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Life Cycle Assessment (LCA)

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Synonyms

LCA; Life cycle analysis; Product life cycle assessment

Definition

Life cycle assessment (LCA) is a systems-oriented methodology for addressing the environmental consequences associated with a product or service. It is used for studies of the material and energy flows and their environmental impacts related to a product or a service, i.e., from raw material extraction, to production and use, to disposal. LCA, together with life cycle thinking, life cycle management, and life cycle sustainability assessment, makes up the portfolio of life cycle approaches.

Methodological Framework

Life cycle assessment (LCA) study is defined both by the product system it models and the procedure used to study it, the LCA model and the LCA procedure, respectively. The LCA model describes the flow system from raw material extraction to waste disposal, including production, transportation, use, and recycling loops associated with a product (or a service). The procedure consists of several steps. The analysis starts with the *definition of goal and scope*, in which the researchers specify the product(s) to be studied and the purpose of the LCA study. In the *inventory analysis*, they construct the life cycle model consisting of the technical processes of the product system, create an inventory of emissions and resource usage in each process, and then calculate the amounts of emissions produced and the resources used in the product system. Results at this stage are called life cycle inventory (LCI) results and consist of amounts of raw materials, energy, and emissions. Next, in the *impact assessment*, the LCI results are translated into environmental impacts. Owing to the complexity of ecological systems and environmental impacts, impacts can be evaluated in various ways. Emissions and resource use can be *classified*, *characterized*, and *normalized* with regard to their potential or contribution to various environmental problems (e.g., resource depletion, global warming, and toxicity). Some environmental problems have been easier to make assessment methods for (e.g., global warming), whereas others have shown to be more difficult (e.g., toxicity, biodiversity loss) and for which methodology development continues. In the *weighting* step, the relative significance of the different environmental problems is evaluated. This leads to the calculation of a sum of the total environmental impact for the studied product system. There are several weighting methods, each representing different perspectives on prioritization of environmental problems, e.g., cultural, economic, or political values, or ecological boundaries. Whether one presents results as LCI results, characterized impacts or weighted impact depends too on the purpose of the study, determined by, for example, what is appropriate for public communication and what is useful for internal use. Finally, the

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interpretation step is the iterative process during which the researchers adjust and ensure that methodological choices fit the purpose and the stakeholders of the study and evaluate the quality of the results. Also, interpretation of results can be enhanced through techniques such as dominance analysis, contribution analysis, payback time, etc.

LCA is principally a methodology for comparisons of, for example, *functionally equivalent* product systems or different parts of a single product system (known as *stand-alone LCA*). Different types of LCA are possible depending on the type of comparison made. Many methodological choices are intrinsically determined by the type of comparison that is intended. The different types of LCA are usually distinguished with a descriptive label or prefix. An LCA study said to be *cradle to grave* indicates that the whole life cycle is modeled, whereas a *cradle-to-gate* study usually covers the part from resource extraction to manufactured product. An LCA with *site-specific* data describes a system with actual data from actual and specified industrial processes; other data options are *average* industrial data, *marginal* data, and *best-case/worst-case* data. When economy-wide data from economic input/output tables is used, one speaks of *IO-LCA* in order to distinguish it from conventional *process LCA*. A *hybrid LCA* is thus a combination where IO-data is used for parts of the life cycle and industrial process data in remaining parts. The time perspective is also specified. In a *prospective* LCA study, the continued use of a present product is compared with the situation where it is replaced with another one sharing its functionality(ies). In these forward-looking studies, the compared alternative can be a new technology or a product under development, but it can also be well-known technologies but new to the setting. The analysis focuses on the identification of differences between scenarios and is often referred to as *consequential* LCA. Such LCAs often model such changes looking at marginal effects and can involve *system expansions* to ensure functional equivalence. In a retrospective study, an accounting approach is taken, and a product is described through *attributional* LCA and can be compared with others with the same functionality – ecolabelling is typically based on this type of LCA.

