DSS5202 Sustainable Systems Analysis

Life Cycle Assessment

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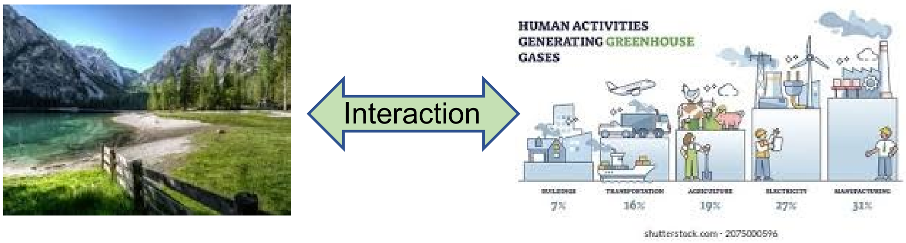
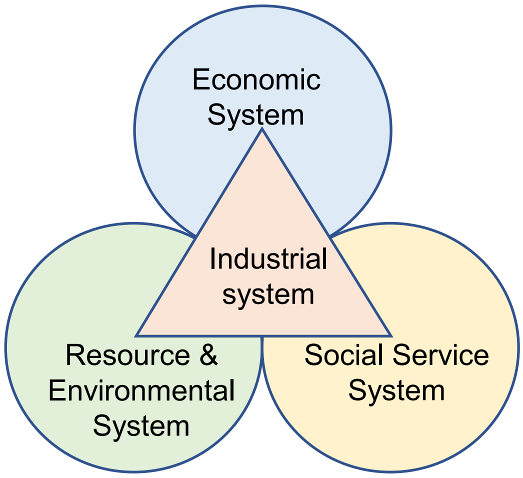
1. Sustainability

- There is an intimate relationship between the environment and human activities:



- Industrial system is the core of the human system for development.



- One of the goals for sustainability is to reduce the environmental impacts from all human activities.

- Environmental sustainability issues have come increasing of great concern globally by all organizations and stakeholders.

- There is trend these days for the markets to reward environmentally responsible organizations.

- Companies are increasingly embracing environmentally responsibility in their corporate core values and introducing them as strategic variables in their businesses.

Key Question:

- How to Evaluate the Environmental Impact from an Industrial Product or Service?

Answer:

- Life Cycle Assessment

2. Life Cycle Thinking

2.1 Six Products, Six Different Carbon Footprints

- Consider the following six products:
  1. Car
  2. Shoes
  3. Laundry detergent
  4. Milk
  5. Beer

- Objective is to determine the carbon footprint of these products.

- Each of the above product goes through five phases in their life time:

  1. Resource extraction
  2. Manufacturing
  3. Transportation
  4. Use
  5. End of life.

- Question: For each of these products, which two of the five phases you think results in the most CO_2 emissions in their life cycle?

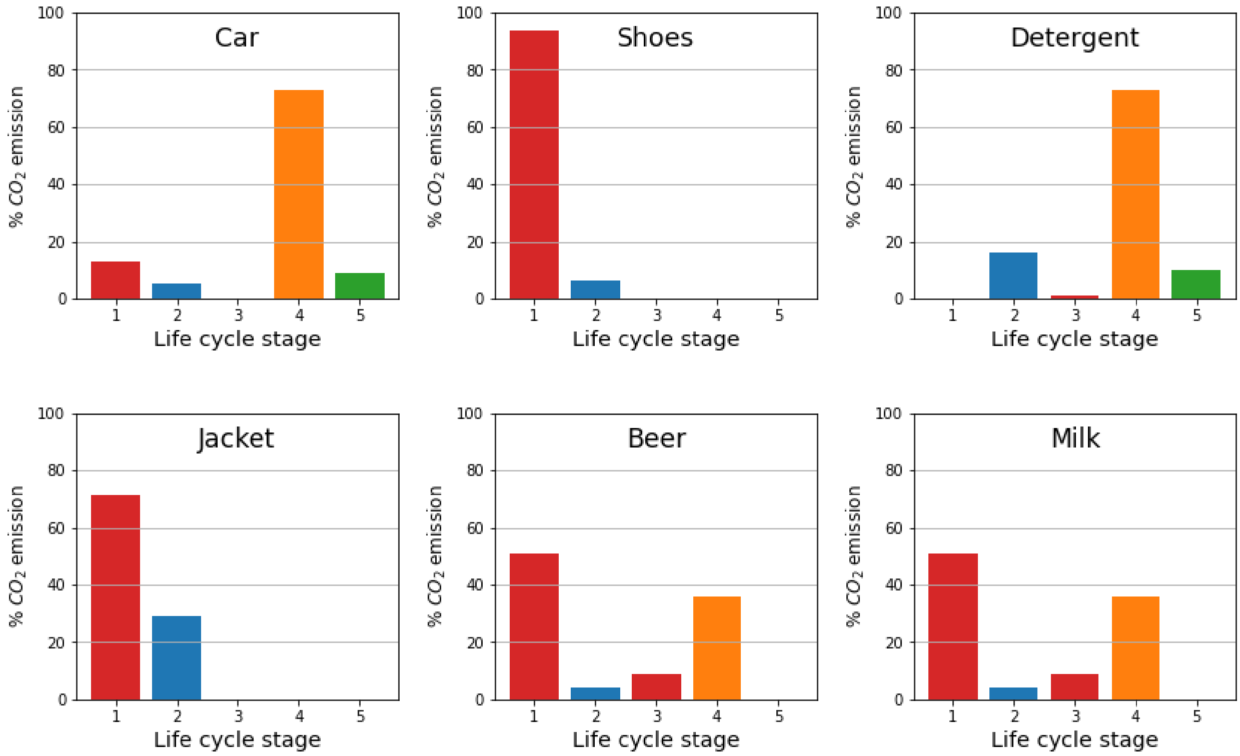
- More Information about the products:

