A Concept for Graph-Based LCA Analysis Tool

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Abstract. Life Cycle Assessment is a comprehensive life cycle approach that quantifies ecological and human health impacts of a product or system over its complete life cycle [5]. The existing LCA and environmental assessment tools do not model the relations between different lifecycle factors or different environmental dimensions and focus mostly on the inventory analysis. The main idea of the proposed concept is to develop environmental assessment tools in order to evaluate the environmental performance and deliver a dynamic environmental profile for products, services and processes, by taking into account the various dimensions of environmental impact, as well as the relations between different factors in their lifecycle. Furthermore, this concept proposes a graph-based representation of different lifecycle factors and dimensions in order to facilitate the visual analysis and simulation of the product/service/process lifecycle. Finally, this concept provides a way to model environmental KPIs as a representation to different lifecycle factors and a simulation environment.

Keywords: LCA, KPIs, Graph-based representation, Visual analysis,

1 Introduction

Environmental assessment is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made [1]. The leading tool for environmental assessment is life cycle assessment (LCA). LCA is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—and others[2].

Environmental processes are often very complex and convoluted that makes it difficult to model an LCA. LCA is often data intensive. LCA software further helps to structure the modeled scenario, displaying the process chains and presenting and analyzing the results [3]. Although, software tools were developed to make the processing and calculation of LCAs easier and faster, most of these tools require expert knowledge to generate meaningful results and takes huge amount of time to make a full evaluation.

Therefore in this paper, we will present the concept of graph-based representation and analysis of the various relations between different aspects of LCA. With this concept we aim to make the decision process faster and far more intuitive. The graph-based representation of LCA factors will facilitate the capturing of implicit knowledge on the LCA domain as well as the knowledge sharing between different actors of the LCA and beyond.

In section 2 of the paper, we present the necessary scientific background, starting from an overview of the LCA approach, its value and requirements. We then provide some key information concerning the graph theory and the significant benefits of using graphs to represent knowledge, as well as some basic background for employing KPIs in LCA. In section 3, we present the concept overview for the graph-based LCA analysis, showing the dependencies and influences between different lifecycle (LC) indicators, as well as the proposed visualization. In the final section, we conclude our work, demonstrate the expected benefits and describe the various next steps of the approach.

2 Background

The authors in [11] and [12] have performed a literature survey gathering and explaining the major current issues and problems in LCA being addressed in recent LCA research. These issues, such as boundary selection, spatial variation, environment dynamics and data availability are spread among the LCA phases and are classified according to their severity and solution adequacy.

In the next subsections, we present some important background on LCA, graph theory and KPIs in order to provide a better understanding of the proposed approach.

2.1 Life Cycle Assessment

LCA is an internationally recognized approach that evaluates the potential environmental and human health impact associated with products and services throughout their life cycle, beginning with raw material extraction and including transportation, production, use, and end-of-life treatment. LCA is the only tool that can make a full evaluation of all sources and types of impact over the entire life cycle of a product. ISO standards have been developed for LCA providing a framework, terminology and some methodological choices (ISO 14040 2006; ISO 14044 2006).

Among other uses, LCA can identify opportunities to improve the environmental performance of products at various points in their life cycle, inform decision-making, and support marketing and communication efforts. LCA exposes the hot spots and strengths of a product, compared to the alternatives. However, in order to make an appreciable LCA, it is necessary to choose the functional unit properly, determine the system boundaries to cover all important stages of the lifecycle of the product and choose the life cycle impact assessment methodology to calculate the desired environmental impacts important for the company.

