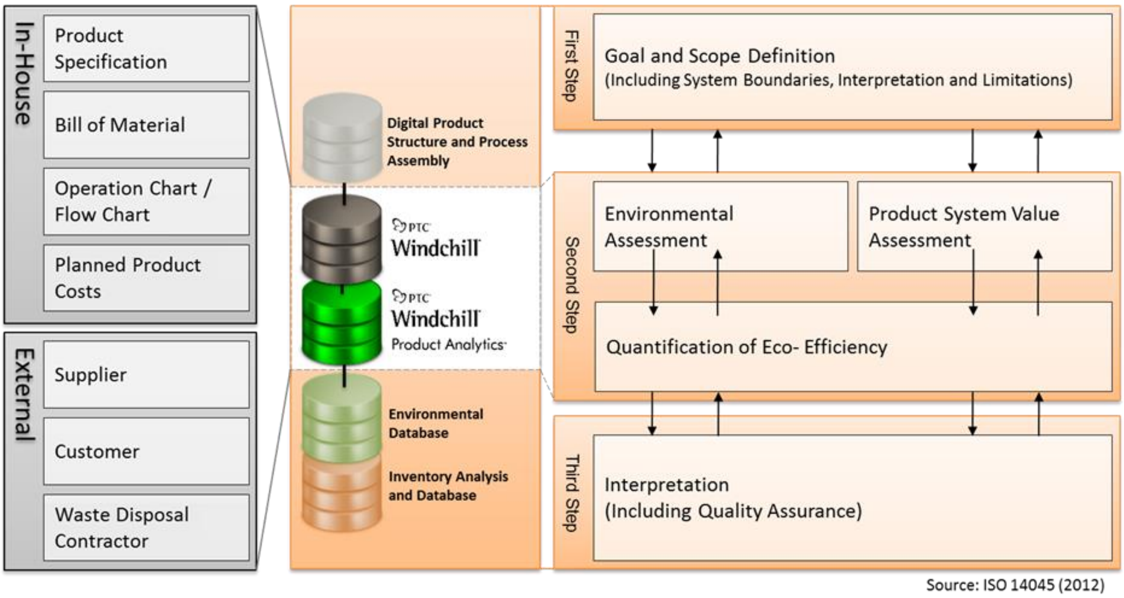



*Figure 1. Concept of an eco-efficiency assessment as part of PLM*

*(adapted from (Eigner et al., 2013))*

## 3 FUTURE NEEDS AND POTENTIALS FOR RESEARCH

Summarizing the open issues and questions related to an eco-efficiency assessment and the corresponding complexity problems as described in Chapters 1 and 2, the following future needs and potentials for research and development arise:

- A holistic consideration of environmental factors in a PLM concept in context of a prospective eco-efficiency assessment.
- Enabling that the increased complexity due to environmental factors remains manageable and environmental potentials for a product can be identified and influenced early.
- An intuitive and innovative human-oriented visualization of and interaction with the appropriate required information.

With today's level of integration the PLM solutions are on a good way. But there is still much effort needed to do an eco-efficiency assessment. The last step towards a complete and seamless integration of eco-efficiency assessment into the PLM solutions has not been undertaken yet. Even in semi-integrated PLM solutions the assessment has to be set up and refreshed by hand. To enhance PLM solutions towards a more easy and intuitive use of eco-efficiency assessment, in the following an approach is proposed that allows a continuous assessment without extra work for the user. To further enhance the ease of use an intuitive, graphically rich user interface enhancement is proposed which is matched for the special needs of an eco-efficiency assessment and enables the new extended PLM solution for the use on management level.

# 4 CONCEPT FOR INTUITIVE AND INTERACTIVE FULLY PLM-INTEGRATED ECO-EFFICIENCY ASSESSMENT IN REAL-TIME

Main subject of this approach is to develop indicators for the measurement of environmental factors and to integrate them within existing information systems. Further, for the manageability of the increasing complexity resulting from this, intuitive visualizations especially adapted to an eco-efficiency assessment have to be developed. This will be done on modern multi-touch multi-user devices to guarantee a better user interaction with the data.