In all types of LCAs, comparison is made possible by relating all environmental impact to a unit that expresses the function of the product system. The unit of comparison is called *functional unit* and its definition is critical to ensure a fair comparison. For example, beverage-packaging systems can be compared on the environmental impact *per liter* of packaged drink, while flooring materials can be compared *per square meter and year*, since compared options (hardwood flooring, wall-to-wall carpeting, linoleum, etc.) may have different life lengths. However, many industrial processes and products are multifunctional, for example, a refinery produces a range of products, a smartphone has multiple uses, and in order for an LCA to focus on select product functionality(ies), it is necessary to ensure equi-functionality between compared alternatives. Methods include *allocation* (attribution of a share of process emissions onto each of its products) and *system expansion* (inclusion of extra necessary product systems in order to obtain equal functionality in studies systems). Allocation is used in attributional LCA to a great extent, while system expansion is common with consequential LCA.

LCA Resources

Comprehensive description of the methodology and its application is found, for example, in the widely used textbook *Hitch Hiker's Guide to LCA* by Baumann and Tillman [1]. A comprehensive handbook for the ISO standards on LCA has also been published by Guinée and colleagues [2]. In addition to the commercial software and databases, there are also open alternatives, for example, *openLCA* and among databases, the *CPM LCA Database*, the European *ELCD*, and *the Canadian Raw Materials Database*, (CRMD) to name a few.

Historical Development

The term life cycle assessment came into general use in the early 1990s – this coincided with the surge of academic interest in the methodology. Before, terms such as ecobalance, cradle-to-grave study, and resource and environmental profile analysis were used. The earliest studies developed in the context of the environmental debate around the "throwaway society" in the late 1960s and early 1970s when disposable packaging, wasteful resource use, and growing landfill problems were criticized. These early studies were carried out by only a handful of people around the world at consultancies and research institutes. Despite their different names, the early studies are recognized as life cycle studies since they all model the whole product system, give simultaneous attention to both energy and material flows and the pollution associated with these, and perform comparison through a quantified unit of analysis representing the function of the product systems under study. During the 1980s and the 1990s, interest in LCA grew and spread into policy-making and other industrial sectors. The growing interest spurred academia to systematize and develop LCA methodology. The Society of Environmental Toxicology and Chemistry (SETAC) provided an early forum in which a "harmonized LCA methodology" was agreed upon [3]. In 1997, the first international standard for LCA methodology was published by the International Organization for Standardization – it has been updated more than once since then, the latest version being from 2006 [4]. Work to develop databases, shared data formats, and software for LCA also started during this period and is still ongoing.

LCA research deals with the methods of life cycle studies as well as its practices. This has given rise to a multidisciplinary research community, with researchers both from the natural, engineering, and social sciences. The scholarly journal, the *International Journal of Life Cycle Assessment* launched in 1996, publishes both quantitative methodological research and qualitative management studies related to the life cycle perspective. Major topics in research and its debate concern modeling in consequential LCA, the choice between consequential and attributional LCA, the development of impact assessment methods, and the handling of objectivity and subjectivity in the overall evaluation of impacts. Since around 2000, efforts to better align LCA with the three pillars of sustainability (environmental, economic, and social) have taken place. The environmental impact assessment in LCA has become complemented with methods for describing also the social and economic impacts along a product chain. This integrated approach is known as *life cycle sustainability assessment* (LCSA). Methodological research has been very prominent, but there is also research into the use and application of life cycle methods in different industrial practices (ecodesign, sustainable procurement, etc.). This field is called *life cycle management* (LCM) and holds its own independent conferences since 2001. Life cycle research is furthermore seen as part of the industrial ecology field, in which methodologies for environmental flow modeling and environmental change are studied.

