Real-time LCA tool for the assessment of environmental impacts in industrial production

Christos Koidis
Engineers For Business S.A.
Thessaloniki, Greece
ck741@efb.gr

Ioannis Tsampoulatidis
Engineers For Business S.A.
Thessaloniki, Greece
it321@efb.gr

Charisios Achillas
Dept. of Supply Chain Management
International Hellenic University
Katerini, Greece
c.achillas@ihu.edu.gr

Dimitrios Aidonis
Dept. of Supply Chain Management
International Hellenic University
Katerini, Greece
daidonis@ihu.gr

Athanasios Bantsos
Engineers For Business S.A.
Thessaloniki, Greece
tb827@efb.gr

***Abstract*—This work discusses the key features of the LCA Simulations Engine, a new tool developed for real-time assessment of environmental impacts in industrial production using widely acknowledged Life Cycle Assessment methodologies. The LCA Simulations Engine provides a number of advantages over LCA software competition such as the dynamical fetching of data from several sensors, an enhanced user experience while using the web-based application, and an API in order to serve requests from other components and/or industrial use cases enabling a machine-to-machine collaboration at a nearly fully automated way. The LCA Simulations Engine is available online at https://lca.efb.gr.**

Keywords—Life Cycle Assessment, real-time, sensors data, environmental impact, ISO 14040, circular manufacturing

I. Introduction

Life Cycle Assessment (LCA) is a widely acknowledged methodology that aims at quantifying the environmental impacts that come out from materials and processes inputs and outputs, such as energy consumption or air emissions, over the entire life cycle of a product, process, or service. The main purpose of LCA is to assist industries and consumers in their decision-making, towards designing and establishing more sustainable products, processes, or services. In brief, LCA is a "cradle-to-grave" approach, beginning from the collection/ production of raw materials required to manufacture the product and ending at the stage in which all the materials are returned to the earth. The goal of LCA is mainly threefold:

- To quantify all the inputs and outputs within the life cycle of a product, process, or service.
- To specify the potential environmental impacts of the material and process flows.
- To propose hotspots and alternative approaches that could minimize the impacts.

The potential benefits of LCA analysis are numerous. Indicatively, LCA; (a) provides an overview of the environmental impacts of a product, process, service or a whole company, (b) quantifies the environmental impacts related to an activity (e.g. the overall energy or water consumption, air emissions, waste production, etc.), (c) allows the comparison with the use of alternative materials and/or processes in order to improve product or service design, (d) provides insights, not only in the "use" phase, but also in the "design" and "manufacturing" phases, (e) highlights inefficiencies or hotspots and areas that can be improved across all life cycle phases, (f) contributes to the reduction of the overall environmental impact and costs of the organization, to name a few.

II. LCA Methodology

Life cycle analysis follows the extraction of a product from the environment and traces it until it is deposited back to the environment. Therefore, LCA refers to the damage imposed in the life span of the product (product system) and is strictly environmentally oriented. Social or economic figures are not part of the LCA, even if possible.

In principle, LCA may handle multiple products and product systems that contribute to a specific function. Moreover, LCA can include extraction processes, as well as waste management activities (cradle to grave analysis) or can be focused on certain processes with a more limited scope. The LCA methodology was developed in the 1990s, by the International Organization for Standardization (ISO), to standardise the structuring and interpretation of such study reports. More specifically, LCA reports should include the following steps, in a strict, standardized, order:

- Goal and scope definition: This section analyses the purpose of the LCA, the type of the LCA, the product system under examination as well as the locational and temporal scope [1]. Sub-steps of this phase are the goal definition, the definition of the functional unit in order the results to be comparable with other studies, and the definition of the system's boundaries.
- Inventory analysis: This section includes all the inputs in terms of materials and processes, as well as all outputs (emissions, waste, etc.).
- Impact assessment: This section presents the resulting impact assessment.
- Interpretation: In this step conclusions are drawn from the whole LCA study, and the impact assessment results are presented and critically discussed.

As illustrated in Fig. 1, an LCA study is a dynamic process, with every step playing its role and contributing to changes forward or backward [2].

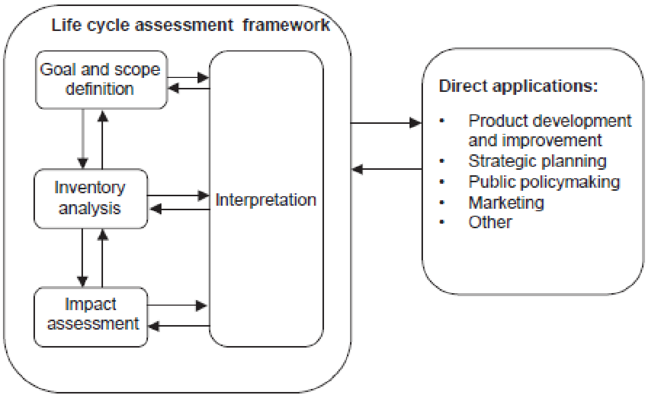

Fig. 1. The structure of the LCA analysis [2].

