LCA RELATED INTERACTIVE KNOWLEDGE VISUALISATION FOR PRODUCT DESIGN

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Abstract: The integration of LCA into today's computer-aided product designs requires the break-down and investigation of the entire life of products and services with respect to economical and ecological impact. As this leads rapidly to a vast amount of different data that has to be stored, structured and analyzed, the necessity of providing computerized tools to support the human expert becomes apparent beyond any doubt. Especially in the stage between inventory analysis and impact assessment, an expert needs a considerable amount of (visual) aid, in order to recognize given multi-dimensional LCI related data sets and to interpret relationships between given product design parameters and their impact in each life cycle phase. Techniques in visualization provide tools for quickly and efficiently obtaining information from data. The aim of the work described in this paper is to provide an initial framework and an experimental testbed to demonstrate and analyze the generation and use of rendered glyphs the attributes of which are controlled by a selected set of mapped LCA related information. Glyphs, by their nature, allow mapped data within a known context to be linked to attributes that in turn control their visualization. This provides sufficient functionality to support designers and LCA experts interactively as they perform LCI information analysis and leads to improvements in speed and efficiency.

Key words: information visualization, glyph rendering, life cycle assessment, product design.

1. INTRODUCTION

Changes have occurred recently in the environmental focus of research in academia and industry. Production related processes and technologies are now less important than services and products and their life cycles, and this has led to ecological and environmental optimization of sustainable product development. Within holistic approaches such as life cycle management and life cycle modeling [Westkaempfer 2000], activities like product data management (PDM), life cycle engineering (LCE) and life cycle assessment (LCA) require large amounts of information to be acquired, stored and correlated. Powerful new information technology (IT) infrastructures, are being developed, but new concepts, frameworks and tools are also required, to allow these complex activities to be integrated into computer-aided product development. Due to the labor-intensive, as well as data-intensive, nature of these activities, it is desirable to partially automate them while providing efficient means to access, process and visualize all kinds of product, process and life cycle inventory (LCI) related data.

In particular, tools to support the efficient computation of the life cycle inventory (see [Mueller and Oestermann 1997; Otto et al. 2001a; Otto et al. 2001b]) and to help the expert to analyze calculated results are either unavailable or rudimentary. However, in recent, promising research into information visualization, computer-aided use of visual processing has assisted in offering a comprehensive and comprehensible display of multi-dimensional data, an area neglected in almost all LCA related systems currently available to both academia and industry.

2. LCA AND INFORMATION VISUALIZATION

2.1 Approaches and related work

The first approaches to what today is called life cycle assessment were developed in the 1960s. The studies of that time dealt mainly with energy issues [Boustead 1995], which were related to general interest in the limited supply of raw materials and fossil fuels. Formalized LCA tools developed in the USA were mainly based on raw materials and energy analysis, such as the REPA method used in [Hunt et al. 1992]. The development of LCA procedures began in Europe in the early 1980s, especially in Switzerland, where the Ministry of the Environment initiated research leading to the development of the Critical Volumes Method, and the Ecopoint Method [Habersatter 1991]. Several European research groups began publishing

materials related to LCA methods in the 1990s, often supported by national agencies (e.g. CML classification method in the Netherlands by [Heijungs et al. 1992]), Environmental Priority Strategies (EPS) method in Sweden [Steen and Ryding 1994]). Related methods, such as the KEA method [VDI-Richtlinie 4600 1995] and Material Intensity Per Service Unit (MIPS) [Schmidt-Bleek 1997], were also developed in Europe. In the recent past the International Standards Organization has issued a framework for conducting LCAs [ISO 14040 1997].

The difficulty with LCA is not the complexity of the methodology, but the complexity of the problem. Each step is very simple and can be understood easily but the thousands of steps required to assemble a complete LCI make a reliable LCA extremely difficult and expensive. To give an impression of the scale associated with compiling an LCI, Bretz [Bretz 1998] estimated that an analyst might require some 10^4 to 10^5 , or even more, numerical data elements for a complex product consisting of thousands of unit processes.

