ROYAL SOCIETY OF CHEMISTRY

SUSTAINABILITY

Life Cycle Assessment

Tools to help us make more sustainable material choices are becoming increasingly important. What something is made out of and how it is made affects its use, but also its environmental impacts through its lifetime, and what happens to it after it has reached the end of its use.

We might choose a material based on purpose, durability, appearance, convenience, availability, or cost. As the impact humans have on the natural world becomes more apparent, the environmental sustainability of the materials and production processes are becoming increasingly important factors - whether we are creating or choosing a product. What happens after we finish with a product is often ignored or forgotten, but it is vital we design for end-of-life as well as for use.

The holistic concept of sustainability urges us to consider not only the environmental impact of a product, but also the economic and social factors in the way the product is made, used, and disposed of.

What is Life Cycle Assessment?

Life cycle assessment (LCA) allows us to measure the environmental impacts associated with a product or service from 'cradle to grave' (ie from the extraction of materials and the manufacturing of a product to the end of the product's life and eventual disposal), or ideally 'cradle to cradle' (ie from the inception of a product through to the materials being recycled or reused in a circular way).

Some applications of the information gathered through LCA include[1]:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle, eg hot spots of high emissions in manufacturing
- Comparing products, materials, processes, services and systems
- Informing decision-makers in industry, government or non-governmental organisations, eg for the purpose of strategic planning, product or service design or redesign
- Marketing and communicating environmental impact to those buying products

Several internationally recognised standards govern how LCAs are conducted. ISO 14040[2] describes the principles and framework for LCA, and ISO 14044[3] specifies requirements and provides guidelines for LCA. There are further standards looking at the quantification and reporting of a product's carbon footprint (such as the British Standards Institution's PAS 2050), and the development and use of environmental product labels.[4]

The four stages of carrying out a Life Cycle Assessment[5]

1 Defining the goal and scope

This is where you define the product or service to be assessed, the question to which the LCA needs to respond, the **functional unit**, the **system boundaries** and the level of detail you wish to go into. The goal and expected use of the LCA can change the depth and breadth of the study.

2 Life Cycle Inventory (LCI) analysis

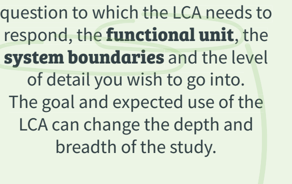
In this phase, you collect and analyse all data necessary to quantify the inputs (ie material and energy flows) and outputs (ie emissions and other releases) within the system boundary. The analysis of these data is based on the functional unit chosen for the LCA. The final inventory is a list, or flow model, of all inputs and outputs associated with the life cycle of your product or service.

3 Life Cycle Impact Assessment (LCIA)

In the life cycle impact assessment, you evaluate potential environmental impacts based on the LCI analysis using a comprehensive set of impact categories that are in line with the goal and scope of the study. This should lead to an understanding and evaluation of the magnitude and significance of the potential environmental impacts of a product or service within the studied system boundaries.

4 Interpretation

Interpretation of results should form the basis for conclusions, recommendations and to support decision making in accordance with the goal and scope of the study. You discuss the results of LCI and LCIA in terms of contributions, relevance, robustness, data quality and limitations, and you systematically evaluate any opportunities for reducing the negative effects of the product(s) or service(s) on the environment while avoiding burden shifting between impact categories or life cycle phases.



FUNCTIONAL UNIT

This is a description of the quantified performance of a product system. When conducting comparative analyses, it is crucial to choose a fair functional unit. For example, if 100g of product A performs the same function as 50g of product B, then the comparison should be 100g vs 50g rather than 100g vs 100g.

If adhering to the ISO 14044 requirements, there is an obligation to document the LCA study in a comprehensive and transparent manner, clearly indicating what has or has not been included in it. The level of detail included in a LCA report will depend on the question asked during the goal and scoping phase. and the intended audiences. There is also a requirement of a **critical review**.

