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COMMUNICATING LIFE CYCLE ASSESSMENT RESULTS TO DESIGN DECISION MAKERS: NEED FOR AN INFORMATION VISUALIZATION APPROACH

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ABSTRACT

Most of the design interventions made in the pursuit of reducing the environmental impact of products, often merely results in shifting the burden from one environmental issue to another, rather than reducing the overall environmental impact. This necessitates the use of more quantitative, comprehensive, life cycle based approaches for eco design decision making. In this paper, it is argued that the complexity of the results of LCA due to their data intensiveness calls for a need for using information visualization approaches to enable interpret LCA results for eco-design decision making.The paper then argues for a support for communicating the results of LCA to various decision-makers in order to improve their chances of building better environment-friendly products.The proposed nove information visualizationl architecture is intended to serve as a basis for a better representation of LCA results and provide deeper insights into the results of LCA, thereby aiding design decision-makers to improve the chances of reducing the environmental impacts of product life cycles being designed.

Keywords: complexity, communication, life cycle assessment,visualization, eco design

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1 INTRODUCTION

Life Cycle Assessment (LCA) is currently the most rigorous, scientifically verified, quantitative decision aiding tool for designing better environmentally friendly product life cycles (Kota, 2010). LCA is no longer a purely "voluntary" or "freestyle" activity; rather, it is seen as a fundamental activity in most of the organizations (Biltz et al , 2012). Application of life cycle assessment is increasingly becoming part of the product development process (Ameta, 2009).

Communication refers to meticulous interpretation of results of LCA to gain insight into the data and methodology and to build credibility on the results of LCA for design decision making. However, the issue of communication of Life Cycle information has been a complex and persistent issue in the LCA community. Although this has been identified (Kloffer, 2000) since early application of LCA, it continues to remain a pressing issue (UNEP, 2009). Dedicated expert group workshops are being conducted to advance the understanding of current issues and to formulate future research needs in this direction, including, a workshop in 2008 about communicating LC Information in the building sector, and another one in 2009 aimed at the retail sector, which called for development of target-specific communication interfaces for design decision makers (UNEP, 2008). Before delving into the issues of communication, this paper briefly discusses the main stages in LCA and applications of information visualization.

LCA (ISO 14040, 1997) has four stages: the first stage, *Goal and Scope Definition* describes the purpose of the study and “comprehensiveness” of an LCA through the breadth of the system boundary and environmental impact categories. The second stage, *Inventory Analysis* stacks the inputs and outputs of each individual process in an “inventory table” with respective units and preferably with a description on the level of uncertainty of the data. The third stage, *Impact Assessment* computes the potential environmental impacts with the input and outputs. The fourth stage, *Interpretation* assesses the results of Inventory Analysis and Impact Assessment stages in relation to the goal of the study (ISO 14040, 1997).

LCA results contain abstract units like eco-points or impact-potentials that are aggregate scores of several parameters e.g. carcinogenic potential, global warming potential, etc. These in turn are obtained from multiple inventory datasets, and hence are difficult to be interpreted strictly in terms of numbers. Moreover, interpretation needs to be done w.r.t the system boundary and goals, using information on uncertainty. Meticulous interpretation of LCA results can improve credibility and provide rationale behind LCA based decisions for designers to communicate to top management or cross functional teams.

Representation is a lens through which decision makers interpret LCA results and build a mental model of the environmental impact of a product’s life cycle. Effective representations could help design decision makers to quickly and easily assess (credibility of) LCA results for decision making. Computer supported information representations, in general, are studied in the relatively recent field of “information visualization”(Mazza, 2004). Information visualization is defined as “use of computer supported, interactive, visual representation of data to amplify cognition” (Shneiderman, 1996). Information visualization as an act or process refers to a cognitive activity, facilitated by graphical external representations from which people construct internal mental representations of the world. Larkin and Simon (1987) in their seminal paper “Why a diagram is (sometimes) worth ten thousand words” classify representations into diagrammatic and sentential; they argue that effectiveness of diagrammatic representations is due to their spatial clarity and the higher visual bandwidth of human brain to perceive information in parallel as opposed to sequential processing required to perceive sentential representation.

Information visualization is moving out of research laboratories with growing number of commercial products for a range of applications like Sport fire or Table lens to domain-specific tools such as molecule viewers for drug discovery or GIS tools for the petroleum industry (Plaisant, 2004). Information visualization has also benefited the general public through real time visualization of traffic information to financial market information through Smart Money.