The use of icons or glyphs to create abstract visualizations of (multi-dimensional) data sets is based on human perceptual abilities. Different parameters describing spatial, geometrical and retinal properties of such icons or glyphs, defining their position, orientation, shape, color, etc., are commonly used to encode more information in a comprehensible format, allowing multiple values to be encoded in those glyph parameters [Post et al. 1995; Ribarsky et al. 1994]. The visualization of icons and glyphs is based on the concept of marks such as points, lines, areas, surfaces and volumes and their graphical properties [Bertin 1983; Mackinlay 1986]. Early work in logic and semiotics [Chang 1989; Feibleman 1969] attempted to relate the meaning of icons to properties of their graphical representation. First technical applications exploited the effectiveness of iconic and glyph-based visualization due to the ability of the human eye-brain system to discern finely resolved spatial relationships and differences in color, texture and shape. These applications appeared in the field of engineering mechanics [Ellson and Cox 1988; Haber 1990]. Glyph-based visualizations followed displaying properties of vector fields [Globus et al. 1991, Walsum and Post 1994] and vortex tubes extracted from flow fields [Villasenor and Vincent 1992] to mention only two examples. Next, frameworks and systems were developed for the interactive generation and investigation of icon and glyph-based visualization [Post et al. 1995; Ribarsky et al. 1994; Ebert et al. 2000]. Further applications successfully employed information visualization in fields other than those mentioned above. These included use with (English) text and program analysis, internet web page navigation, displays of complex graphs and analysis of large telecommunication data sets [Rohrer et al. 1998; Eick et al. 1992; Cugini and Scholtz 1999; Abello and Korn 2000;

Koutsofios et al. 2000]. Work on information visualization taxonomy and the systematic analysis of point designs in this field, accompanied by numerous examples and a well compiled list of reference literature, can be found in [Card and Mackinlay 1997; Chuah and Roth 1996; Card et al. 1999].

2.2 Problems and scope

In order to integrate LCA into today's computer-aided product design, it requires the break-down and investigation of the entire life of products and services with respect to the economical and ecological impact of all product life cycle stages. This must be carried out during the design stage itself. Of most interest here are activities such as the acquisition and bulk processing of raw materials, manufacture and assembly, delivery, use and maintenance, remanufacture, reuse, and recycling of materials. These activities are categorized into pre-use, use and post-use. A complete LCA always requires several iterations incorporating goal/scope definitions, inventory analysis and impact analysis, as described in [ISO 14040 1997]. This requires first the retrieval and collection of inventory information on all processes with which a product or any part of it comes into direct and indirect contact. As this leads rapidly to a vast amount of different data that has to be stored, structured and analyzed, the necessity of providing computerized tools to support a human expert becomes apparent beyond any doubt.

Especially in the stage between inventory analysis and impact assessment (cf. Figure 1), an expert needs a considerable amount of (visual) aid, so that he can recognize given multi-dimensional LCI related data sets as efficiently as possible and rapidly interpret relationships between given product design parameters and their impact on each life cycle phase. Up until now, unfortunately, there has not been much computer-assisted aid available from any systems supporting LCI relevant or LCA related data representation, other than value based tables (nominal, ordered, quantitative), 2D / 3D diagrams and charts.

Figure 1. LCA Framework according to ISO 14040

The purpose of the work described in this paper is to provide an initial framework and an experimental testbed to demonstrate and analyze the generation and use of rendered glyphs the attributes of which are controlled by a selected set of mapped LCA related information. Glyphs have a natural tendency to link (mapped) data within a known context to the attributes that in turn control their visualization. This is believed to provide sufficient functionality to offer interactive support to designers and LCA experts performing LCI information analysis and to allow them to operate faster and more efficiently than at present.

3. APPROACH

3.1 Overview

Techniques in visualization provide tools for obtaining quickly and efficiently information from data. These may range from basic presentation techniques which merely display data in a plain way, to sophisticated techniques capable of extracting, mapping and displaying an information set automatically. Within the scope in this paper, we will focus on the use of the latter, employing the particular technique of glyphs, which act as symbolic representations displaying essential characteristics of a data domain to which they are linked. This visualization concept replaces original data with a carefully designed symbolic, interactive display, featuring a better structured and more compact, hence more clear and meaningful, representation. The well-known advantages of glyph-based information visualization, as already

encountered in other technical applications mentioned above, will be investigated.