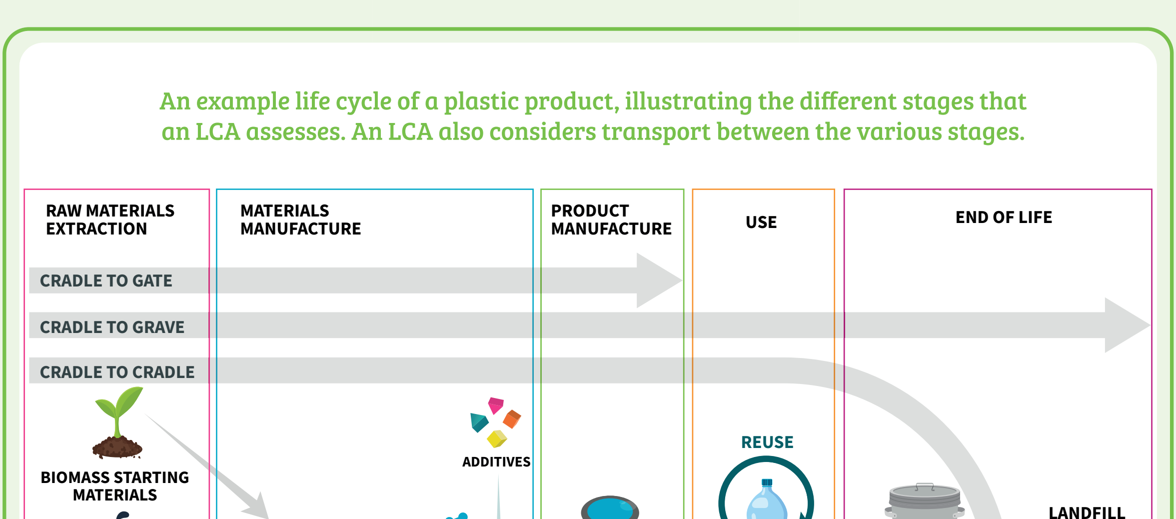
SYSTEM BOUNDARY

The system boundary distinguishes the activities within the product's life cycle phases included in the analysis from those outside of the scope of the study. For example, a 'cradle to gate' assessment ignores activities after the product has left the manufacturing facility, considering them beyond the system boundary.

CRITICAL REVIEW

A critical review of an LCA study conformity assessment by one or more independent expert(s) to confirm adherence to the requirements of ISO 14044. This review is intended to increase the credibility, and the ability to communicate the results, of the LCA study. An ISO-compliant LCA study must be externally reviewed by independent experts if a company wants to disclose to the public claims of environmental superiority over a competing product.

An example life cycle of a plastic product, illustrating the different stages that an LCA assesses. An LCA also considers transport between the various stages.



* Polymers can be formed from monomers via addition mechanisms, or from raw chemicals using condensation routes. Waste carbon dioxide can also be transformed into polymer feedstock, for example through the solid-phase catalyst technology developed by the chemistry SME ViridiCO2 (**youtu.be/l_WWyTe2yzA**).

What are the impact categories of an LCA and what do they mean?

When thinking about the environmental impact of a product or a service, a factor that often comes to mind is the associated greenhouse gas emissions – which correlate to global warming impact. However, there are many other areas of impact that should be considered, and an LCA assesses the potential impact on human health, ecosystems and resource use.