	Product	Functional Unit
1	Car	2007 Prius driven 126,000 miles at 42 mpg
2	Shoes	1 pair of hiking boots
3	Laudry Detergent	1.5 liter, 20 load bottle
4	Fleece Jacket	1 Jacket
5	Beer	1 six-pack of beer
6	Milk	Half-gallon of organic milk

- Total emissions found:

	Product	Total CO_2 emissions
1	Car	44,000 kg
2	Shoes	55 kg
3	Laudry Detergent	14 kg
4	Fleece Jacket	30 kg
5	Beer	3.2 kg
6	Milk	3.3 kg

Results:



Conclusions:

- Consideration of all stages of life cycle is important.
- Different products have different dominant stages for environmental impacts.
- Identification of impact "hotspots" can help a more targeting direction for improving the relevant phase of the product.

2.2 LCA: A Life Cycle Based Methodology

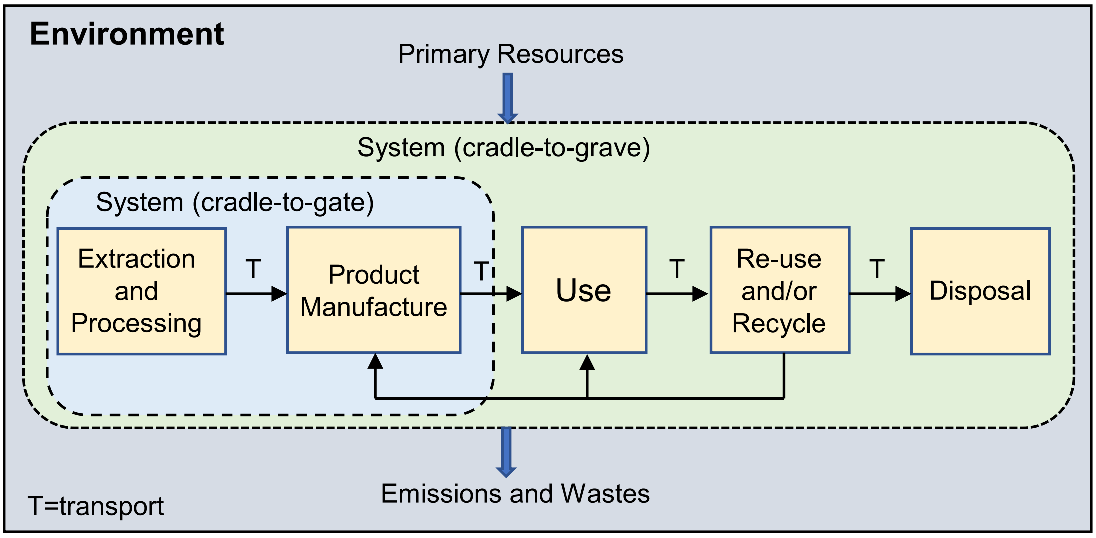
- LCA takes a life cycle perspective of the environmental problem and consider the totality of the system in the analysis, including the evaluation of the product's entire life cycle, with a long-term time horizon and a multidimensional view.