For this purpose, in a first step concepts for the measurement and simulation of environmental factors such as global warming potential (GWP), stratospheric ozone depletion (ODP), tropospheric photochemical ozone creation (POCP), acidification (AP), eutrophication (NP), human toxicity (HTP), ecotoxicity (ETP) and land use (Pickel et al. 2012) have to be developed and to be integrated into existing PLM solutions. The determination of the environmental impact of a product already in the early phases will be done by a mapping between product structures and process structures. The required information are obtained interdisciplinary from the IT systems used in product planning, product development, process planning as well as production. Through the comparison with environmental indicators therefrom originate templates which show process-relevant product properties and which are made available to the subsequent lifecycle models for further processing. In this manner, with the knowledge of existing linkages between the process-relevant product properties of an existing product and their distinctive product-characteristic process patterns, the basis for a determination of the environmental properties of a product already in the development phase can be created. In particular with the aim to further reduce $CO_2$ emissions and to increase the recycling rate, here especially the prospective eco-efficiency assessment as part of the product development process is of particular importance. To guarantee the manageability of the environmental factors for the users, visualizations have to be developed which are adapted to the specific environmental factors.

Remark: New visualization concepts for a better handling and control of complexity have to be developed in general. But, in this paper the authors focus on presenting new visualization concepts by the example eco-efficiency assessment.

In context of eco-efficiency assessment the aim is to create a natural, intuitive and human-oriented interface between the users and the product information enriched with environmental factors. This will be done through the use of modern multi-touch multi-user input devices, such as tablets, touch tables or power walls. As a result of the improved usability of complex product structures now with integrated environmental factors it should be possible to significantly reduce the decision period between various design variants (i.e. hydraulic drive vs. fully electric drive). Here, the difficulty in visualization is to illustrate the large number of parts (components, assemblies, purchased products, self-production, etc.), data (material data, $CO_2$ data, personnel data, cost information, etc.), data aggregation (e.g. energy consumption simulated over the lifecycle) and environment (environmental requirements, cost constraints, liability rules, etc.) on a limited display space in a way that, despite the variety of information and the many relationships between the pieces of information, the overview

does not get lost and the user can make with few interactions an ecological balance according to his respective, individual criteria.
The technical realization of the proposed concept has a three level design build up on an existing component called Engineering Network (EN) concept (Mogo Nem, 2011), on experiences from the research project ERMA and on knowledge from the field of human computer interaction. These three levels are stacked on each other beginning with, first, the Engineering Network concept that provides the base framework which is, second, customized for the purpose of an eco-efficiency assessment according to the knowledge retrieved during the ERMA project. On top of the customized framework, third, an intuitive user interface is set up which aims to ease the access to the eco-efficiency information on regular devices as well as on modern multi-touch multi-user devices. The concept is composed of three parts – core model, customizing and user interface – which are derived from the named levels above to allow an implementation of the concept in today's common PLM solutions.

## 4.1 First Level: Engineering Network Concept

The Engineering Network concept is an enhanced flexible object-oriented meta-model for the modeling of composite and integrated multi-disciplinary product data and process models and it supports the mapping of data into data management systems. The product data models and process models derived from the meta-model provide user-specific views and flexible variant-rich development processes. With its flexibility and customizability, the EN concept contributes to handle the complexity resulting from the further enhancement of the product structure by eco properties.
Commonly, the Engineering Network concept is used as a PLM backbone. It is based on two core components (Mogo Nem, 2011), (Dankwort et al., 2012):