The LCA methodology is standardized by a series of ISO standards and includes the following phases:

- Goal and scope definition (ISO 14041) [8]
- Inventory Analysis (ISO 14041) [8]
- Impact Assessment (ISO 14042) [9]
- Interpretation (ISO 14043) [10]

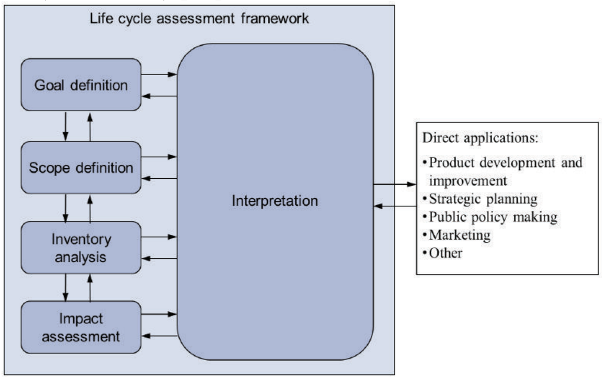

Fig. 1. LCA Methodology (ISO 14040) [7]

2.2 Graphs

Graph theory is a very useful visual representation because the elements of the graph can be defined in such way so that they have a one-to-one correspondence with elements of many kinds of engineering or general real-world systems and situations. A graph is a finite set of dots called vertices connected by links called edges and exist in a variety of forms, from simple graphs where up to one edge can connect two vertices to more much more complicated graphs, such as multigraphs, pseudographs or digraphs. Graph theory has been systematically investigated and widely used because through their graphical representation of real-world systems, it provides a better understanding of many of their properties and relationships whereas the theorems and algorithms of graph theory can allow for an effective representation of their behavioral attributes. [6]

Graphs provide a unique visual way to represent knowledge in various kinds of forms such as facts and constraints. They possess very useful modeling and computational qualities and the knowledge of the mathematical properties of these graphical representations can be used to achieve an augmented overall understanding of a domain and even deduce implicit knowledge that was not known even to human experts. Conceptual graphs in specific provide the formalism for graphical representation that expresses knowledge in a manner that is logically precise, humanly readable and computationally tractable whereas with their graphic representation, they serve as a readable, formal design and specification language. [6]

2.3 KPIs

KPIs are quantifiable metrics that reflect the environmental performance of a business in the context of achieving its wider goals and objectives [4]

Concerning LCA, adequate environmental performance management and reporting can lead to significant benefits for both business and environment perspectives [4]. The environmental performance management and reporting require the consideration of a set of appropriate environmental indicators.

3 Graph-based LCA

The main idea of the approach is based on the concept of graph based representation of different lifecycle factors which influence a product/service/process during its lifecycle. Factors are defined as the various activities during the lifecycle which influence its environmental performance e.g. farming, manufacturing. They are represented as KPIs which could have mutual dependencies and can influence each other in many different dimensions. These interdependencies are represented as relations between the factors.

In this paper we propose an approach which covers all the phases of the LCA methodology, as shown in Fig.1. Graph-based representation of different LC factors supports the visual interpretation of the different aspects and phases of LCA. For example, using the graphs it is possible to visualize how the change of one factor (KPI) will affect the other. This concept provides the capacity to set up the goal and scope of analysis (e.g. carbon footprint below a threshold), and the system may then find all the possibilities and opportunities in order to achieve that goal. Furthermore, this supports the use of more advanced concepts, such as impact analysis which is specifically based on simulation scenarios and what-if analysis.

3.1 LC Dimensions

Lifecycle factors were mainly being considered until now as one-dimensional, meaning they could have only one aspect of influence corresponding usually to only one type of externality (e.g. carbon footprint). In this case, all the other types of externalities were modeled as completely separate indicators. Other dimensions such as time or location were often being neglected. As a result, it was impossible to model the different cross-dimensional relations and therefore to perform the cross-dimensional analysis.

In our concept we try to solve these issues by introducing the novel concept of dimensions and by proposing the new multi-dimensional definition of the lifecycle factors. Dimensions represent the different aspects of influence on the same factor, corresponding to different types of externalities. In this work, we have identified the following four basic LC dimensions based on different types of influences:

- **Temporal dimension**. E.g. change of one factor will affect the other in a month later.