LCA and Nanopolymers

LCA has been used to investigate the environmental consequences of nanopolymers (see Table 1). These studies show nanopolymers having both greater and smaller environmental impact than conventional materials depending on the type of nanopolymer and the alternatives it is being compared with. Such conclusions can be greatly influenced by methodological choices for handling of uncertainties around nanopolymers. Notable methodological choices concern the definition of functional unit, data availability in face of uncertain or developing production processes, uncertainty about new environmental impacts and availability of appropriate assessment methods, and contextualization of the studied nanopolymer (type of component, product, or use context the studied nanomaterial is used in). Some of these

Table 1 Overview of selected LCA studies of nanopolymers. PLA stands for polylactic acid, PHA for polyhydroxyalkanoate, and PHB for polyhydroxybutyrate

Study	Filler nanomaterial	Polymer material	Functional unit
Joshi [7]	Nanoclay	PLA, PHA, PHB	Mass of filler
			Function-adjusted mass or volume of composite
Lloyd and Lave [8]	Nanoclay	Polypropylene	Strength-adjusted mass of composite
Roes et al. [9]	Nanoclay	Polypropylene	Strength-adjusted mass of composite
Khanna and Bakshi [10]	Carbon nanofiber	Polypropylene	Strength-adjusted mass of composite
		Polyester resin	
Roes et al. [11]	Nanoclay, silica, and carbon nanotubes	~20 different	Strength-adjusted mass of composite
Pizza et al. [12]	Graphene	Epoxy	Mass of composite

methodological issues are shared with LCA study of new technologies in general and to some extent to nanomaterials [5, 6].

Joshi [7] found that the nanoclay-biopolymers investigated were environmentally preferable to the same biopolymers without nanoclay [7]. However, they also reported that the environmental performance of the nanoclay-biopolymers depended on the functional unit. The magnitude of the benefit thus varied depending on whether the materials were compared on a kg-to-kg basis or whether the different functional performances of the materials were also considered. In cases of nanopolymers with enhanced strength, such adjustments to the functional unit are typically done by applying the so-called Ashby's material index [cf. 8–11], effectively lowering the functional mass of the material due to lower mass requirement for obtaining the same strength. Lloyd and Lave [8] compared the environmental performance of a nanoclay-propylene polymer to that of aluminum and steel [8]. They found the nanoclay-propylene polymer to be environmentally preferable over the two conventional materials for almost all included impact categories, including energy use. Roes et al. [9] assessed nanoclay-propylene polymers used as agricultural films, packaging films, and automotive panels [9]. They concluded that the nanopolymer had similar environmental impact as traditional materials for packaging films and automotive panels, but it had lower environmental impact for the agricultural film. Khanna and Bakshi [10] found that their investigated carbon nanofiber polymer was approximately 2–10 times more energy intensive than steel, even when adjusting the functional mass for increased material strength due to the nanomaterial filler [10]. Roes et al. [11] assessed the nonrenewable energy use of 23 combinations of one of the nanomaterial fillers nanoclay, silica, and carbon nanotubes (single- and multiwalled) and approximately 20 different polymer materials [11]. Of the total 23 different combinations, 17 got lower nonrenewable energy use with increasing nanomaterial filler content compared to the same polymer without nanomaterial filler. Pizza et al. [12] assessed various environmental impacts from production of epoxy-based polymer enhanced with graphene [12]. They reported that raw material extraction, and the preparation of fillers and polymer, had the highest environmental impact but did not compare their results to those of traditional materials.

LCA research is ongoing in order to develop *prospective LCA* methods that can cope with methodological challenge related to uncertainties around future technical system of a nanomaterial product (e.g., [13, 14]). Further research is needed in order to enable comprehensive assessment of environmental impacts related to nanomaterials, in part because some environmental impacts of nanomaterials are unknown and others not well captured by existing impact assessment methods in LCA. Early attempts

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exist for assessing toxicity impacts from emissions of nanomaterials, for example, emissions of carbon nanotubes [15].

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Related Entries

- ▶ Biodegradability
- ▶ Biodegradation of Polymers

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