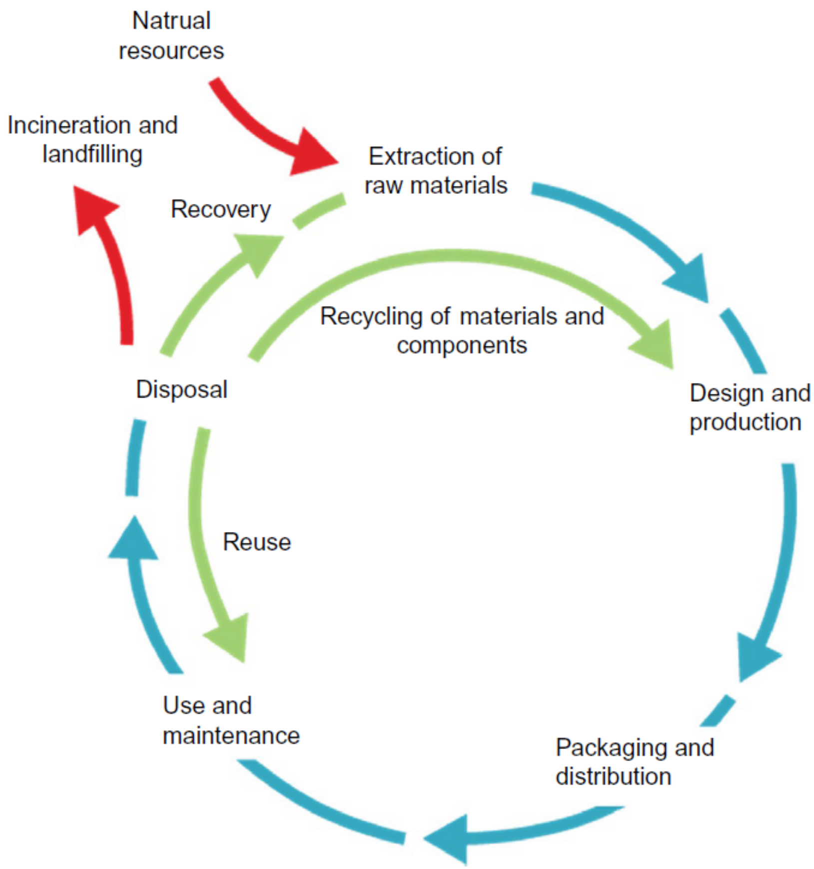
- A product's life cycle can begin with the extraction of raw materials from natural resources in the ground, and with energy generation.

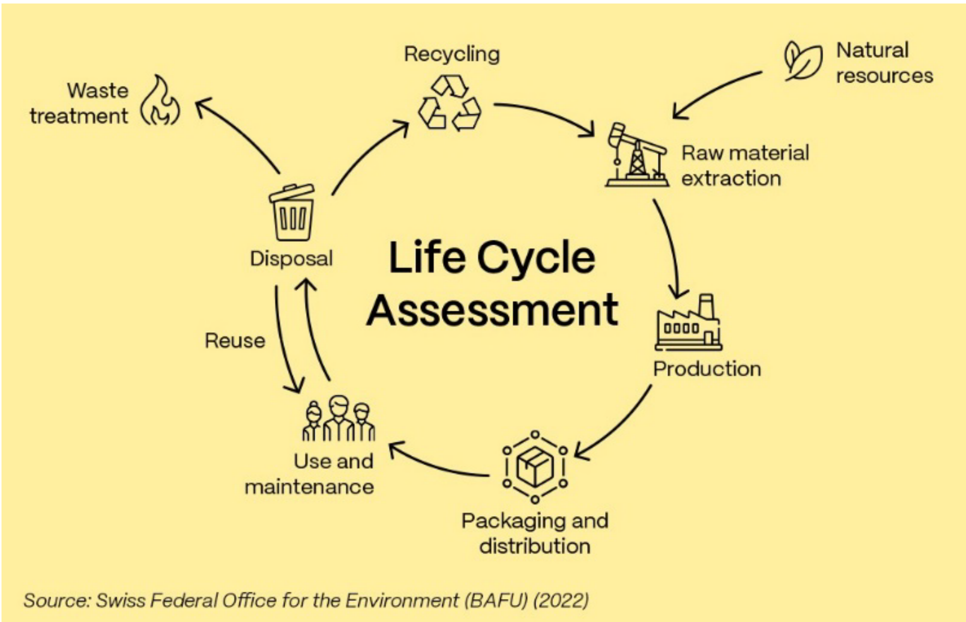
  - Materials and energy are then part of production, packaging, distribution, use, maintenance, and eventually recycling, reuse, recovery, or final disposal.

  - In each life cycle stage there is the potential to reduce resource consumption and improve the product's performance

- The life cycle of a product or service system from Cradle to Gate and from Cradle to Grave.




Natrual resources
Incineration and landfilling
Extraction of raw materials
Recovery
Recycling of materials and components
Disposal
Design and production
Reuse
Use and maintenance
Packaging and distribution


Waste treatment
Recycling
Natural resources
Raw material extraction
Disposal
Life Cycle Assessment
Reuse
Production
Use and maintenance
Packaging and distribution
Source: Swiss Federal Office for the Environment (BAFU) (2022)

2.3 Strength and Features of LCA

- LCA provides a comprehensive holistic analysis leading to solutions for reducing impacts in an absolute and not a relative way. It models cause-effect relationships in the environment and thus helps to understand the environmental consequences of human actions.

- LCA has four features:
  1. it takes a life cycle perspective (Cradle-to-Grave)
  2. it can cover a broad range of environmental issues
  3. is quantitative
  4. is science-based

- Although LCA is primarily quantitative in nature, but qualitative aspects can be taken in to account to provide a more complete picture on the environmental impacts involved.

