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Corresponding author:
Bianca-Maria Köck (TU Wien – ICEBE), bianca.koeck@umblick.at

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Integrating LCA in process development

Bianca Köck[1*], Anton Friedl[1], Bettina Mihalyi[1]

1: Institute of Chemical Engineering, TU Wien, Austria
* Correspondent author: bianca.koeck@tuwien.ac.at

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ABSTRACT

In addition to the technological and economic aspects, the integration of environmental considerations can help to assess the process paths of emerging technologies from the beginning, but there are many uncertainties involved in early application. This paper outlines the standardised quantification methodology of life cycle assessments (LCAs) and challenges addressed in the PhD thesis focusing on biorefineries as well as different types of LCAs in process development.

INTRODUCTION

The development of environmentally friendly processes & products is becoming increasingly important to meet global challenges, but how can we prove that our development is really more sustainable than existing systems? Or how can we find out for different process variants on which substances we should focus in terms of sustainability? One of the preeminent tools for quantifying environmental sustainability is the life cycle assessment (LCA). It aims to quantify the environmental impacts by capturing relevant environmental flows across a product's life cycle (from raw material extraction and manufacturing, through distribution, use and disposal), assigns these flows relevant impact categories and converts those within an impact category into common units such as litres of water withdrawal or kg CO_2 equivalents/unit[1]. Life cycle analyses have been trying to make these effects measurable since the 70s and are often used with objectives such as product optimisation or product comparison [2]. Mostly, however, the focus here was on already existing products with established processes, so that working with processes in development places new demands on the methodology. The political support for a change towards a more sustainable way of doing business is also driving the need to assess products for ecological compatibility from the very beginning in the field of technology development and therefore enables companies and researchers to reduce cost consuming exploration of process ways, who will have little chance of standing stricter environmental legislation.

In my dissertation I am dealing with exactly this field of LCA implementation, namely process development and handling of uncertain data originating from high variable process parameters of laboratory or pilot plants.

However, since LCAs are more and more often prescribed in projects and scientists should be able to use the results for their own work in order to further develop processes, an introduction to this matter is given here, introducing the current PhD-work and outlining LCA-types that might be encountered at low Technology Readiness Levels (TRL).

LCA FOR PROCESS DEVELOPMENT

One of the key discussion topics of the European Commission in the paper "Towards a Roadmap for Engineering & Upscaling" in 2015 was the implementation of LCAs in the production of new parts in order to support decisions on whether the technology is worth implementing or not. It is stated there that LCAs should be implemented in an early stage before scale up to pilot [3]. This early implementation may lead to benefits for the process developing body. At the beginning of a design process there are a lot of possibilities regarding the processes and input parameters to be applied. The earliest [4] possible implementation of LCA's can help to evaluate this variety of options in terms of environmental impact, whereas in a later stage most design parameters have been already locked in and altering of the technology is more difficult. However, in early stages the knowledge about the technology is spars. This design paradox is also referred to as Collingridge dilemma as shown in figure 1 [5].

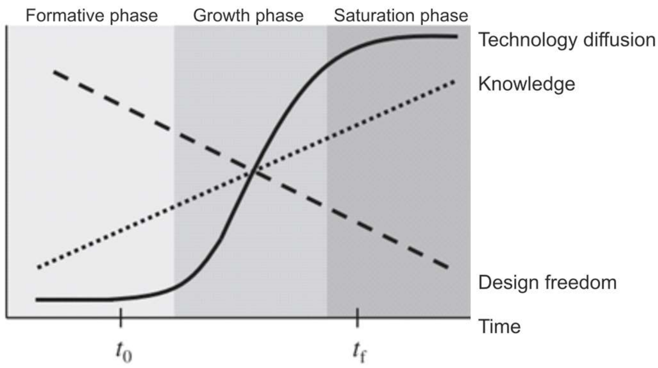


Figure 1: Schematic illustration of the technology diffusion, knowledge, and design freedom curves. In order for an LCA to be prospective, the technology should be in the formative phase or early growth phase at the current time of the assessment (t0) and should be modelled at a future time (tf) in the saturation phase or late in the growth phase. LCA = life cycle assessment [modified, 5]

One key finding of this dilemma is that the earliest possible application of an LCA results can lead to an easier adaptation of the process/product design. However, since there is limited knowledge about the processes available, there is a high degree of uncertainty.