IMPACT CATEGORY EXAMPLES	DESCRIPTION AND TYPICAL UNITS OF MEASUREMENT[6]
Climate change impacts	A measure of energy trapped or temperature change, expressed relative to an amount of CO_2 over a specified period of time, typically 100 years. Measured in metric tonnes of CO_2 equivalents (tCO_2e).
Ozone depletion	Indicator of emissions to air that contribute to the destruction of the stratospheric ozone layer. Depletion of the ozone (O_3) layer leads to higher levels of UVB ultraviolet rays reaching the Earth's surface with detrimental effects on humans and plants. Measured in equivalents of trichlorofluoromethane (CFC-11), a major ozone-depleting chlorofluorocarbon.
Acidification	A measure of emissions (such as nitrogen oxides and sulphur oxide gases) that cause acidifying effects to the environment. Potential effects include increased mortality in aquatic life, forest decline and the deterioration of building materials. Measured in SO_2 equivalents or sometimes expressed as moles of H^+ ion equivalents.
Eutrophication • freshwater • marine • terrestrial	Potential impacts of excessively high levels of macronutrients, the most important of which include nitrogen (N) and phosphorus (P). Nutrient enrichment can cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems (eg, potentially toxic algal blooms). Measured in phosphate or nitrogen equivalents.
Photochemical ozone formation	Measure of emissions that contribute to ground level O_3 formation, produced by the reaction of volatile organic compounds and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone can be detrimental to human health and ecosystems and may also damage crops. Measured in equivalents of non-methane volatile organic compounds (NMVOC).
Resource use – fossil fuels	Indicator of the depletion of natural fossil fuel resources. Measured in kilograms oil equivalent or sometimes in megajoule (MJ) energy equivalents.'
Resource use – minerals and metals	Indicator of the depletion of natural non-fossil fuel resources. Measured in kilograms of antimony (Sb) equivalents.
Human toxicity • cancer • non-cancer	Potential impact on humans of toxic substances emitted to the environment, divided into non-cancer and cancer related toxic substances. Measured in comparative toxic units for humans (CTUh).
Eco-toxicity • freshwater • marine • terrestrial	Potential impact on an ecosystem of toxic substances emitted to the environment, including damage to species or changes in the function of an ecosystem. Measured in comparative toxic unit equivalents (CTUe).
Water use	Indicator of the relative amount of water used, based on regionalised water scarcity factors. Measured in m^3 water equivalents.
Land use	Measure of the use (occupation) and conversion (transformation) of a land area by activities such as agriculture, roads, housing etc. Measured, for example, in m^2 years per kilogram or also kilograms deficit of soil organic matter (SOM).'
Ionising radiation	Damage to human health and ecosystems linked to the emissions of radionuclides (also known as radioactive isotopes). Measured in kilobecquerel (kBq) of uranium-235 equivalents.
Particulate matter emissions	Measure of particulate matter emissions and precursor gases to secondary particulates (such as SO_x, NO_x, and NH_3) from sources such as fossil fuel combustion, wood combustion and dust particles from roads and fields. Particulate matter is associated with a range of negative human health impacts, including respiratory illness and an increase in overall mortality rates. Measured in equivalents of fine particulate matter 2.5µm or smaller in size ($PM_{2.5}$)

Using a broad range of impact categories when performing an LCA can help avoid unintended displacement of impacts from one area to another (eg accidentally increasing a product's carbon footprint as a result of trying to reduce water use across its life cycle).

Researchers are developing methods to include the impacts of littering and marine plastics in LCA, as these are currently not captured. This could be via a new impact category, or in a separate phase of the assessment.

What are the impact categories of an LCA and what do they mean?

The assessment of life cycle impacts typically involves the following steps:

Classification: Once life cycle inventory data are classified according to the causal relationship between the inputs or outputs (eg the release of a chemical into freshwater) and their potential effect on the environment, they are assigned to the most relevant impact categories (eg eco-toxicity).

Characterisation: The extent to which each input and output contributes to its impact category is calculated and contributions are aggregated within each category.

Normalisation and weighting: Depending on the chosen LCA approach, the aggregated impacts may then be compared to reference values. To aid interpretation and communication of the LCA results, each impact category may also be given an importance value which allows calculation of a single overall score.

Bio-derived plastics are made from renewable plant-based starting materials rather than fossil fuels.

Assessing the overall sustainability of bio-derived plastics can sometimes be difficult due to a lack of clear data.[7] Making bio-derived plastics from purpose-grown crop (rather than waste materials) can raise additional questions, including whether an existing crop was displaced, whether extensive irrigation is needed and so on, all of which would alter the results of the LCA. As a result, some bio-derived plastics may be considered more sustainable than fossil-based plastics, others less so.