- **Lifecycle phase.** E.g. one factor affects the other only in Middle-Of-Life phase.
- **Location**. E.g. one factor is related to the other in Germany, but not in Switzerland.
- **Type of externality**. E.g. two factors are related if we consider the CO_2 emission.

These dimensions can be used as filters and overall consist a powerful tool to visualize and analyze different types of influences. This concept is especially helpful for impact assessment of changes concerning different LC factors as well as for cross-dimensional analysis.

3.2 Reference model of LC KPIs and their interdependencies

Employing the graph-based representation of KPI interdependencies, we propose an reference interdependencies model which can be retrieved and/or inferred from the reference lifecycle inventory database or defined by an LCA expert. This concept supports capturing the experts' implicit knowledge about the different LCA processes. The abstract model represents the generic LC KPIs and the relations between them whereas for different cases it is possible to instantiate the abstract model and even to add new and/or override some relations and values of the LC KPIs.

Each KPI is defined by its name, formula and dimensions of the influences. KPIs are calculated based on their formula and LCIs retrieved from the reference database. Relations between KPIs are modeled as functions and it is possible to have multiple relations between the same two KPIs. These relations represent the influences regarding the different dimensions. Every KPI instance can have multiple values which correspond to the dimensions they are analyzed for. The relations between KPIs are defined by specified functions for each dimension, if they exist. It is important to note that if there is temporal dependency between two KPIs, then the relation is the function of *t*, which represents the time. Fig. 2 illustrates the multidimensional representation of a single KPI.

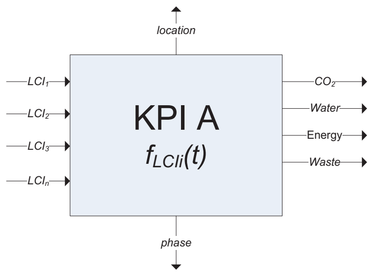

Fig. 2. Multidimensional representation of KPI

Using the graph-based presentation of KPIs interdependencies, unexpected or undesired KPI state changes can be easily detected. In this way, different kinds of analysis are supported and impact assessment can be easily performed. The user can also detect possible risks as well as infer new relations between KPIs which are not explicitly modeled. The elements of the one dimensional graph-based presentation are shown in Fig. 3.

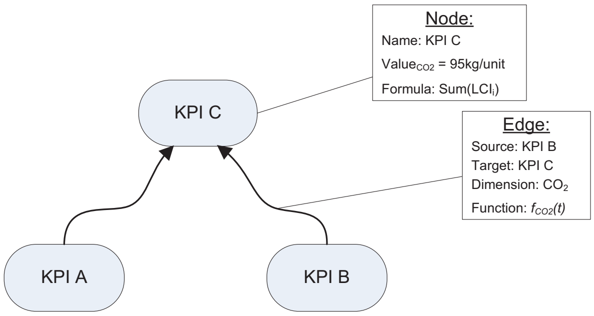

Fig. 3. One-dimensional visual representation of KPI dependencies

In order to implement the interdependencies model, the use of ontologies is recommended since they represent a very powerful concept and suitable for modeling graph-based knowledge. Furthermore, by using the advanced features of ontologies, it is possible to infer new knowledge which in this case would be new relations.

3.3 Visualization

This concept is based on the visual analysis and interpretation of the dependencies and influences between different KPIs. KPIs are represented as nodes (rectangle shape) and the relations between them are represented as arrows. For the representation of the status (or values) of different factors, the traffic light color-scheme is employed. For example, if one KPI surpasses a predefined threshold and thus is critical for the environment, it is colored in red.

This visualization method supports the so called cross-dimensional analysis, since it is possible to filter on different dimensions of lifecycle factors or KPIs which represent them and to visualize multiple dimensions and their mutual influences.