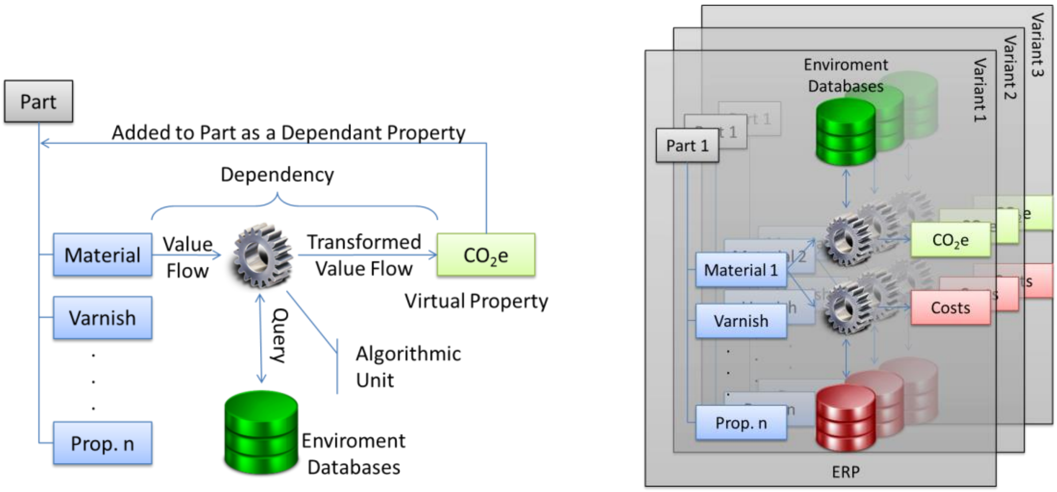
- Enhanced Object (EO) component: EOs are used for the modeling of product-related information and allow a user-specific, individual presentation of the data. Today different models are used for this purpose. Different disciplines (software, electronics, mechanics) have various different models. Some of them are defined in ISO 10303 (STEP). An EO is a virtual object which is fed by information from models of various globally distributed systems. The position of the "Viewer" determines which information is included. For this purpose, the EO component includes and offers "Viewpoints" which are linked by different "Views" to the virtual EO. By taking a "Viewpoint", a real object is created which holds and presents real data. Furthermore, an EO has properties which carry the specific values of the EO. The EO has interdependencies/relations to other EOs. Relations can be of types EO ⇔ EO, EO ⇔ Property, EO ⇔ View, View ⇔ View and Property ⇔ Property. The Property ⇔ Property relations are fully programmable and offer the possibility to attach algorithms, methods, etc. to them (e.g. to execute operations such as transformation, calculation, check, etc.). This for example allows an automatic update functionality by which a value change of the source property is automatically transferred to and/or compared with related properties (within defined and valid constraints. Exceeding the constraints has to stop the process).
- Engineering Process (EP) component: EPs are used to model the business processes associated with the EOs. In the EN concept, the assumption is made that there is a strong correlation between a product and its associated processes. Thus, the EO is the processes' data context. According to the concept of object orientation, a process is defined as a dynamic behavior of an object. In EN, processes are therefore mapped to object methods and reside in the EOs. EPs can access other EOs by traversing the relationships between EOs. Thereby a process can change not only its own EO but also related EOs. In the context of engineering design, EPs serve for capturing the various design processes and mapping them onto some formal and executable structure.

With its flexible relations, the EN concept enables building virtual properties that do not exist in the original data. This is essential for an eco-efficiency assessment because the result of the assessment depends on the original data but does not exist in it. With this capability virtual eco properties can be modeled that retrieve their value from real value properties by using the flexible EN relations. As the relations allow adding extra code which transforms, aggregates or enriches the dataflow, the dependent property value can be modified freely. These virtual properties are called dependent properties.

## 4.2 Second Level: Customizing the EN Data Model for Eco-Efficiency Assessment

To enable the EN data model to support an eco-efficiency assessment it has to be extended by eco properties. For demonstration purpose the global warming potential (GWP) measured in $CO_2$

equivalent ($CO_2e$) has been chosen. As shown in figure 2a an eco-property is modeled within the EN data model by a virtual property that depends on the material of a part. To transform the material value into a $CO_2$ equivalent by a transformation function which is included in the dependency (modeled within the EN data model by a relationship), an eco-database is queried for the material's $CO_2$ equivalent and finally the value of the virtual eco property is set.