For such a task the entire structure of a set of glyphs must be specified according to the subject of visualization and their appearance. First, the number of degrees of freedom of the glyph must be fixed, i.e. the parameters or so-called glyph attributes which can be varied and separately linked to data of a known context. Second, the symbolic appearance of the glyph itself, i.e. its structural generation, needs to be specified. This is done by determining the way characteristic values of a pre-computed information set are mapped onto the glyph's attributes. This process, a kind of data abstraction, provides an excellent, and by its nature quite natural, opportunity to enrich semantics, as will be shown later. Third, the actual visualization of the glyph on a computerized device using its specified (generic) structure needs to be defined and linked to actual data (streams) of pre-computed characteristic values. These steps are illustrated and described in detail in the following sections. Note that, to avoid difficulties in reading material that is relying heavily on complex mathematical notation, only informal glyph specifications are used, though work has been undertaken to specify these glyphs and related concepts on a formal basis employing semantics domain theory and computational geometry.

3.2 Concepts and domains

The set of glyph attributes that defines the number of degrees of freedom, i.e. a glyph's set of control parameters, can be divided into three major groups. First, *spatial parameters* that define position and orientation. Second, *geometrical parameters* that define shape. Third, *descriptive parameters* that define texture, color, transparency, opacity, saturation and sound. Thus a glyph's degrees of freedom can be specified as a domain consisting of a cross product of a spatial, a geometrical, a retinal and an acoustical domain.

The computed, measured or otherwise experimentally obtained data within a known context, i.e. the information gathered representing knowledge of a discourse within a field or discipline subject to analysis and visualization, can be abstracted as a *reference domain*. A selection of these data (the reference domain), which is important or relevant in some respect can be abstracted as a *selection domain*. The space in which a glyph exists can be abstracted as its *appearance domain*, a cross product of a *display domain* that contains all graphical objects allowed and an *acoustic domain* that contains all sound and voice items allowed. Note that, within the scope of this paper, the appearance domain is equal to the display domain, because

the advantage of acoustical parameters is not clearly anticipated in this application yet. The structural generation of a glyph, i.e. the computation of proper glyph attributes based on a selection of characteristic data, can be abstracted as a mapping from the selection domain to the appearance domain. The mapping is specified by relationships between data to be visualized and the sets of control parameters discussed earlier. Finally, our glyph-based information visualization space can be abstracted as a *glyph domain* that consists of an ordered mapping of the reference domain, the selection domain and the appearance domain.

3.3 Framework and structures

Within the framework developed, glyph attributes and their control, when visualizing LCA relevant information for computer-aided product design, are defined as follows. The existence (in the selection domain) and spatial location of any LCI parameter and LC phase entity subject to investigation and visualization is represented by a sphere. Additional information related to this initial entity is spatially located and geometrically represented as a set of ellipsoids attached to this sphere (cf. Figure 2). Since all glyph elements are 3D geometrical objects, as is the glyph itself, the spatial location of some of the ellipsoids being attached requires the central sphere to be transparent, in order to make possible the visual recognition of all ellipsoids, independent of the current point from which the glyph is being viewed. Similarly, to prevent the obscuring of smaller ellipsoids by very large ellipsoids, they have to be transparent as well, though to a lesser degree than the centered sphere. Although each individual glyph, once rendered completely, can be interactively rotated and zoomed by the user, the basic idea is to present information efficiently at first glance, and this concept must be given high priority in glyph design. To support quick and efficient identification of a glyph component and its linked information, each ellipsoid is colored in one of six colors: blue, green, red, yellow, magenta or cyan, with standard basic hue and saturation values. To further enhance quick visual recognition of the basis of a glyph, the initial gray-scale of the central sphere (see again Figure 2) can be changed to a pre-defined color (as shown in Figure 3) according to the type of information conveyed, though to distinguish the sphere from the attached ellipsoids, the color will appear with a reduced saturation value. Note, that due to printing limitations all figures are in gray scale. Full color images of the figures shown can be found in [Otto and Mueller 2001].