For example, in Fig. 4 we propose a way to visualize the proposed concept and perform the cross-dimensional analysis in the form of a software tool mock-up. The mock-up window is consisted of three main panes: LCA Graph pane, Dimension Filtering pane and the KPI Details pane. The LCA Graph pane visually presents the various dependencies between selected KPIs as well as their statuses. The Dimension filtering pane is consisted of several sliders which represent the different dimensions of the environmental influences. Lastly, the KPI details pane shows the details on the selected KPI such as its value, status, etc. with the capacity to generate reports.

In this example the user has selected to visualize specified KPIs and analyze its impact regarding selected dimensions (location: Germany; externality: CO_2) while observing the details on the overall Environment KPI.

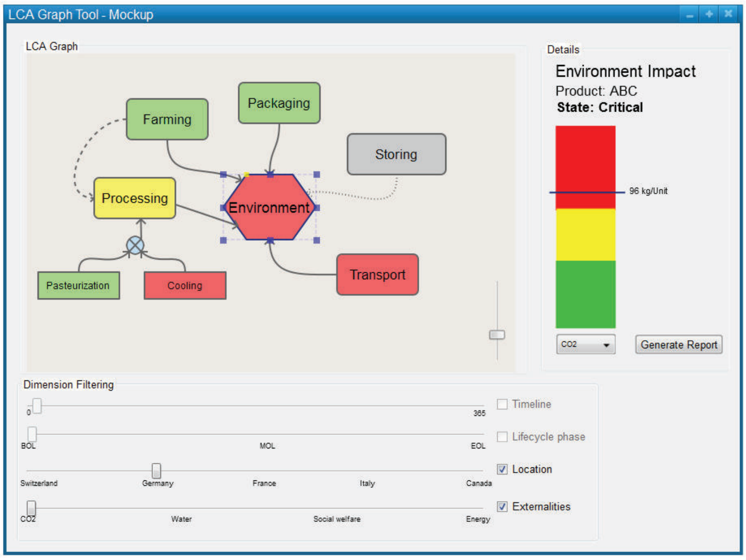

Fig. 4. LCA graph tool mock-up

In simulation mode, it would be possible for the user to change KPI values and visualize the impact on the other dependent KPIs and overall in the environment KPI. Furthermore, this concept supports setting up a goal in form of certain KPI value or value range, and the software should calculate all the possible opportunities and suggest the optimal strategies in order to achieve it. For example, the user can set the maximum value for the overall environmental KPI to be below the critical (red) threshold.

4 Conclusion and Future Work

In this paper we proposed a novel approach for LCA cross-dimensional analysis using a graph-based representation of different lifecycle factors in order to facilitate the visual analysis and simulation of a product/service/process lifecycle. The concept of dimensions was introduced in order to cover different aspects of LC influence, such as time, LC phase, location and type of externality. We presented a graph-based model of LC KPIs interdependencies visualization corresponding to specific LC factors and encapsulating multiple dimensions in order to deliver a dynamic overall environmental profile.

Concerning the expected benefits of the proposed approach, it would be possible for a user to evaluate the overall environmental performance of a product/service/process or even a firm, and through the visualized interdependencies to achieve better information visibility for improved decision support. This new type of analysis, entailing the novel dimensions, the easy customization and flexibility of the model and graph-based visual interpretation could provide much potential for a firm's optimization of environmental activities. The concept could provide new ways for identifying actions for e.g. reducing carbon emissions and significantly reduce the overall time needed for impact analysis.

The next step for this approach would entail the use of ontologies and the creation of a semantic model, since graphs convey the structural relationships of an ontology and possess the formalism to be represented by ontologies. By using the advanced features and specifically the reasoning capabilities of ontologies, it is possible to infer new knowledge by creating connections between data. The most important step would then be the implementation of the model and the application in a case study in order to evaluate its applicability and efficiency. Lastly, it would be significantly beneficial to further elaborate the model by linking the proposed concept for LCA with Life-Cycle Cost (LCC) analysis.

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