*a) Dependent eco property modeled with EN*　　*b) Eco-efficiency variant comparison*

*Figure 2. Dependent properties modeled in EN*

To have real-time updates of the eco property, EN provides change events that get triggered when the material value changes. Through this simple mechanism the eco property is always up-to-date providing a real-time view on the ecological impact of the chosen material. Figure 2b shows a further enrichment of the EN model by cost properties which are also modeled as dependent properties.

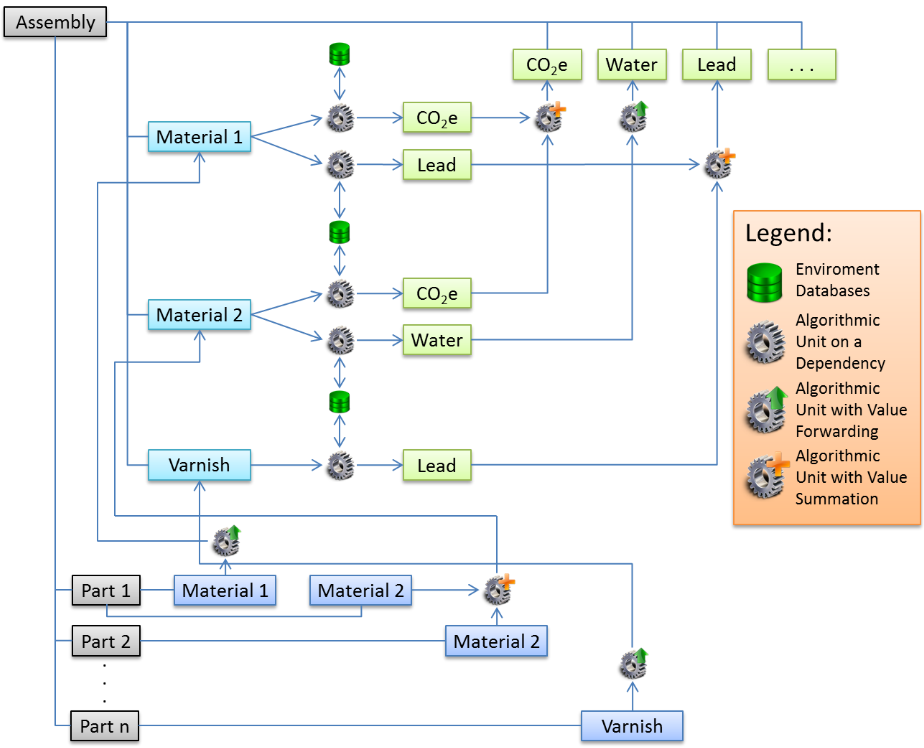



*Figure 3. Value aggregation, transformation and forwarding on assembly level*

As in EN a part is modeled as an EO, different variants of this part can be subjected in an eco-efficiency assessment by comparing the EOs. With the need to do an eco-efficiency assessment not only on part level but also on assembly or product level, the eco properties have to be aggregated. For this purpose, EN offers a variety of possible modeling strategies. For large data quantities the aggregation can be done by an over-night job. In the case of large data quantities all properties on assembly level are modeled as regular properties. However, here the eco properties on assembly level are no longer updated in real-time but this can save a considerable amount of computing power. Another way is to use the dependency capabilities of EN to model all properties on assembly level as dependent properties (see Figure 3). This will offer a maximum flexibility and keeps all values on assembly level up-to-date in real-time. Applying this strategy up to the top on huge products like cars, airplanes or ships with a lot of engineers involved in the product development can result in rapidly changing values which make it impossible to assess the ecological impact of the current product version. For that reason EN supports mixed modeling strategies.

### 4.3 Third Level: Concept for an Intuitive User Interface for Eco-Efficiency Assessment

Objective of this concept is to provide the user a quick and easy access to the results of an eco-efficiency assessment without overstraining him. The interface shall offer access to the regular product-relevant information as well as to the derived eco information. As the derived information does not belong to the product itself, it has to be marked as additional information to give the user a good overview about the core product information and the product information enriched with eco information.