The accuracy of the impact assessment of an LCA study depends highly on the data used for the analysis, namely the Life Cycle Inventory (LCI). An inventory analysis includes all inputs and outputs of the system. More specifically it includes the construction of a model for the examined system (in the form of a flow diagram), data collection (input and output definition), and reporting of all elementary flows.

Usually, LCA studies are conducted with the use of a software. In most, if not in all, software, there are prepopulated databases that contain data for materials and processes and the inventory analysis is automated to a great extent [2]. Specific materials and processes are assigned to material and energy consumption, as well as with certain emissions to air, water, or soil. In the literature (and in the market), there are many free or commercial LCI databases available such as ecoinvent [3], which is probably the most well-known database. A list of such LCI databases is provided in [4].

Moreover, in literature, there is a number of different Life Cycle Impact Assessment (LCIA) methodologies available, indicatively CML 1992, EDIP, TRACI, Eco-indicator 95, Eco-indicator 99, IMPACT2002+, ReCiPe. A more detailed list of such LCA methodologies is provided in [5].

III. The LCA Simulations Engine

Today, there are several LCA software available in the market. Some of them share their academic background on LCA, while some others have been developed to support businesses on measuring their environmental footprint and/or are focused on specific industries [6].

The most widely used such LCA software are openLCA [7], SimaPro [8], GaBi [9], Ecochain Mobius [10] and oneclicklca [11]. However, all the aforementioned LCA tools provide a static view of the environmental impacts that are related to a product, process, or service. This means that the results are calculated on quantitative inputs in terms of e.g., materials, water, and energy, but taking into consideration only average values. Moreover, the results with the use of the conventional LCA software, heavily depend on average values as those are included in the LCI databases that are connected with the tools.

In this light, and in order to overcome these deficiencies, the LCA Simulations Engine has been developed as a key component of the innovative KYKLOS 4.0 circular manufacturing ecosystem based on novel Cyber-Physical Systems (CPS) and Artificial Intelligence (AI) based technologies, enhanced with novel production mechanisms and algorithms, targeting on personalised products with extended life cycle and promoting energy efficient and low material consumption intra-factory production processes, resulting in reduced greenhouse gas emissions and air pollutants [12].

The LCA Simulations Engine (available online at https://lca.efb.gr) presents a number of advantages over LCA software competition, in different aspects, as briefly presented below:

- **Real-time functionality:** The LCA Simulations Engine can receive input and provide output in (near) real-time and detect hotspots for improvement when the environmental impact indicator, or indicators, exceed pre-defined threshold values set by the user. The Engine enables the dynamical fetching of data from several sensors, linking them to flows and processes both via the User Interface (UI) and the Application Programming Interface (API) (machine-to-machine), which constitutes a major differentiation to market competition, which is based in average data, as discussed before. The output(s) of the analysis (e.g., environmental footprint) can be compared with results from other databases, real-life trials and/or pilot validation trials for process improvement. The LCA Simulations Engine can be totally automated from existing design data and fully integrated into the workflow, without disrupting it or slowing it down, enabling cost-efficient and circular benchmarking.
- **User Interface:** The LCA Simulations Engine provides an enhanced user experience, while using the web-based application. Since its early implementation phase, special focus has been given on the design of the user interface and the overall Human-Computer Interaction (HCI).
- **Flexibility:** In order to serve requests from other components and/or industrial use cases, an API has been created. In this context, machine-to-machine, collaboration is enhanced in a nearly fully automated way.

LCA Simulations Engine is used in several pilot industrial use cases providing dynamic results on the environmental impact of the processes [13].

Currently, the tool supports multiple databases but demands manual pre-processing in order to make them available to the UI. Ideally, in the future, users will be able to define a customised db-schema for importing new databases via a wizard like step-by-step instructions mechanism.

IV. Technical Specifications

Due to performance issues that arise when scaling up monolithic applications, the LCA Simulations Engine was intentionally built as a service-oriented application from the beginning, rather than attempting to disentangle a large application later on. This section provides technical details about the LCA Simulations Engine, focusing on its highly decoupled architecture. Each layer of the tool - namely the frontend, backend, and storage layer - can be deployed separately on servers in the cloud or containerised either partially or entirely. This section explains the features and functionalities of each layer, as well as technical specifications, the information model, and the interface model. Additionally, it provides a brief explanation of the ecoinvent database [3], which is used during the implementation phase to interpret data.