2 OBJECTIVE AND METHODOLOGY

The objective of this paper is two-fold. One is to *identify the current issues* in communicating the results of LCA; the other is to *propose a novel information architecture* based on information visualization principles along with an eco-design decision taxonomy to address some of these issues. By design decision makers we mean those who are involved in decision making at strategic levels, e.g. industrial designers, engineering heads, directors of marketing, etc., and at operational levels, e.g. design engineers, manufacturing planners, supply chain managers, process engineers, environmental specialists and so on. LCA results refer not only to the computed *outcomes* of life cycle impact assessment models, but also to all the *information* required to *make sense and assess credibility* of the outcomes; these may include geographical information about the supply chain, environmental causation of materials and processes, and quality of input data used to compute these outcomes. Depending on the level of detail of data required for assessment, LCA is categorized into comprehensive LCA (which is data-intensive) and streamlined LCA(which is useful when data is scarce).

The questions asked in this research are the following:

1. What are the issues in communicating comprehensive LCA information to design decision makers?

This question is addressed by reviewing literature on: application of LCA in product development, process industry, marketing and retailing; methodological developments and issues of LCA, and survey of LCA commercial tools

2. What among these issues can be attributed to issues in information representation and why?

This question is addressed by reviewing literature on visual representation of information, visual perception, and requirements of design decision makers for eco-design

3. What information representation is effective in communicating comprehensive LCA for design decision making?

This question asks as to what information is necessary for design decision-makers for taking eco-design decisions, and is addressed by applying the following two steps. The first is to map information requirements of designers for eco-design decision making to the information that can be retrieved from LCA. The second is to map and visualize this information within a novel information architecture proposed in this paper for communicating LCA results; the architecture is based on environmental information requirements of eco-designers and theories of visual perception and representation.

A survey of literature on tools for supporting communication of life cycle information indicates that such tools are rare, with the exception of *Source map*. Source map is an open-source streamlined LCA communication tool that geographically maps the location of a supply chain and computes the carbon footprint of upstream supply-chain processes. Source map has been useful in engaging all stakeholders of a product in its life cycle, and helped exchange data in a transparent, collaborative manner, enabling them to think about whole life cycle (Bonanni et. al, 2011). However, Source map currently uses only carbon footprint as the indicator and lacks in representation of target-specific information.

3 ISSUES IN COMMUNCIATION OF LCA RESULTS

Issues in Communication of LCA can be broadly categorized into two sets. The first set contains technical issues, such as lack of an effective representation for communicating LCA results (Ragnerstam, 2010; Mueller, 2003), lack of tools that provide insight into uncertainty (Kota, 2009; Bjorklund, 2002), lack of tools that provide target-specific life-cycle information needs (UNEP, 2009), lack of availability of representative inventory datasets(Sonneman,2011; Ameta 2009), and lack of spatio-temporally differentiated models for life-cycle impact assessment (Reap, 2008).The second set contains socio-cognitive issues such as lack of willingness to adapt in organizations, lack of training to employees, customers and supply chain in environmental issues, lack of integration of environmental issues with organizational mission at every level of decision making and inclusion of all stakeholders in organizations (Boks, 2006). Most of the pressing socio-cognitive issues lie outside the technical sphere, and many of the technical issues are too complex (e.g. developing life cycle impact assessment models) to be addressed within an individual research problem and calls for collaborative multi-disciplinary approaches. In this paper, we discuss only those issues that are related to representation for communicating LCA results.

3.1 Issues in Representation of LCA Results

In order to provide an understanding of the representational issues and delineate the scope for adoption of information visualization approaches, the complexity of communicating LCA information is discussed in terms of the data intensiveness and information flow in LCA.