- The life cycle perspective avoids shifting the environmental problem of a product from one stage to another stage in the product's life cycle.

- LCA is now a highly regarded framework for assessing the potential environmental impacts of products. It assesses quantitatively the environmental impacts of goods and processes from cradle to grave.

- LCA can play a useful role in both public and private environmental management of products. Main applications of LCA are

  1. Analysing the roots problems related to a particular product.
  2. Comparing improvement variants of a given product.
  3. Development of new products.
  4. Comparison between existing products.
  5. Comparison between existing and new product under development.

2.4 Limitations of LCA

- The holistic nature of LCA is both a major strength and at the same time a limitation. The broad scope of the analysing the complete life cycle of a product can only be achieved at the expense of simplify other aspects.

- LCA does not provide the framework to adequately address localised impacts. It focusses on the impacts on the environment outside the system boundary.

- LCA takes a steady-state state view of the system. It does not consider the transient states or the system dynamics.

- LCA focuses on physical characteristics of the industrial activities and other economic processes It does not include market mechanisms or secondary effects on technological development.

- LCA basically assumes and models all processes as linear in behaviour, both in the economy and in the environment. It assumes constant return to scale on all processes and ignore any economy of scales.

- LCA focuses mainly on the environmental aspects of products, and says nothing about their economic, social and other characteristics. The "potential impacts" are not specified in time and space and are often related to an arbitrarily defined functional unit.

- LCA is highly dependent on data. It can be limited by the availability of up-to-date accurate data at the correct level or finest in details.

- LCA cannot replace the entire decision-making process. It is a very useful analytical tool that provides information for decision support. It may be necessary to combine LCA with other methodologies:

- Other methodologies that can be used together with LCA:
    - Life Cycle Costing (LCC)
    - Multiple Criteria Decision Making (MCDM)
    - Multiple Objective Optimization (MOP)
    - Data Envelopment Analysis (DEA)
    - Environmental Input-Output Analysis (EIOA)

2.5 Application of LCA under different decision situation

- How LCA is applied depends on the situation and intended use.

1	Global exploration of options	LCA is performed to get a first impression of the environmental effect of certain options.
2	Company internal innovation	LCA is performed to assess the environmental impact of company internal product improvements, product development and technical innovations.
3	Sector driven innovation	Similar to the above, except that it is sector-oriented in a formal organization representing a group of companies.
4	Strategic planning	LCA is performed to assess the environmental impact of strategic scenarios.
5	Comparison	LCA is performed to assess whether a product or system meets certain environmental standards, or whether it is environmentally sounder than another product or system.
6	Comparative assertion disclosed to the public	LCA aims to provide an environmental claim regarding the superiority or equivalence of one product versus a competing product which performs the same function.

Source: Handbook on life cycle assessment.

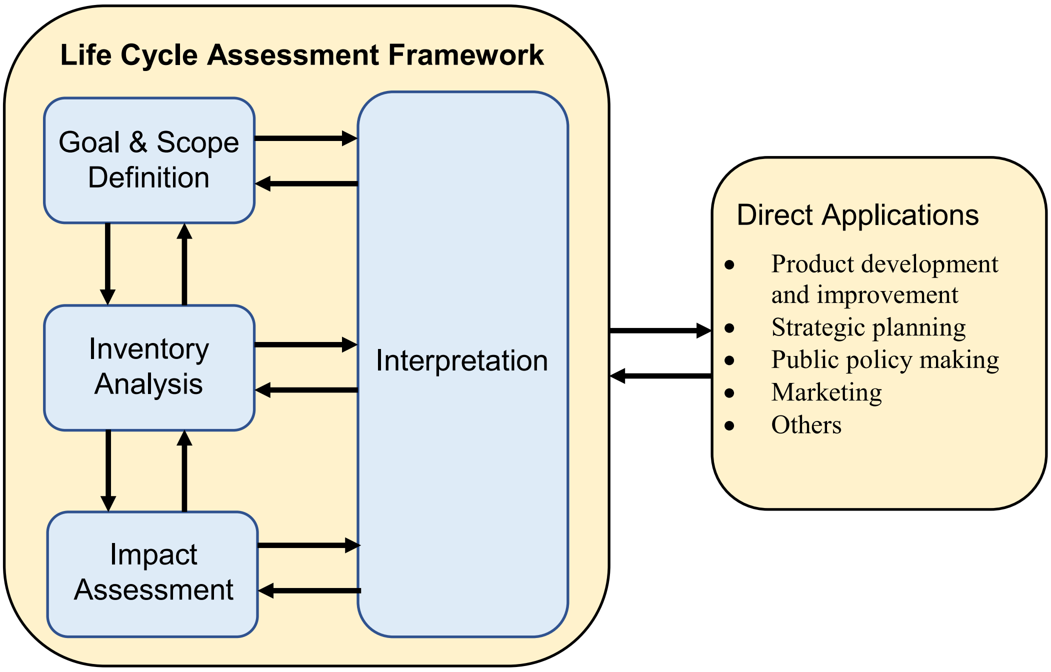
3 An Overview of the LCA Methodology

3.1 What is LCA?

- Life Cycle Assessment (LCA) is a methodology used to compile, analyze and evaluate the environmental impacts and burdens of a product, process, or service throughout its entire life cycle at both operational and strategic levels.