The conceptual high-level architecture and the key components of the LCA Simulations Engine are depicted in Fig. 2.

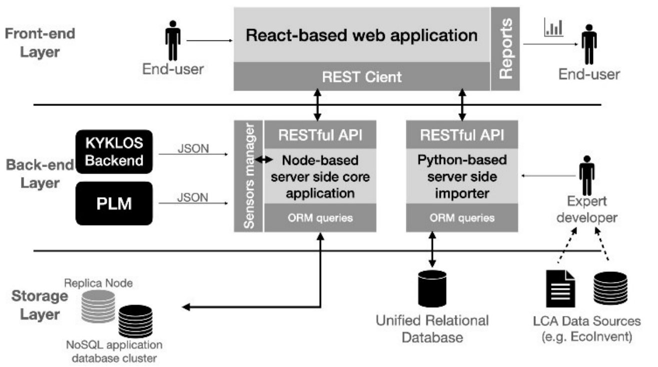

Fig. 2. Diagram of the LCA Simulations Engine architecture.

A. Front-end layer

This UI layer contains the frontend, which is the main gateway of the LCA Simulations Engine for the end-users. It is a web-based application implemented in React.js, using the Next.js framework [14]. The latter gives a variety of advantages, in comparison with plain React, such as lazy loading, image optimisation, code-splitting and bundling, and others. Special care is given to smart caching which allows a flawless experience without blocking factors and long loading times.

The LCA Simulations Engine adheres to best practices from the field of HCI in its interaction with the user. These practices include avoiding blocking error dialogs and inactive buttons. For instance, if a user is not permitted to add a new process, instead of displaying a pop-up message, an animated bell icon highlights the issue. A message, also known as a toast, appears briefly with a potential solution and automatically disappears unless the user hovers over it with the mouse. The tool employs animations in various situations, but they are designed not to distract the user. When feasible, sidebars are also used to avoid transitioning between pages (e.g., the settings layout is adjusted when being accessed directly from the project page). Moreover, page transitions are instantaneous as the tool preloads the layouts.

The LCA Simulations Engine utilises intelligent caching and other techniques to improve the user experience while retrieving data from the server. For example, the tool automatically retries (up to three times by default) when attempting to contact the server before encountering an error. Additionally, smart synchronisation and adept state management techniques are employed when data is altered.

As illustrated in Fig. 3, the UI is accessible from every device, no matter the screen resolution or orientation. It automatically adapts its layout to make it functional and usable. Dark mode is also supported to help users using the app in dark light conditions.

React based apps need a way to keep the local state and take the necessary measures to avoid unnecessary re-renders. For this purpose, React.Context and Zustand, were used in order to provide a seamless experience for the end-user. For the look-and-feel of the application, Chakra-UI library was selected, also applying some extra customisations, to cover third party components and the industrial use cases supported by the app.

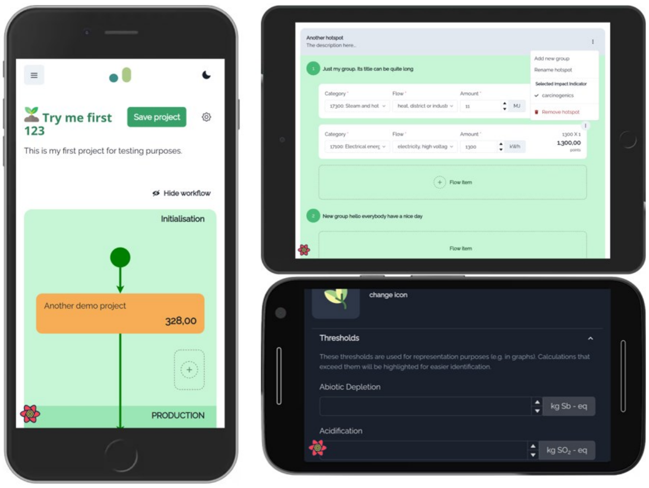

Fig. 3. The LCA Simulations Engine application responsive design.

B. Backend layer

The backend side of the LCA Simulations Engine acts as a middleware between the frontend and the storage (database) layer. It hosts the complete application programming interface of the app, allowing third party systems and other KYKLOS 4.0 ecosystem's components and industrial use cases to exchange data with the LCA Simulations Engine. It also handles streaming from connected sensors to the frontend by pulling data from the corresponding REST methods offered by the Product Lifecycle Management (PLM) and the KYKLOS 4.0 Backend components.