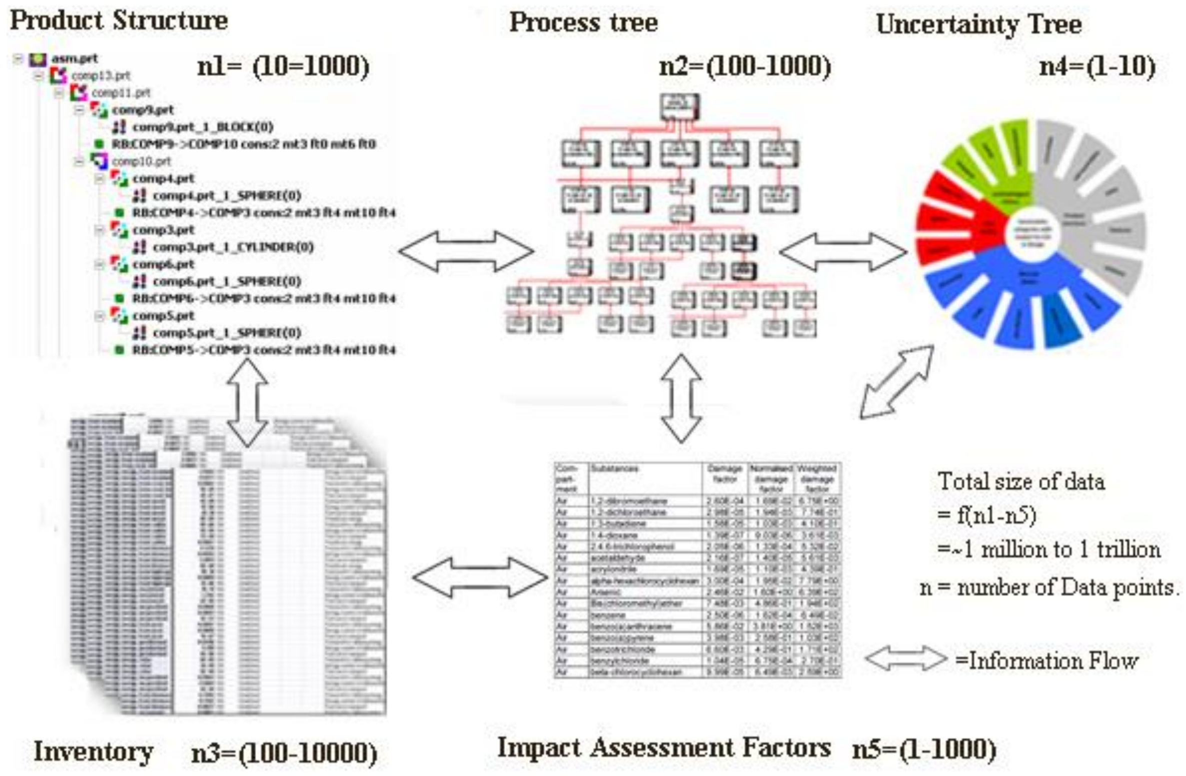

Figure 1. Complexity of LCA: Various dimensions

Life cycle assessment approaches systematically split the product down into its components (Figure 1, shown as product structure) and associated manufacturing processes (Figure 1, shown as process tree), and measure their impacts on ecosystem health, human health and resource depletion by compiling each input and output from all the processes from the beginning of material production till the final disposal of the product. For each component of the product or system, the analysis can run into thousands or more of discrete, individual processes (Goleman, 2010). Each process represents an aggregate set of data on input-output materials, energy and emissions, which may run into several thousands. Each data-point can contain information about its accuracy, spatio-temporal relevance and representativeness for the assessment being conducted. For each input/output data, there can be characterization factors which indicate the relative severity of a particular compound to various environmental categories. Therefore, for a complex product, the size of the dataset may be anywhere between one tenth of a million to a tenth of a billion, depending on the system boundary and number of impact factors considered.

Comprehensive LCA

A review of the commercially available comprehensive LCA tools has been done by reviewing the full versions (where accessible), demonstrations (where full version was inaccessible), and using analysis reports on LCA software (e.g. Cooper, 2006; Rice, 1997). Based on this review, various issues related to representation of results that could strongly influence interpretation of the results and usefulness are identified. It is found that, currently comprehensive LCA results are represented either in a set of impact categories at the midpoint level (e.g. climate change, acidification, etc.), or at the end point level (e.g. human health, eco-system health, etc.). One has to navigate through multiple data-points before being able to interpret the causes that are responsible for the impacts to occur. However, such tracking of results through navigating large datasets multiple times causes cognitive overload, affecting interpretation (Shrinivasan, 2008). LCA results are currently computed from multiple scattered data sources and retrieval for information for interpreting is time consuming and requires proficiency in using the tools.

