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Integrated Computational Life Cycle Engineering — Application to the case of electric vehicles

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A B S T R A C T

Modelling and analysing lifecycle environmental impacts of product systems demands often specialized knowledge and is time-demanding. Product systems are typically defined by complex technical foreground systems and immersed in highly diverse contexts and background systems. Available software tools fail to streamline the modelling and analysis of this complexity, leading to extensive iterations or rough simplifications. The approach introduced in this paper supports the modelling of complex systems and their interactions with diverse backgrounds. This enables developing flexible and comprehensive environmental assessment tools. The applicability and advantages of the approach developed is demonstrated through its application for the environmental assessment of electric vehicles.

1. Introduction and motivation

Life Cycle Assessment (LCA) is an established systems analysis methodology that enables the quantification of environmental impacts of product systems on a life cycle perspective [1]. The methodology as defined by the ISO standards [2] consists of four phases (i.e. goal and scope definition, inventory analysis, impact assessment and interpretation) along which the LCA practitioner continuously iterates. Different aspects inherent to the LCA methodology have hindered it from becoming a mainstream engineering tool in production engineering. On the one side, LCA demands high amounts of expert knowledge as the modelling process is fraught with modelling choices that in some cases are subjective [1]. On the other side, the application demands high amounts of resources and time for tasks such as data collection, processing and development of life cycle inventories.

An Integrated Computational Life Cycle Engineering (IC-LCE, Fig. 1) approach is proposed to overcome these barriers. The main contribution of the IC-LCE is the enhancement of the applicability of the LCA methodology to support engineering decisions. This goes beyond the estimation of the environmental impacts of a particular product system in a specific context or scenario. The IC-LCE aims at integrating rapidly and reliably LCA calculations within engineering models without needing oversimplified models (e.g. using aggregated environmental impacts from data sets, assuming the same geographical boundaries, disregarding data system models, allocation procedures, etc.) but rather by respecting the LCA modelling logic and disclosing and interpreting significant issues worth to analyse and understand in shorter periods of time and with reduced LCA-modelling efforts.

While the methodology is applicable to different product systems, in this paper the methodological development of IC-LCE and its implementation is described for the particular case of electric vehicles (EV). EVs are highly complex product systems [3]. The environmental impacts of EVs are influenced by a large set of influencing factors in both the foreground system (i.e. design considerations, manufacturing scenarios, etc.) and the context where the EV is used (e.g. regional infrastructure, weather, etc.) [4,5]. This causes an extreme variability of modelling parameters

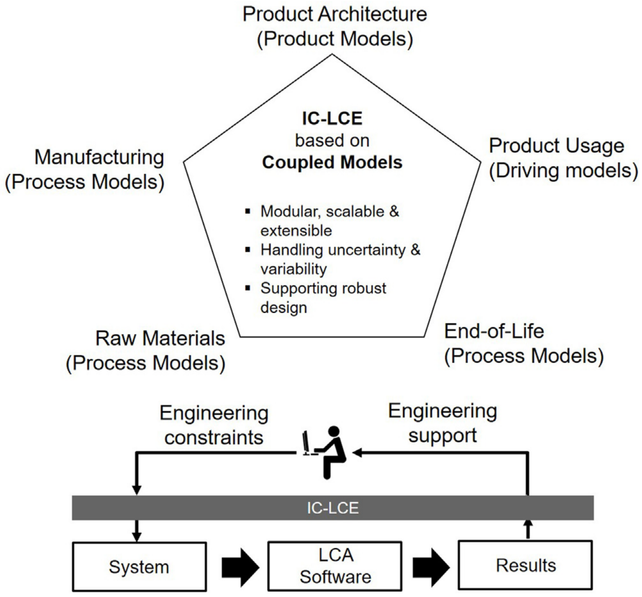

Fig. 1. Integrated Computational Life Cycle Engineering (IC-LCE) approach.

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which hampers a transparent application of the LCA methodology, rises the uncertainty of the results [6] and makes it difficult to translate the underlying results into valuable conclusions that might support decision making in engineering and policy making processes.

2. State of the research and research demand

With the purpose of providing more robust life cycle oriented insights allowing to derive measures that reduce the environmental impact of product systems, LCA calculation approaches for specific engineering sectors have been increasingly developed. Particularly for the case of mobility and EVs, the GREET model [7] provides a modularized platform for the definition of vehicle systems considering a well to wheel (WTW), a tank to wheel (TTW) and the vehicles life cycle perspective. Other approaches have developed tools giving life cycle environmental information for future mobility scenarios [8]. For the analysis of the use phase, different approaches using simulation tools have been developed (e.g. Ref. [8]). *Egede* introduced an approach to integrate and visualize the effect of regional influencing factors on the operation phase of EVs [9]. While plenty of research has been done in order to broaden the understanding of the environmental impacts of electromobility, the variability of the results is still very large [10]. Moreover, most of the approaches developed to calculate LCA results of EVs are based on simplified models that lack transparency and comprehensiveness. The approaches reviewed cannot handle fast and efficiently the inherent parameter variability of LCA of EVs.