Uncertainty can be defined quantitative, through the spread of values attributed to a parameter, or qualitative, referring to the lack of precision in data and method due to incomplete data, lack of transparency, unrepresentative methods and the choice made [6], [7]. Most LCAs address uncertainties by performing uncertainty (UA) and/or Sensitivity Analysis (SA). Those are systematic techniques to quantify uncertainty in LCI results due to variability and inaccuracy of data and model (UA) or to assess the effects of methodological choice and data on the result (SA) [6], [8]. However there are still many LCAs not accounting for parameter correlation structure, for example only 17 % of LCAs accounting parameter correlation in a review in 2007. This lack of knowledge influences the spread of values tough. Not taking into account correlation for the computation of random sampling vectors, leads to a larger sampling space and an undetermined number of parameter combinations will not reflect the situation observed in the real world and therefore lead to unrepresentative results [9], [10].

METHODOLOGY

The PhD-research, which will be performed, concentrates mainly on parameter uncertainty in the Life Cycle inventory 16th Minisymposium Verfahrenstechnik and 7th Partikelforum, TU Wien, September 21st – 22nd, 2020 analysis (LCI). During process development, input and output data from a wide variety of sources, such as laboratory and pilot plant tests, literature, databases, process simulations or similar established processes can be used and lead to different Life Cycle Inventory values. Also, due to the early test stage, there may be little data available which may also be subject to a certain measuring error

The LCAs will be performed according to the ISO 14040 standards, which consists of four phases. Based on the definition of the objective and the scope of the study, the Life Cycle Inventory Phase (LCI) quantifies the emissions and resources along the life cycle of the product under investigation. During the Life Cycle Impact Assessment (LCIA), the data collected are converted into indicators. These indicators express the impact on different environmental and health issues, such as global warming, water and air pollution, nutrient enrichment or summer smog. In the fourth phase, the interpretation phase, the results are interpreted with regard to the initially defined objectives of the LCA [11], [12].

Parameter, with the highest impact, will be selected through performing a Global Sensitivity Analysis, which includes also possible uncertainty due to lack of knowledge of the description of parameter variability (value distribution). GSA are a good basis for performing parameterized LCA models [13].

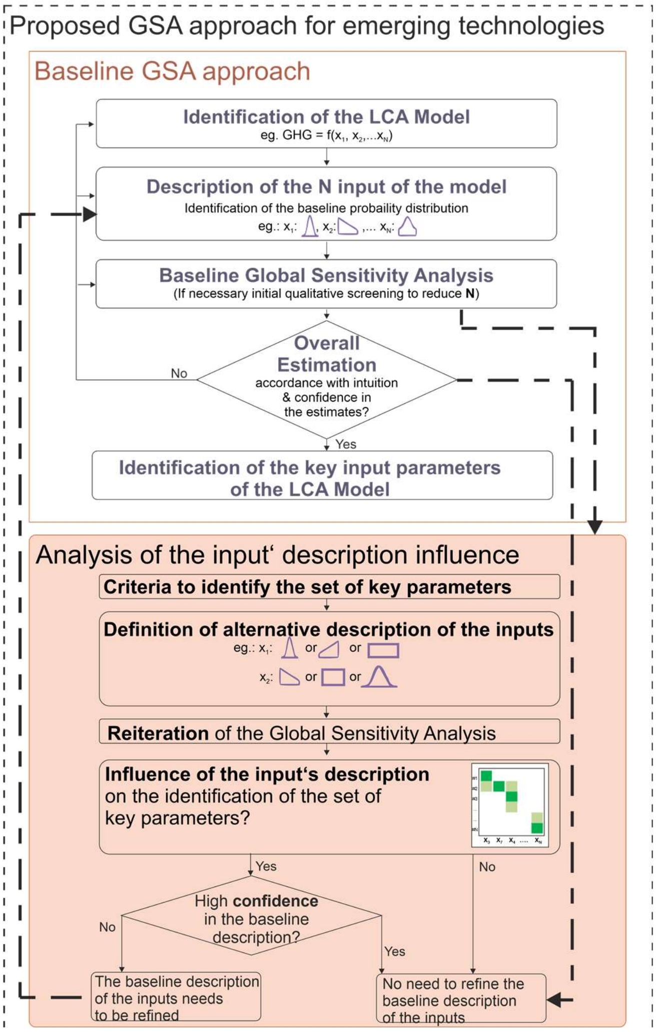
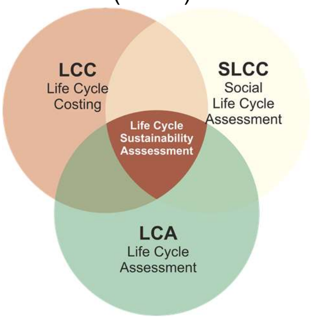


Figure 2: Methodology Steps for GSA [modified, 13]

Working additionally to the LCA software closely with the process simulation software, by using a programme, which has to be developed and which is able to work with both software, different process conditions will be modelled including estimated errors and parameter uncertainty.