Streamlined LCA

Streamlined LCA provides a blackbox representation of LCA.A black box representation is a special case of two-dimensional data representation, in which there is no facility for representing methodological data used for calculation. For example, Fig 2(a) shows an explicit representation of the methodological data used for calculation of end scores for the lifecycle of a common wood-graphite pencil. In streamlined LCA, there is no such facility to represent underlying data. This reduces the credibility of such tools for use in a decision making context. Stream lined LCA tools are useful in the conceptual stage of product development, where availability of life-cycle information is scarce. However, most of the streamlined LCA studies remain merely academic exercises, without supporting decision-making in an industrial product development context. The intent is not to criticise the use of Streamlined LCA, but to encourage using Comprehensive LCA to compliment the inferences derived from streamlined LCA wherever possible. Comprehensive LCA provides more accurate information, and more precise picture of the consequences of a lifecycle using methods such as impact assessment, scenario analysis, uncertainty analysis and contribution analysis. Therefore, it is argued here that interpreting comprehensive LCA results should help designers improve the rigor of lifecycle thinking through gaining insight into the parameters that influence the lifecycle of a product, and how a change in such parameters is likely to influence the environmental impact of the product.

3.2 An Information Visualization Approach

Information visualization provides promising tools for handling large datasets (typically of size more than 10^4) and has been widely used in representing large datasets in medical domains, ecological domains, social networks and financial markets to obtain insights into the data and aid decision making (Natarajan, 2010, Shneiderman, 1998).Although there have been efforts to apply its principles into LCA (Otto 2004),no evaluation studies have been conducted on how effective the representational examples provided by these authors have been in decision making. Consequently, there has been no adaption of these principles into commercial tools. In this paper, current LCA representations have been revisited from an information visualization perspective. Information visualization literature offers guidelines for designing effective representations, and general methods for evaluating effectiveness of large data representations (Mazza 2009). The representations used in the three categories of current LCA tools (i.e. Comprehensive LCA, Streamlined LCA, and (Stream lined) LCA-Communication) have been evaluated using a multi-criteria evaluation method. The effectiveness criteria of interactivity and dimensionality have been adapted from the Information Visualization domain (Park, 2010) and Uncertainty and Target Specificity have been adapted from the LCA domain (UNEP 2009, Bjorklund 2002).

Table 1.Current representational issues in LCA tools

Representational Issue		Full LCA tools	Streamlined LCA tools	LCA communication
Interactivity	Overview	No	No	No
	Details on Demand	Yes	No	No
	Filter	Yes	No	No
Dimensionality	Category	Over-reduction	Black box	Black box
	Environmental Pathways	No	No	No
	Spatio-temporal	No	No	Yes
Uncertainty	Data quality	Yes	No	No
	Uncertainty types	No	No	No
Target specificity		No	No	No

Interactivity: This refers to facilitating users to look into the data by providing interfaces for querying the data and gaining insight. Interactivity is an essential part of information visualization. Without interaction, representations become static or autonomously animated images (Yi, 2007). Static representations are common in current LCA tools. However, even though statistic representations have analytic and expressive value, they have limited use in exploring large datasets (Yi, 2007). An overview can be useful in assessing the scope and system boundary. Overview with details on demand can be potentially used to quickly identify causes for hotspots, key parameters, etc. Filters help in reducing the complexity of representation by eliminating display of elements contributing insignificantly.

Uncertainty: This refers to providing insight into the sources and types of uncertainty associated with the data. Although several quantitative approaches for estimating uncertainty exist (Lloyd, 2006; Kota, 2010), visualization of uncertainty is relatively new and growing area of research (Skeels, 2008). Current full LCA tools provide aggregate representation of uncertainty, without indicating the types of uncertainty.

Target Specificity: This refers to the ability of representations to provide specific information for decision making (i.e. to target users). Such need for providing target specific information for various decision making tasks is emphasized by several authors (Sonneman, 2010, Kota, 2009; Bauman, 2004).

Dimensionality: This refers to the number of independent variables needed to represent life cycle results.