Figure 2. Rendered standard glyph

Figure 3. Rendered glyph with colored sphere

The mapping between scaled scalar values or n-dimensional vectors of the selection domain and geometrical properties of the glyph is defined as follows. The radii of the sphere (equal value for each radius within the x-y-plane and the y-z-plane) represent the absolute value (or vector norm) of the sum of mapped data linked to the glyph. This radius-based representation was chosen over a more usual volume-based representation to better highlight the impact effects of LCI parameters. This is particularly pertinent in visualizations where several glyphs are displayed simultaneously for one life cycle phase in respect to several environmental items or vice versa. The sphere also acts as a filter with a user defined threshold value, to prevent

visualization of related data entities with insignificant relative values. To visualize this concept of a filter regarding data mapped to the central body of the glyph and to its attached ellipsoids, a central sphere was chosen, due to its obvious property of providing an equidistant measure from each of its surface points to its central origin. The size of the attached ellipsoids is mapped volume-based through their radius in the x-axis to linked data of the selection domain. The maximum value of this radius is three times the radius of the sphere to which it is attached. This would occur should the relative value it represents be almost equal to the sum of all mapped values, with other components being close or equal to zero. The other two radii of the ellipsoid in the y- and z-axes are related to the radii of the sphere, and remain fixed within any one glyph. This mapping scheme was found to offer a balanced appearance for each glyph without restricting its information visualization capability.

4. EXAMPLES

4.1 Test data and experimental environment

To start practical work on verifying and analyzing glyph-based information visualization within the context of life cycle assessment, we considered an electrical display device such as a TV set or a computer graphics workstation monitor, as mass-produced in Asia, with a total product weight of 25 kg. For experimental work, to illustrate visualization effects linked to data properties in the reference domain, calculation of the simplified product inventory regarding the use phase was based on two very different user profiles. We considered a heavy use of 2000 hours per year and a quite moderate use of only 250 hours per year. The total time of the use phase was fixed at five years.

Hardware platforms employed to compute data of the product life cycle inventory and to generate all rendered glyphs shown later consisted of Pentium 4 powered, Microsoft Windows 2000 Professional operated graphics workstations.

4.2 Visualization results

In the following, glyph-based visualization results for a selection of computed LCA related data and an interpretation of the same will be presented and discussed. For generation of the glyphs shown in this section,

the following settings have been used. Transparency was 75% in the case of rendering spheres and 25% in the case of rendering ellipsoids. The four main life cycle phases were assigned colors as follows. Pre-manufacturing: blue, manufacturing: green, use: red and post-use: yellow. Selected environmental items were assigned colors as follows. Carbon dioxide (CO₂): blue (over a 20-year horizon carbon dioxide results in global warming due to the greenhouse effect); carbon monoxide (CO): cyan; sulfur dioxide (SO₂): green (sulfur dioxide causes winter smog and acidification); nitrogen oxides (NO_x): red (nitrogen oxides cause acidification and eutrophication); dust: magenta; and lead and cadmium (Pb, Cd): yellow (heavy metals cause long term contamination and also enter the food chain).

Within a given scope, three visualization scenarios are important for product designers and LCA experts. First, displaying the importance of individual life cycle phases in regard to one environmental item. Second, displaying the importance of several environmental items in regard to one life cycle phase. Third, displaying the importance of all selected environmental items in regard to the whole life cycle.

Examples visualizing LCA relevant information for the first two scenarios are shown and discussed below. However, the third scenario still presents some problems. The environmental impact analysis (EIA) involves the linking of the inventory inputs and outputs to real world environmental problems. This is often controversial, since many effects depend on the concentration of the emissions. Various methods for impact analysis have been proposed. The EIA methods can be categorized as methodologies that attempt to measure actual impacts, while other methodologies are based on predicting potential impacts. Impact assessment criteria can be categorized into three main groups [Wenzel et al. 1997] namely environmental impacts, resource consumption and impacts on the working environment. According to the recommendations of SETAC [Fava et al. 1990] and ISO 14040 ff. [ISO 14040 1997], an EIA should comprise a determination of the relative contribution of the pollutant to the various types of environmental impacts, normalization of the potentials with respect to e.g. the impacts of society as a whole (i.e. this may be used as an indication of whether the impact is great or small), and weighting the potential impacts to determine the most important. The process of normalizing and assigning weights is, in a sense, a conversion of the varying units of the inventory into the same units. However, in most evaluation schemes, the weighting in particular relies on the (often subjective) judgment of the evaluator [Fu and Cebon 1997]. When using impact analysis data the glyphs too can be used for visualizing results, but it is important to realize that any normalization and weighting procedure has limitations and interpretation is difficult. For these reasons, and the fact that examples for the remaining two scenarios will suffice to illustrate the

approach taken, no example for the third scenario has been included in this paper.