All today's standard PLM solutions like PTC Windchill, Siemens Teamcenter, Dassault Systèmes Enovia etc. use graphical standard controls to display the product structure. These are lists, tables, tabs, sometimes a 3D CAD visualization and similar controls. For regular workplaces equipped with a regular monitor, a mouse and a keyboard, these controls are quite good and have been proven for a long time. But since new touch and multi-touch and in the near future multi-touch multi-user interfaces enter the business world, the question arises whether the long-time proven controls are still appropriate. So, within the here presented concept a multi-touch table with tangible support allowing collaboration around the table will be used for the creation of a prototypical implementation. By taking a closer look on the graphical user interfaces developed in the field of human computer interaction, e.g. (Jetter et al., 2011) and (Heilig et al., 2011), there appear new and innovative controls that allow the visualization of product structures and all the information bound to it in a completely new way. The appropriate visualizations and gestures to interact with the prototypical implementation of the concept will be identified in a field study. As the here presented concept aims on developing an intuitive user interface, also a measurement for intuitiveness is needed. According to (Hurtienne et al., 2007) 'a technical system is intuitively usable if the users' subconscious application of prior knowledge leads to effective interaction'. As measuring intuitiveness is obviously depending on the prior knowledge of the particular person, it is very hard to define a general measurement. So, for measuring the intuitiveness of the presented concept it is planned to develop a special survey that takes the prior knowledge of the participants into consideration. It is expected that this will lead to differentiated results depending on the respective visualization and the individual user.

The user interface (UI) of the concept is build up on the EN data model, all information displayed or used in the UI originates from the underlying EOs. Each control uses one EO as data source. As the EN concept supports views, it makes sense to divide the enriched product into views that can be added by the user. So in a first step towards a user-friendly interface, the interface has to be easily customizable by the user. Next, it has to be solved how to visualize a huge bunch of views and information inside the views. As standard displays are too small to see all information at a time, the information has to be visualized in a way that the user sees only the information he wants to see and nothing of that one he does not want to see. Further he should be able to get this information very quickly, if needed.

Figure 4 illustrates a concept how the user can quickly drill down from a high-level perspective with views including low details to the deepest level with many details available. This concept of a zooming functionality can be operated by a mouse wheel or standard two-fingers touch gestures for zooming in and out. Such zoom functionalities are used e.g. in many computer games but for engineering data they are currently uncommon. To navigate through a huge bunch of engineering data the different parts, assemblies and products can be visualized in zoom level 1 on an infinite drawing surface. They can be structured by similarity or other criteria, like relations, or user-individual grouping criteria. Structuring and filtering of this high-level data on a regular screen can be done by drop-down controls, checkboxes or textboxes and other common controls. Using touchscreens, the use of touch interaction, gestures and tangibles (tangible physical objects for interaction) offers a great variety of interaction possibilities for these operations. To further drill down into the filtered or structured results a selected area could be zoomed in. The area where the mouse pointer points to or the touch-zoom-gesture is centered is smoothly enlarged and more and more space on the drawing surface is assigned to it. Hence, the objects outside of the focused area are pushed out of the visible area of the drawing surface. So, the zooming function is used to reduce and enrich information at the same time. By drilling deeper into the zoom levels the not focused elements are smoothly reduced and the focused elements are enriched with each consecutive zoom level. To give the user a good feeling while zooming, the zoom function should be implemented in a way which allows the user to glide deeper into the details. The stepping from one zooming level to the next one (forward and backward) shall not be performed abruptly.