3. Methodological development and implementation concept

The methodology integrates flexible and modular LCA software routines that calculate the impact of the configured product systems without any interaction of the user. Each layer provides a cohesive set of software modules and overarching layer functions (1–8). The modules are able to provide a service to both the external layers and to the internal overarching functions. The concept was implemented completely in Python. The system is implemented in such a way that the working flow starts with user requirements and ends by delivering results and visual information to the user. The reference architecture shown in Fig. 2 maps all the system elements that implements the functionality of the proposed IC-LCE approach. It is structured in six different layers: *Data, logic 0, logic I, logic II, logic III and GUI (graphical user interface).*

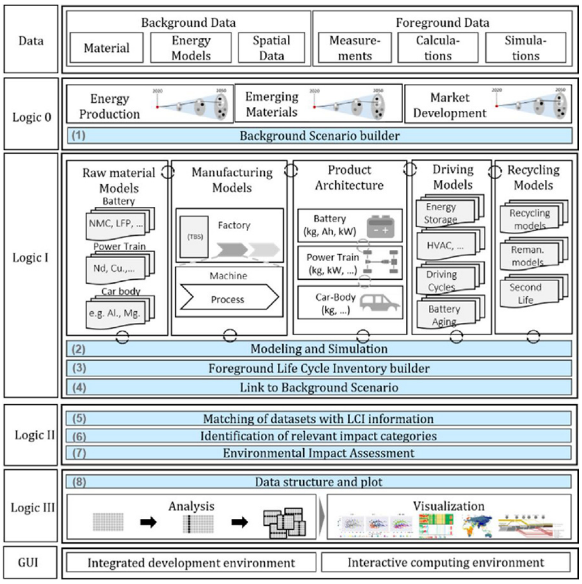

Fig. 2. Reference architecture for an Integrated Computational Life Cycle Engineering.

3.1. Data layer

The data layer consists of organized embedded data allowed to be accessed by the different functions in *logic 0* and *logic I* of the system requiring information for its application. The end user is also allowed to access the elements of this layer through query functions for maintenance and update purposes. This layer consists of data sourcing the foreground system (i.e. processes and models of the product system for which the LCA is being performed) and the background system (i.e. the system consisting of processes and models that are not the main focus of the LCA but that have strong influence the foreground system). The foreground data embedded in the system refer to repositories of experimental results coming from measurements, simulations, calculations or reports regarding materials, components or processes (e.g. aging of a battery cell, average energy consumption by mixing a batch of active slurry, energy density of a particular cell chemistry, vehicle sizes, etc.). Also industry specific data bases (e.g. data from the international material data systems, IMDS — www.mdsystem.com) as well as company internal information about processes can be integrated. Additionally, the data layer includes data required for the definition of scenarios in the background system such: (i) as regional aspects of material supply chains (e.g. origin of and market mix composition for a particular material), (ii) information on current and projected composition of regional electricity mixes (e.g. from national statistics or reports from the international energy agency) and (iii) geographical data influencing the environmental implications of electric vehicles. Further data that can be stored in this database is socioeconomic information having an impact in the deployment of EVs (e.g. statistics on car ownership, new EV registration and political incentives). Inter-individual data affecting the energy consumption of an electric vehicle per trip such as driving patterns and behaviour for specific driver groups or missions and average commuting times and distances for a specific city can be as well integrated.

3.2. Logic 0: background system modelling

The *logic 0* is allowed to be accessed by the user and by the functions in *logic I*. The group of functions contained in this layer are configured to build scenarios for the particular contexts in which a technology modelled in *logic I* is to operate or be implemented. As an example, this set of function receives arguments indicating geographical and temporal location of a particular event (e.g. city and time in which an EV operates, country and year in which a kWh of electricity will be produced). The functions passed such arguments to the software elements able to build background context scenarios such as (i) the estimation of the daily temperature profiles for the city where the vehicle is to be driven, (ii) the composition of the electricity mix composition for a particular time and place and (iii) the traffic and driving patterns of the time and place under analysis. Depending on the scope of the analysis, this layer offers the possibility to integrate market oriented models in order to evaluate the environmental impact of EVs on a fleet level considering consumer behaviours and market deployment of EVs.

3.3. Logic I: foreground system modelling

The *logic I* is divided in five software elements (e.g. raw material, manufacturing, use phase, product architecture and recycling) (see Figs. 1 and 2). Each of the elements consist of engineering models. The element *raw material* contains process based models for the production of active and inactive materials for battery cells (e.g. Ref. [11]). The element *manufacturing* comprises several process based models for the production of traction battery cells (e.g. Ref. [12]), whole factory models (e.g. Ref. [13]), technical building services models (e.g. Ref. [14]). Additionally, this layer can be complemented with energy oriented simulative approaches for manufacturing systems (e.g. Ref. [15]) and multiscale simulation

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