- LCA identifies and quantifies potential environmental burdens associated with each stage of the life cycle (from cradle to grave) of a product, including resource depletion, energy consumption, emissions to air, water, and soil, and waste generation.

- Environmental burdens may include:
  - Extraction of different types of resources
  - Emission of hazardous substances
  - Different types of land use.



- The LCA process is a systematically phased approach and comprises four main steps:

  1. **Goal and Scope Definition**
     - Define and describe the product, process or activity.
     - Identify the objectives, the intended audience, the functional unit.
     - Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

  2. **Inventory Analysis**
     - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges.
     - The data is compiled in a life cycle inventory (LCI) and helps to quantify the environmental impacts of the product or process.

3. **Impact Assessment**
   - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
   - Impact categories may include global warming, resource depletion, water and air pollution, etc.
   - This step involves converting the inventory data into impact scores using specific impact assessment methods and models.

4. **Interpretation**
   - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.
   - Draw conclusions, identify hotspots (stages with the highest environmental impacts), and make recommendations for improvements.
   - Sensitivity analysis and uncertainty assessment may also be conducted to evaluate the robustness of the results.

- By following above steps rigorously, a comprehensive life cycle assessment can be conducted to better understand and manage the environmental impacts of products, processes, or services.

3.2 What Does LCA Offers?

- LCA is thorough, systematic, and scientific. It considers the totality of the system in the analysis with a long-term time horizon and a multidimensional view.

- LCA encompasses all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product.

- LCA provides a comprehensive analysis leading to solutions for reducing impacts in an absolute and not a relative way.

- LCA allows companies and organizations can make informed decisions to minimize environmental impacts, optimize resource efficiency, and reduce the carbon footprint of their products or activities.

- LCA can help decision-makers compare all major environmental impacts caused by products, processes, or services and decide between two or more alternatives that has the least impact to the environment.

- LCA provides an important decision-support tool among other things that allows:
  1. Companies to benchmark and optimize the environmental performance of products.
  2. For authorities to design policies for sustainable consumption and production.

- However, it also be emphasized that LCA provides only one perspective and can be used with other factors such as life cycle cost (LCC) and technical performance data to select a product or process that represents the best trade-offs between the major factors.

3.3 Standardization of LCA

1. ISO14040:2006/AMD 1:2020 Environmental management—Life cycle assessment - Principles and framework—Amendment 1.
    - Describes the principles and the framework for conducting LCA.

2. ISO14044:2006/AMD 2:2020 Environmental management—Life cycle assessment - Requirements and guidelines—Amendment 2.
    - Specifies the requirements and provides the guidelines for conducting LCA.

- These standards provide information about the steps/phases to develop an LCA study:
    1. Definition of the goal and scope of the LCA
    2. Life cycle inventory (LCI) analysis
    3. Life cycle impact assessment (LCIA)
    4. Life cycle interpretation

- They also include a critical review of LCA, the limitations of LCA, the relationship between the LCA phases, and the conditions for the use of value choices and optional elements.

4. LCA Principles and Practice

4.1 Phase I: Goal and Scope Definition

- Phase I is the description of the goal and scope, which includes defining the objectives of the study and setting the methodological bases to develop the LCA.

- Questions raised during this phase:
  - Why are you conducting the LCA?
  - What do you hope to achieve?
  - Are you assessing the environmental impacts of a specific product, service, or process?
  - Are you comparing alternatives to inform decision-making?

- The **Goal** definition must establish unambiguously
  - what is the intended application.
  - the reasons to carry out the study
  - the audience which it is intended for
  - if the results be used for comparative study

Example of a Goal statement

"The goal of this LCA is to understand the environmental impacts of both the most common artificial Christmas tree and the most common natural Christmas tree, and to analyse how their environmental impacts compare"

"This comparative study is expected to be made publicly available to refute myths and misconceptions about the relative difference in environmental impact by real and artificial trees" (Source: American Christmas Tree Association, 2010)

- The **Scop**e must clearly define the extent, depth, and detail of the study. It has 3 main components:

  1. Functional Unit
  2. System Boundary
  3. Product system studied: Which specific process(es) to manufacture a product.

Functional Unit

- The functional unit serves as a reference for comparing different alternatives and ensures that the results are meaningful and relevant to the intended application.

- It is defined in ISO 14044 as the "quantified performance of a product system for use as a reference unit".

- It is the basis for which impact calculation or comparison of product and services are made.