The LCA Simulations Engine backend is datastore agnostic and has adapters for supporting multiple databases out-of-the-box. This means that several databases concurrently can be handled painlessly due to a consistent query interface. Currently, the backend uses MongoDB (via the mongoose ORM), but it is future-proof to support other databases as well. Moreover, the backend provides instant CRUD functionality via services, exposing a RESTful API which also allows machine-to-machine communication. The backend is a Node.js based app, using the feathers.js framework which provides out-of-the-box functionality such as hooks, models, and services.

C. Storage layer

The storage layer, as depicted in the architectural diagram (Fig. 2), provides the means to store every data that is needed for having the system function properly. It is totally decoupled from other layers and can be hosted in any cloud infrastructure or standalone server or be part of a virtualised container.

V. Impact Indicators Calculation

As already described, the LCA Simulations Engine receives impact calculation metrics from the database. The LCIA database is populated by entries that mainly correspond to methods, flows (material or process), and impact indicators. The source provides the data for numerous materials and processes, along with their functional units and respective impact indicators, linked to a specific method, as those were previously discussed. These pre-calculated metrics enable the LCA Simulations Engine to serve practically instant results to the user, or the machine, querying the module for the flows and/or processes (group of flows) in each lifecycle stage.

The calculation relies on the following discrete steps:

- As a first step, a specific LCA methodology is chosen. LCA methodologies are linked with specific environmental impact indicators, therefore, from this first step those impact indicators are defined.
- Then, the processes and flows are populated with data according to each stage of life. The numerical values (e.g., quantities of materials used, energy consumption) are either user input, external database entries or live sensor readings.
- As a last step, the Engine calculates each flow and process's partial impact indicator resulting in both a break-down of impact indicator score contribution by all processes and flows as well as the total environmental impact indicator score.

The look-and-feel of the LCA Simulations Engine is illustrated in Fig. 4.

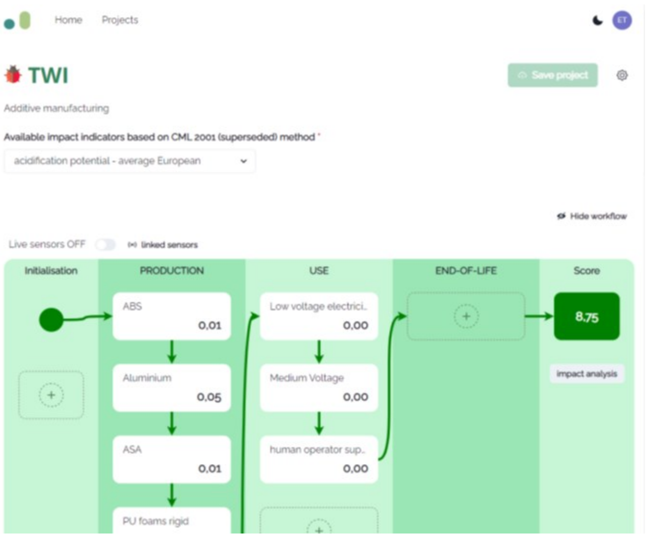

Fig. 4. Screenshot of the LCA Simulations Engine frontend.

VI. Conclusions

The LCA Simulations Engine is a professional web-based tool to collect, analyse and monitor the sustainability performance of products, processes, and services. Practical and concrete environmental data are introduced with indicators enabling the elaboration of comparative studies and the estimation of the progress over the environmental targets leading to the continuous improvement in the production. The tool enables the measurement of the environmental impact across all life cycle stages in (near) real-time and provides hotspots for improvement.

The primary innovation of the LCA Simulations Engine is its ability to receive input from sensors, generate output fast, and promptly identify hotspots by comparing predefined thresholds per impact indicator at near real-time. The tool allows the comparison of environmental footprints and other results with data from real-life trials, pilot validation trials, and other databases. As a result, end-users can assess the environmental impact of their products, processes, or services and evaluate production units in terms of their environmental performance and potentially for further improvements.

The LCA Simulations Engine can be totally automated from existing design data and fully integrated into the workflow without disrupting it or slowing it down. This enables cost-efficient, circular benchmarking, the continuous improvement in the production, and the optimisation in using materials and resources. Through its web-based user-friendly interface, the component provides the user high accuracy of baseline assessment definition, and therefore the ability to operate in higher levels of production control and environmental impact assessment.

A joint service including the LCA Simulations Engine and other components such as a Decision Support System (DSS) and the PLM could provide additional analysis, and recommendations on how to reduce the environmental impact.

Acknowledgment

This work has received funding from the European Union's Horizon 2020 research and innovation programme KYKLOS 4.0 under grant agreement No 872570.

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