Figure 4. A manufacturing phase glyph with a CO₂ dominance

When we take a closer look at the LCI data computed for different parts of the product used in the examples, we find in one sample a dominance of CO₂ (blue colored ellipsoid on top in Figure 4) over other environmental items in the manufacturing phase. The glyph also shows that the relative contribution of heavy metals must be less than 10%, since their representation as a yellow colored ellipsoid is missing from the glyph in Figure 4. Since there is a dominance of CO₂ in the life cycle glyph, let us examine whether this trend is valid for all life cycle phases. This can be done by switching to an environmental item glyph, linking the glyph's center (sphere) to the selection domain of CO₂ data and visualizing its relevance in each life cycle phase. In the use phase, CO₂ values were 440 kg for heavy use and 55 kg for moderate use. Total CO₂ for all life cycle phases was 486 kg and 101 kg respectively, so the values for the post-use, in each case only 5 kg, seemed insignificant. Only the CO₂ value (30 kg) for pre-manufacture seemed to be of some interest within the second (moderate) use profile. Total CO₂ for the manufacturing phase was as small as 11 kg, and represented a (relative) contribution of only about 2.3% for heavy use and about 10.9% for moderate use. The glyphs depicted in Figures 5 and 6 show all these qualitative relationships at a glance. For example, the blue sphere (CO₂) with one large red ellipsoid in Figure 5 represents a 90.5% (relative) contribution for this item with all contributions in other life cycle phases being less than 10%, and therefore not displayed, due to the filter level being set at 10%.

Figure 5. A CO₂ glyph with a dominance in the use phase

Figure 6. A CO₂ glyph with a dominance in the pre-manufacturing and use phases

Our framework also allows us simultaneously to visualize LCI data for several parts of a product within a chosen scenario. An example of such a (3 x 3) glyph matrix is shown in Figure 7, visualizing CO₂ glyphs and displaying the importance and contribution to each life cycle phase of individual parts. Within such a visualization structure, the relative importance of the pre-manufacturing phase (glyph (3,1)) or the manufacturing and use phase (glyph (2,2)) for an individual part can be recognized as easily as the absolute contribution of CO₂ by each part in respect to the entire product.

Figure 7. CO₂ glyphs for several parts of one product with a dominance of different LC phases

5. CONCLUSIONS

This paper has introduced an approach to visualizing LCA related information based on the concept of glyph rendering. Structures and framework were presented informally to provide for a transparent definition while omitting descriptions that rely too much on complex mathematical notation.

The results of glyph-based visualizations obtained from the experimental work conducted proved to be as promising as anticipated. Visualization of LCA related information was indeed found to be compact and easy to understand. Qualitative relationships of the LCI parameters considered could be recognized at a glance in each visualization generated. With traditional representations of these data using numerical spread sheets and tables, it took far longer, and required much more concentration, to recognize the same trends, impacts and relationships. The concept of glyph matrices provides an excellent means to display any scenario, and offers an additional dimension, which may include, for example, the contribution of each part within a selection in respect to the entire product. Such a representation of

information is impossible to achieve with traditional representation schemes without loss of transparency, clarity and compactness.

To provide support for a more detailed quantitative analysis, an extension of our framework is planned, featuring a limited bi-directional mapping between the selection domain and the appearance domain. This would permit an interactive user dialogue displaying some quantitative data of user-selected items from the glyph, and would save time by establishing a link backwards between visualized information and original data and their quantitative values. Further enhancements currently under consideration are the integration of two further glyph dimensions, namely time and sub-divided life cycle phases. Time could be used as a natural parameter to display animated glyphs which change their appearance as a design solution evolves. Life cycle phases could also be sub-divided. For example, the post-use phase could be divided into recycling, re-manufacturing, disposal, etc., with additional glyphs replacing current ellipsoids. The additional glyphs would display further details of the information and knowledge available and could be used to increase the information content of the appearance domain as introduced.

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