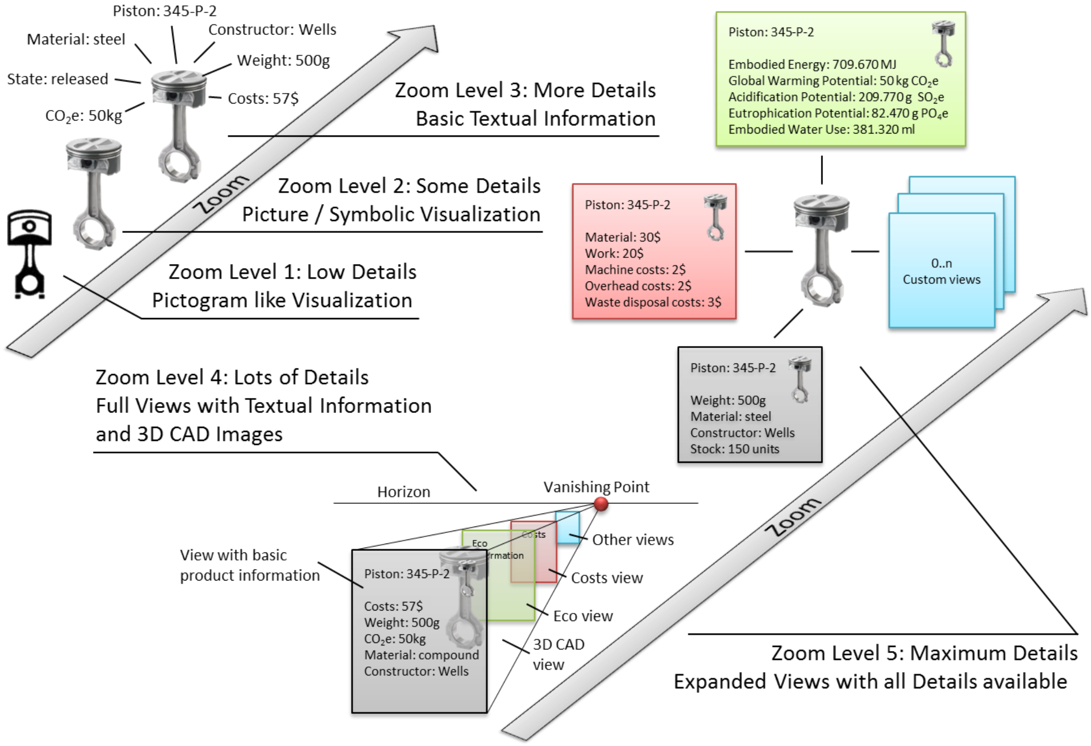



*Figure 4. Zoom level for space optimization*

Finally, to do an eco-efficiency assessment the user needs at least two objects to be compared with each other. After determining one object in the way described above, the user can lock the object for an assessment by e.g. using a tangible or a button in the menu. Then the user can search for a second object to compare it with the locked one. To make the access to comparable objects easier, the last zoom level can offer additional context sensitive buttons or touch gestures to show possible comparable objects on the same zoom level side-by-side to the locked one.
There are many more possibilities to implement a user-friendly interface for an eco-efficiency assessment. The benefits of this solution result from the combined search and compare functionality which makes it really easy to find objects and assess them in an eco-efficiency assessment.

## 5 CONCLUSION

In this paper, a concept for intuitive and interactive eco-efficiency assessment is presented which also can be fully integrated in PLM solutions. It allows a prospective and comprehensive consideration of environmental factors. Further, this concept enables that the increased complexity due to environmental factors remains manageable and environmental potentials for a product can be identified and influenced early. Moreover, an intuitive and innovative human-oriented visualization concept for an easy management and control of the appropriate required information is introduced. The technical realization of the proposed concept has a three level design build up on the Engineering Network concept, on experiences from the research project ERMA and on knowledge from the field of human computer interaction. The proposed customization of the EN data model allows an assessment by using the named graphically rich user interface in real-time. In addition, the proposed concept includes

a new visualization concept which makes the information included within today's PLM solutions accessible to a company's management level. Especially in decision situations the management can profit by the fast and easy access to all relevant information from the eco-efficiency assessment.
The introduced concept is/will be researched, developed and implemented within actual running and upcoming applied industry and research projects.

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