The results will be tested with multivariate exploratory methods. For this purpose, e.g. principal component analysis, non-linear mapping and different cluster analyses are used, as well as afford will be made to recognize the correlation structures between parameters and their multivariate distributions.

From the results multivariate calibration models can be derived to model process properties by the process parameters. Upscaling of this model to perform a LCA on emerging technologies using different scenarios, and making the results comparable to LCAs of existing technologies is also aimed as well extending it to a life cycle sustainability assessment (LCSA), including life cycle costing (LCC) and Social Life Cycle Assessment (SLCA). This will add value to the development and pre-enforcement of combined LCSA methods [14].



This integrated approach for data evaluation is demonstrated for process selection procedure for biorefinery products.

Figure 3: The overlap between the three pillars of sustainability resulting in LCSA [modified, 14]

The aim is to increase the robustness of prospective LCA results especially in the biorefinery field and to get a better understanding of the influence of process variables in a multivariate sense on the process properties that influence the life cycle features.

BIOREFINERIES

Biorefineries are from special interest as bioeconomy is one of the European strategies to tackle the most important environmental problems and to maintain the competitiveness of Europe [15]. In the sense of sustainable development, the substitution of fossil fuels by renewable raw materials is a necessary step for a new economic and goods system. With the updated bioeconomy strategy, the European Commission [16] wants to support the facilitated development of sustainable biorefineries and assumes a potential of up to 300 new biorefineries in 2030.

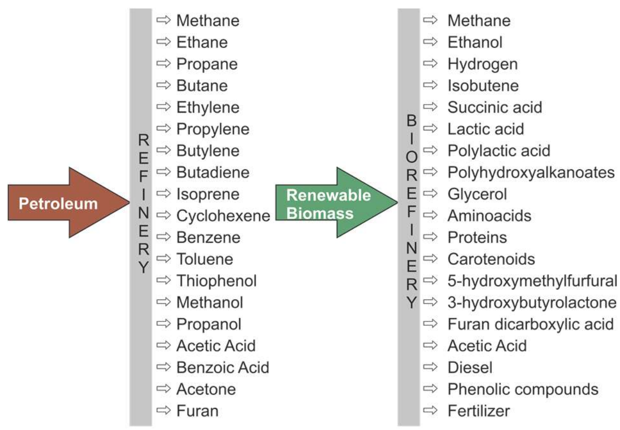


Figure 4: Overview of products and chemical compounds that can be obtained in a traditional [modified, 17]

The fact that many products and chemicals can already be produced from biorefineries is shown by a comparison with traditional products from petroleum refinery, see Figure 4 [17].

Research interest in this area is growing steadily, as can be seen from the annual increase in publications [17]. There are processes and products in different Technology Readiness Levels (TRLs) and this generally poses new challenges for life cycle analyses, e.g. the comparability of different products and manufacturing options. However, an early assessment is important because decisions made at an early stage of development have a major impact on the associated environmental impact of an end product.

It should not be forgotten that renewable raw materials are also not available in unlimited quantities and their processing into energy, chemicals or products does not automatically have to be more sustainable or environmentally compatible. Therefor it is especially interesting to make methods for their development available, which incorporates the uncertainties to target environmentally friendly processes.

Clarification of LCA Types

Next to the traditionally known applications of LCAs like Next to the traditionally known applications of LCAs like comparison of existing products or improvement of products the need to use LCA as a tool in strategy processes and longer term planning is raising [18]. Therefore, the variety of LCA methods and types is growing consistently and differ a lot, which can lead to problems regarding credibility or comparability.

Two major types of LCAs, which are for example defined in the Global Guidance Principles for Life Cycle Assessment Databases of the UNEP are the consequential and the attributional LCA. The attributional approach, also called "accounting" or "descriptive approach", evaluates on what portion of the global environmental burdens can be associated with a product, while the consequential, change-oriented, approach gathers information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product [7], [19]..