Use of renewable resources alone does not imply sustainability. Sustainability is highly dependent on how a material is made, where it is used and how it can be recycled.[8]

It is important that we continue to explore the use of renewable resources. When developing more sustainable plastics, it is crucial that the full life cycle, including end of life, is considered.

How are LCA data collected?[9]

The level of detail of an LCA can depend on its scope, time and data availability.

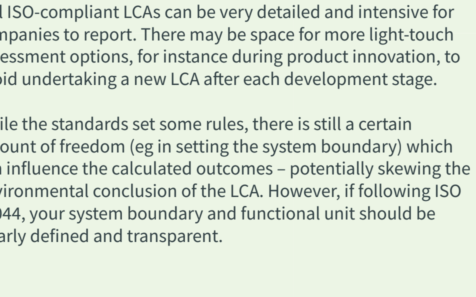
Sources of primary data include utility bills, meter readings, procurement records and direct measurement of other parameters. Secondary data sources include commercial LCA databases and technical literature. All collected data should be quality-assured and checked for completeness and consistency.

What are some of the challenges with LCA?

A single LCA can provide useful information about hotspots in the lifecycle of a given product but on its own often provides insufficient information to compare products. There is potential for industry-led benchmarks to be used, and LCAs for different products can be compared with each other so long as they cover the same function and system boundaries.

Full ISO-compliant LCAs can be very detailed and intensive for companies to report. There may be space for more light-touch assessment options, for instance during product innovation, to avoid undertaking a new LCA after each development stage.

While the standards set some rules, there is still a certain amount of freedom (eg in setting the system boundary) which can influence the calculated outcomes – potentially skewing the environmental conclusion of the LCA. However, if following ISO 14044, your system boundary and functional unit should be clearly defined and transparent.



Making a product that is designed to be durable and reusable may require a lot of materials and energy, but an LCA may also show us that its lifetime use (compared to a single-use product) makes up for that. However, even for products designed to be reused, the impacts of production and materials should be as low as possible.

Another variable is the timeframe used in the LCA, ie whether you are identifying impacts 1 year, 5 years, 10 years or even 100 years into the future. Different timeframes can result in greatly divergent LCA conclusions, and it is not always straightforward to decide on which timeframe to base your decisions. For example, is it better to use a domestic appliance (eg a refrigerator) for 10 years or change it after 5 years for a new, more energy-efficient one?

It also gets more complicated when there are many potential downstream uses for a product, or many by-products of the process used to make the primary product. For example, in the chemical industry a manufactured ingredient may be used in many diverse applications, which could all be included in an LCA.

How can the LCA approach be improved?

There is work ongoing, including across the EU, to further harmonise LCA approaches and provide information on best practice in conducting, interpreting and using LCAs.

Sustainability should ideally encompass not just environmental considerations, but economic and social impacts. The European Commission's Joint Research Centre has developed a framework for defining design criteria for sustainable chemicals and materials that includes a socio-economic dimension in its definition of sustainability[10]. ORIENTING, a project funded by the EU[11], is developing new methodologies for Life Cycle Sustainability Assessment (LCSA) that encompass a full analysis of environmental, social and economic impacts. This includes additional aspects of the life cycle such as impacts on communities, workers' rights, and ethical sourcing of materials.

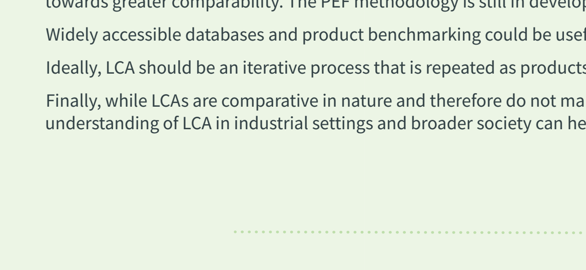
LCA is just one assessment methodology among several and may not be the most appropriate approach for every situation. Some experts recommend the Joint Research Centre's Product Environmental Footprint (PEF) and Organisational Environmental Footprint (OEF) assessments, which are LCAs with particularly rigorous requirements regarding data quality and reporting clarity and are geared towards greater comparability. The PEF methodology is still in development[12].