- It should be based on the service or process provided by the product.

- It is a scaling factor for all calculations and is integral to the outcome of the LCA.

- It must be clearly defined, measurable, and consistent with the goal and scope of the study.

Example:

- Suppose that there are two alternative processes A and B to manufacture a certain chemical X. What should the functional unit me?

- Functional Unit: 1 litre of chemical X of concentration Y.

Example:

- To compare the environmental impact of 3 different cars:
  1. An electric vehicle
  2. A conventional petrol engine car.
  3. Biofuel vehicle

- Functional Unit: 1 km of distance driven in a 4-seater car on highway under summer condition.

Example:

- **To compare five different types of cup:**
  1. Glass
  2. Ceramic
  3. Plastic
  4. Paper
  5. Styrofoam

- Functional Unit: 100 number of tea/coffee drinks.

Some common problem with selection of functional unit.

1. Failure to express the function with/without units.
   A power plant cannot be just simply "Generating Electricity".

2. Confusion with systems inputs and outputs:
   kg of CO_2 is not a valid functional unit.
   kg of CO_2 per kWh is not a valid functional unit.

3. Inconsistency across the alternatives to be compared.

Product System

- A product system is a set of processes or activities that provide a certain function or service.
  - Product: any goods or services.
  - Function: Performance characteristic of the product system.

Example:

- Power plant is a product system and generating electricity is the function.

Challenges in defining the Product System

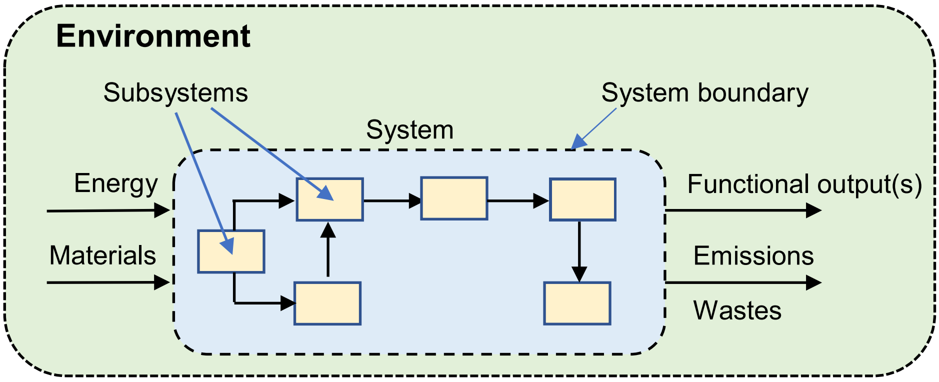
- In real application, product system can be very complex comprising a very large number of processes.
- Reliable data may not be available for all components.
- Computational difficulty may be encountered during calculations.
- **System boundary** manage the complexity by identifying the components that are to be considered in the study

System Boundary

- Define the boundaries of the LCA by specifying which processes, inputs, and outputs will be included in the analysis.

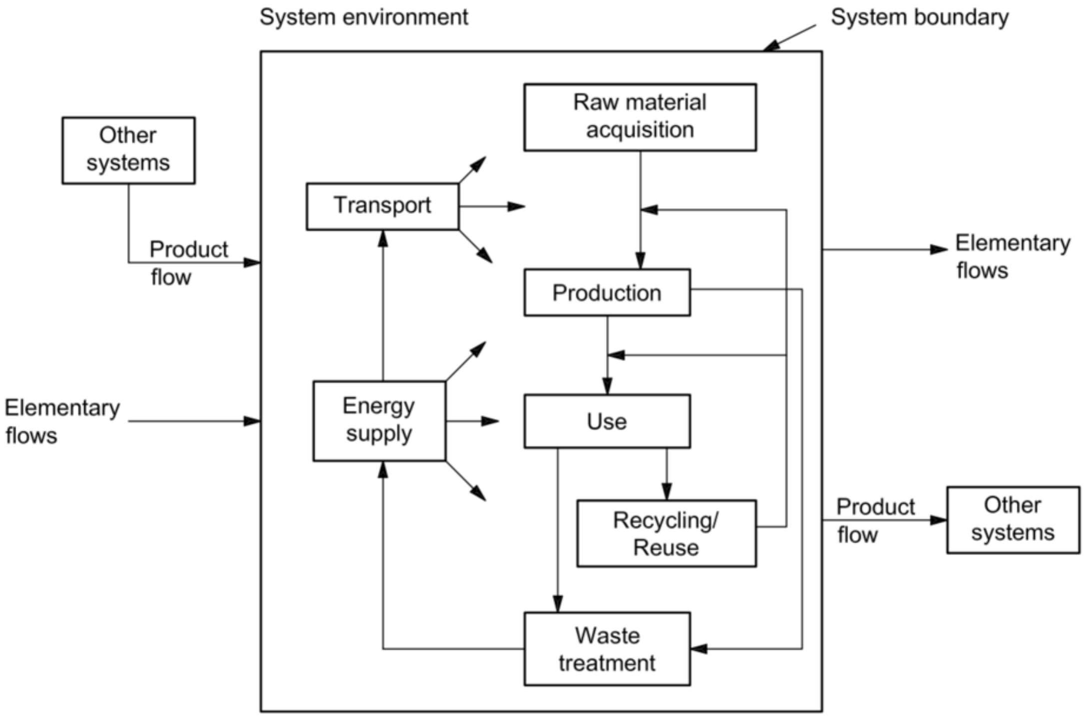
- Consider the entire life cycle of the product, service, or process, from cradle to grave, including raw material extraction, manufacturing, distribution, use, and disposal.