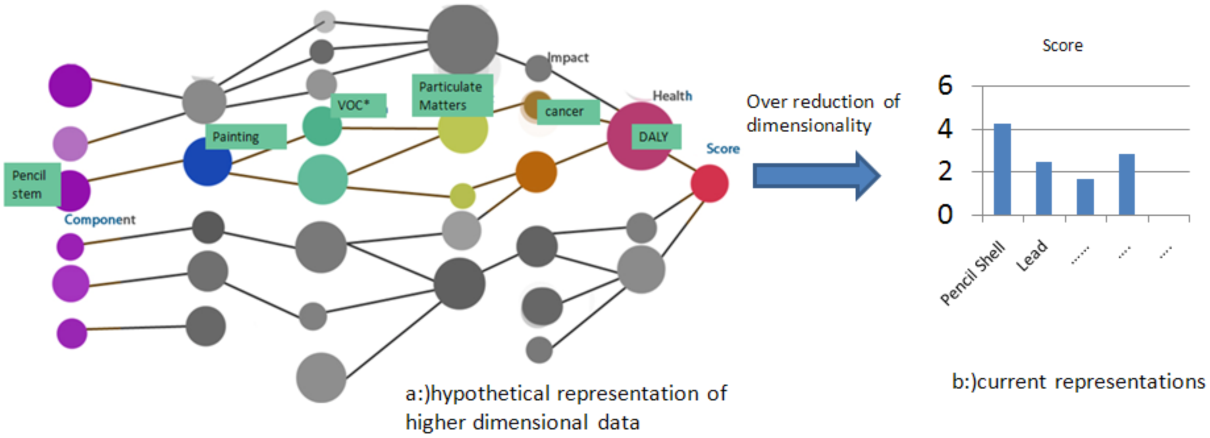

Figure 2 Demonstrating reduction of dimensionality of the data

The tree representation (Fig 2a) shows a multi-dimensional representation of results for an LCA of a pencil, as carried out in an earlier study (Devadula et al., 2012). Insight into inventory and methodological data can be made more explicit using a multi-dimensional representation as against a two-dimensional representation such as a bar chart (Fig 2b). For instance, in the pencil study, the bar chart indicates only the value of the aggregate environmental impact for the component called Pencil Shell, without indicating the factors and relationships contributing to this impact (the two dimensions are the impact value in eco-points and the corresponding component). On the other hand, a multi-dimensional representation could potentially provide rationale for the higher impact of a component by linking the endpoint scores to methodological data (e.g. potential risks of carcinogens) and inventory data (e.g. emission of volatile organic compounds) through environmental pathways as represented in Fig 2a. A geographical map can also be shown while zooming over a particular data point to indicate the spatial relevance of the data. Given such possibilities, reduction of the dimensionality of the data in current representations in LCA tools into two-dimensional bar charts hinder potential insights that could be obtained from the richer, original data.

4 AN INFORMATION ARCHITECTURE FOR COMMUNICATING LCA RESULTS

In this paper, it has been argued that it is important to provide decision makers comprehensive information on the whole lifecycle of the product in order to support them in exploring the consequences of their decisions, in the upstream supply-chain processes or in the downstream use or after-use processes. However, given the data intensiveness of such lifecycle information, it is equally important to be cautious of the resulting, potential, information-overload. In order to address such contradictions, we propose use of the golden principles of information “Overview first, zoom/filter, details on demand” (Schniederman, 1998) to present information at various levels of granularity within the decision-making context.

The information visualization approach consists of the following phases, as described in Fig 3.