Widely accessible databases and product benchmarking could be useful to facilitate good LCAs and improve comparability.

Ideally, LCA should be an iterative process that is repeated as products and services are developed and made more sustainably robust.

Finally, while LCAs are comparative in nature and therefore do not make absolute statements about a product's sustainability, a broader understanding of LCA in industrial settings and broader society can help drive improvements in its use and also overall sustainability.

How can LCAs be communicated?



LCAs are usually performed by specialist practitioners and can be difficult to interpret for those unfamiliar with the methodology. As LCAs become more widespread, and sustainability forms a larger part of manufacturing and purchasing decisions, it is important that information is communicated clearly, including by being transparent about assumptions and system boundaries.

One avenue could be to include sustainability labels on products, including information from LCAs. However, experts warn that such labelling may not necessarily be useful to laypeople due do the multi-dimensional nature of LCAs. How do you communicate the relative importance of different impacts? Labelling also moves responsibility for making sustainable choices from the manufacturer to the non-expert consumer.

To move towards net zero, it is important that suppliers and producers know at least the carbon footprints, and ideally broader markers of sustainability, of their products and services.

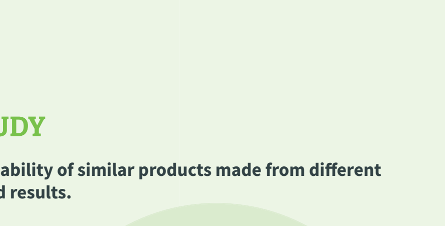
More widespread use of standardised life cycle assessment, alongside greater efforts to make information transparent and accessible to non-experts, will improve sustainable decision making.

This should go alongside increased engagement between government, policy makers, academics and wider society with LCA and complementary tools.

CASE STUDY

Life cycle assessment can be used to compare the sustainability of similar products made from different materials, with some interesting and perhaps unexpected results.

Researchers at the University of Manchester investigated the environmental impacts of takeaway food containers[13] – focussing on the three most widely used options, an aluminium box, polypropylene hard plastic box with lid, and an extruded polystyrene 'clam shell' box. They also compared these single-use options with a reusable polypropylene 'Tupperware-style' box. To allow fair comparison between containers, the functional unit was defined as "production, use and disposal of a container storing a meal for one person", with a container volume of 670ml.



The findings suggest that single-use polypropylene containers are the least sustainable option for seven out of 12 impacts considered, including global warming potential. They are followed by the aluminium alternative with five highest impacts, including depletion of ozone layer and human toxicity.

Overall, extruded polystyrene 'clam shell' containers have the lowest impacts due to the lower material and electricity requirements in their manufacture. Still, extruded polystyrene containers are currently not recycled and should not be considered a sustainable option.

When factoring in recycling, the impacts were reduced for all single-use container options. The researchers calculated that - depending on the impact category - you would need to reuse 'Tupperware'-style containers between 16 to 208 times to lower their environmental impact to that calculated for the other container types. Actually, in terms of terrestrial ecotoxicity, reusable containers were found to always be a worse option – regardless of the number of times used – due to the electricity required to heat the water for washing them. However, the sustainability of the reusable option can be increased by reducing water, energy and detergent use when cleaning them by hand. Other scenarios which reduced its impact included using low-carbon energy, and better dishwasher design.[14]

Reusable options are better in terms of circularity, but there is often a minimum number of times something should be reused to capture the benefits, as well as being made of sustainable materials and using renewable sources of energy'.

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[1] https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en
[2] https://www.iso.org/standard/37456.html
[3] https://www.iso.org/standard/38498.html
[4] https://pre-sustainability.com/articles/lca-standards-and-guidelines/
[5] https://sphera.com/glossary/what-is-a-life-cycle-assessment-lca/
[6] https://sphera.com/glossary/what-is-a-life-cycle-assessment-lca/, https://ecochain.com/knowledge/impact-categories-lca/, https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A32013H0179&from=EN
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[10] https://data.europa.eu/doi/10.2760/487955
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[12] https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf
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