- Decide whether to include upstream and downstream processes, as well as indirect impacts such as transportation or waste management.



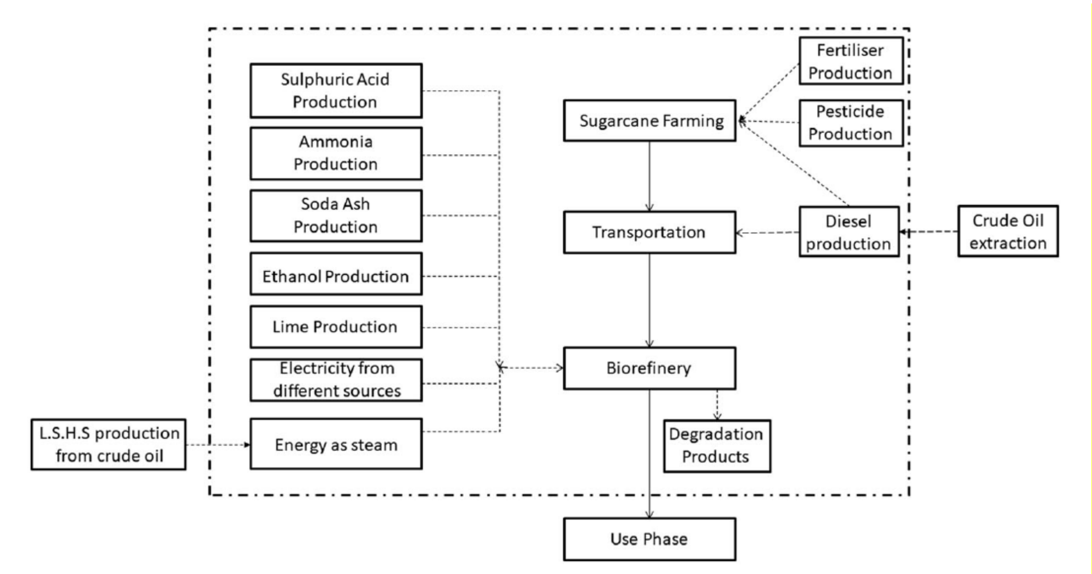
Example: A Generic Product System and System Boundary

- Components of a product system diagram (also known as process flow diagram).
  - Boxes represent various form of processes
  - Arrows represent flows
  - Solid or dashed lines represents system boundaries.