Therefore the research question of the LCAs differs as well, for example a research question for a attributional LCA (ALCA) is: "What is the life-cycle impact of 1 kWh of electricity at grid in France in 2006? [20], [21] while a consequential LCA (CLCA) asks for an additional unit, eg.: "What are the consequences of an increased demand of wheat in Denmark? [21], [22]". Figure 5 additionally demonstrates an important difference. The circles represent the total global environmental exchanges. In the left circle, attributional LCA seeks to cut out the piece with dotted lines that belongs to a specific human activity or product. In the right circle, consequential LCA seeks to capture the change in environmental exchanges that occur as a consequence of adding or removing a specific human activity or product [23].

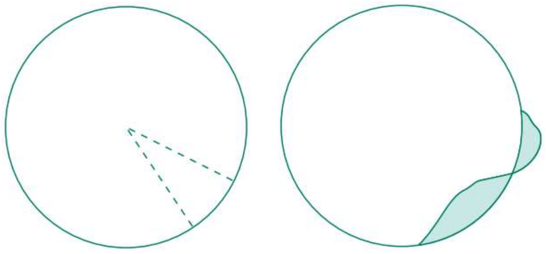


Figure 5: Conceptual differences between attributional and consequential approaches [23]

Although it was sometimes mistaken, consequential and attributional LCAs can both be prospective or retrospective [5], but ALCAs model the situation (either in the past, present or future) as it is, without any changes [19]. However other newly developed models like NLCA (Anticipatory LCA), PLCA (Prospective LCA) and SLA (Scenario-based LCA) focus mainly on emerging and not yet marketed product systems while ALCA, CLCA and DLCA (Decision LCA) mainly focus on commercially existing product systems [19]. The different in the types for emerging technologies can be for example seen in the main focus. NLCA draw a specific focus on integrating assessment techniques of decision theory that should allow for the explicit inclusion of the values of decision-makers in the analysis, whereas SLA are based on scenarios, separating modelling processes, life-cycle modelling, scenario modelling, and valuation modelling [19], [24], [25]. Prospective LCAs deal with technologies in the future and have a broader temporal horizon, whereas retrospective studies deal with products in the past. The need to implement an LCA at an early stage of product or process development leads to LCAs who are prospective in nature and to adjust or change the purpose of a LCA [18]. Those prospective LCAs anticipate the possibility of large changes in the object of study and its surrounding over time, examining changes in the foreground and the background system. The foreground system is often declared as the operations of the life cycle which are modelled directly by the study, however are also sometimes defined as the processes which can be affected by the manufacturer or, where the product or technology under study impose larger changes over a longer time horizon while the background system, representing the global industrial system, which can be changed in the boundary conditions, like the national power supply, availability of materials, cycle in national economy or costs of energy and commodities [1], [18], [26].

However, one must also differentiate between the technology readiness levels (TRL) of prospective LCAs. In process or product development we typically deal with technologies in an early stage/low TRL, just being a basic idea, or in a proof-of concept, a lab environment or an industrial pilot plant phase, still needing multiple research cycles before becoming available at an industrial scale [25], [27]. The environmental interventions of future systems are a product of very complex interactions and dependencies and have many uncertainties [18]. As mentioned above there are many different types of LCAs used to evaluate emerging technologies. Buyle et al. [27] tries to bring those in his methodology framework for ex-ante LCAs together, including the entire technology life cycle, from the early design phase up to continuous improvements of mature technologies, as well as including their market penetration. The creation of a uniform methodological approach facilitates the transparency of LCAs in general, but especially those dealing with future scenarios and the comparison of different studies among each other as well as with mature technology counterparts. This also allows for a categorization and evaluation of the applied techniques, concepts and procedures in order to address technology development, technological learning and technology diffusion. Integrating the technological learning curves, especially of cost reduction of direct inputs, have been observed from researchers to correlated with improvement of environmental performance. However only few studies have combined changes in both, foreground and background systems, until now nor combined technology learning, development or diffusion. Assessed topics are mainly technology development of energy systems, electric vehicles and nanotechnology, so there is an opportunity to broaden the field through integrating it in ongoing process and chemical engineering research, even including expected future legislation, like the circular economy concept, sale-and-take-back, lease or pay-per-use contracts [27].

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