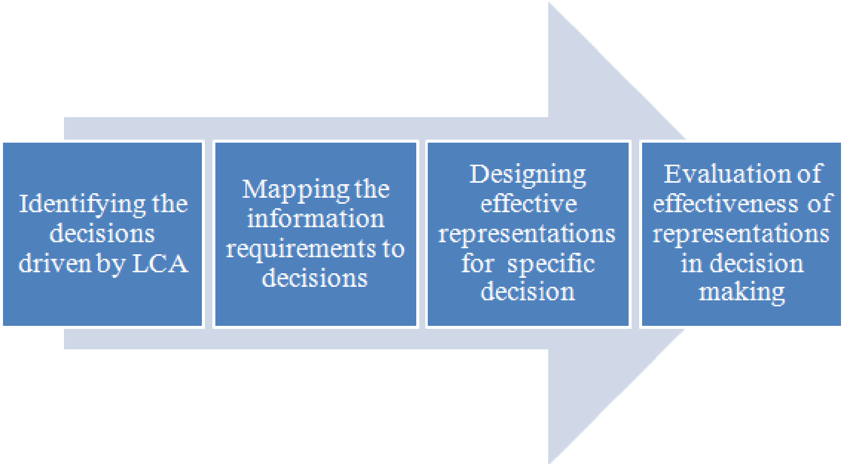

Figure 3. An Information Visualization Approach

The first two phases of information visualization have been addressed in this paper through literature review. An "Understand, Evaluate & Validate" (UEV) taxonomy of decision-making, and an information architecture has been developed based on the following literature. Through analyses of protocol studies on designers Kota et al (2010) identified "understand, evaluate, modify, select, and generate" as the key decisions in eco-design processes. Srinivasan and Chakrabarti (2010) proposed the GEMS of SAPPhIRE model of designing, where Generate-Evaluate-Modify-Select (GEMS) has been identified as designers' decision tasks that are common to any design. Bakker (1994) conducted case studies and semi-structured interviews on industrial designers engaged in eco-design projects within organizations to develop an Environmental Information Matrix where he maps the supply-side of environmental information to the demand-side, for each stage in eco design. Although these studies are useful inputs for eco-design tool developers, none of these studies provided information according to target-specific applications, a desirable aspect in information visualization as it absolves decision makers from having to make a large number of queries to retrieve required information. The above literature includes both analysis and synthesis types of tasks in design. However, supporting synthesis-based decisions are beyond the scope of the current research, as LCA results do not provide any explicit guidance or stimuli for synthesising new designs, or for modifying existing designs.

Decisions	Sample Information Requirements	Sample Representations	Sample Application	Sample Validation Questions
Understand	End Point scores Key Life cycle phases Goal and Scope	Interactive 2D (pie/bar) Interactive tree chart Overview	Setting environmental targets Setting environmental targets Eco labeling	What are the hotspots? Which are key processes? What are various scenarios?
Evaluate	Process input/output Environmental Pathways Product Input/output	Interactive tree +Maps Zoom/Filtering Multiview	Evaluation of the design alternatives Competitive benchmarking Evaluation of life cycle scenarios	What are the causes for hotspots? What are the key design parameters? What are better design alternatives?
Validate	Inventory Data Methodological Data Data quality	Interactive tree +Maps Zoom/Filtering Multiview	Critical Review Communicating market information Compliance with ISO standards	Are outcomes reliable? Are the data representative? How comprehensive are the results?

Figure 4.A Proposed Information Architecture for Information visualization

Since supporting decision making is the major goal for visualization of LCA results, the proposed information architecture is centered on decisions (Figure 4). The information requirements have been mapped into each decision task based on the premise that *Understand* provides the lowest granularity of data (e.g. aggregated or weighted data) that is useful in identifying key hotspots, processes, materials, lifecycle phases and key impacts, whereas *Evaluate* provides data of medium granularity that is useful for understanding different inputs and outputs (e.g. Process data) that cause impact, and for locating of such inputs and outputs in the lifecycle phases. *Validate* provides data at the highest level of granularity (e.g. raw data which may contains qualitative or quantitative description on uncertainty) useful for gaining credibility on the quality of the data, and for making environmental claims. The information has been sequenced according to the level of granularity. Decision makers at the strategic level may need highly granular data (For example life cycle carbon footprint) whereas decision makers at operational level may need less granular data (For example toxicity-potential of an emission process).The proposed information architecture can potentially reduce information overload as it structures the information in a logical sequence as required for various decision making tasks at various degrees of granularity, and to provide a framework for organizing target-specific information for various decision-making tasks. The resulting visualization could be extended to communicate to consumers by interfacing with mobile devices and RFID devices where consumers should be able to visualize the environmental and health impacts of their purchasing decisions. The visualization could also aid LCA experts to quickly and easily communicate the results of LCA studies to policy makers, and influence policy decisions. The usefulness of the proposed architecture will be driven primarily by the availability inventory and methodological data for a each product category. Thus such approaches would be applicable for comprehensive LCA tools and of little use for Streamlined LCA tools as they do not provide much inventory and methodological data.

5 CONCLUSIONS AND FUTURE WORK

In this paper, representational techniques used in current LCA tools have been reviewed, and issues with these from an information visualization perspective have been identified. A new information architecture to serve as a framework for visualization of LCA results as per the target application has been developed.

Future work includes execution of the remaining phases of the visualization approach. This involves designing alternative representations for a hypothetical LCA example, Evaluating of the effectiveness of alternative representations based on the effectiveness criteria and sample validation questions proposed in Figure 4. The proposed information architecture is intended to serve as a framework for developing an effective representation for LCA results and to ultimately support design decision-makers to improve the chances of reducing the environmental impacts of product life cycles they design.

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