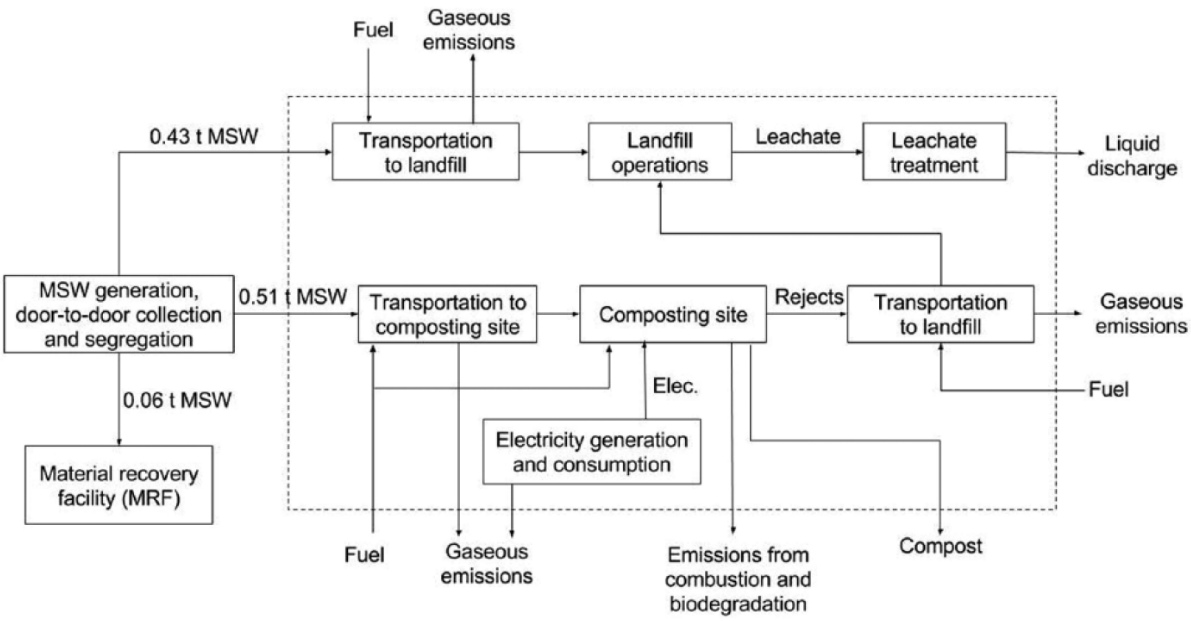
Example: Biofuel Production

- Crude oil extraction is excluded from the system boundary.



Example: Municipal Solid Waste (MSW) Disposal.

- MSW generation, door-to-door collection and segregation are not included.
- Material recovery facilities are not included.



Impact of System Boundary.

- Different system boundary can result in drastically different results.

Example:

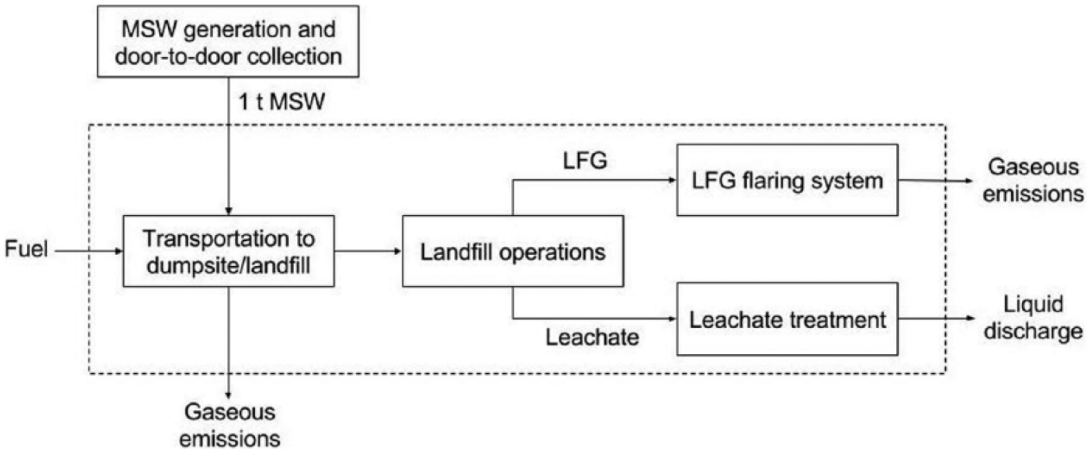
- In comparing EV and Petrol car? If we include or do not include the electricity generation within the system boundary, the results will very much different.

- Biofuel production. If we include not include land use within the system boundaries, the results will be much different.

Process Flows

1. **Elementary flows**

   Material or energy entering the system being studied that has drawn from the environment without previous human transformation, or material or energy leaving the system that is released into the environment without subsequent human transformation.



2. **Product flows:**

   Products are output of product systems and a product flow represents the connection of a product between product systems where it may be output of and an input of another.

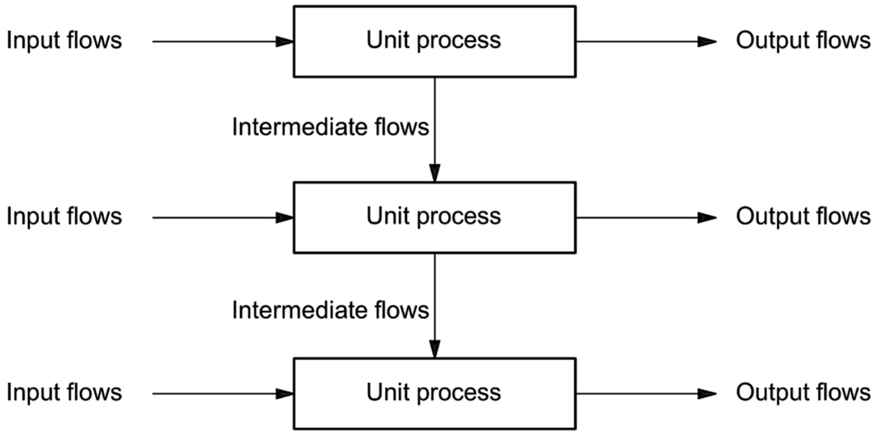
3. **Reference flows:**

   When the functional unit has been defined, the reference flows can be determined. A reference flow is the product flow to which all input and output flows for the processes in the product system must be quantitatively related. In other words, the reference flow is the amount of product that is needed to realise the functional unit.

Unit Process and Flows

- A unit process is the smallest element considered in a life cycle inventory model for which input and output data are quantified.

- A generic interacting series of three-unit process that may a subcomponent of a product system.



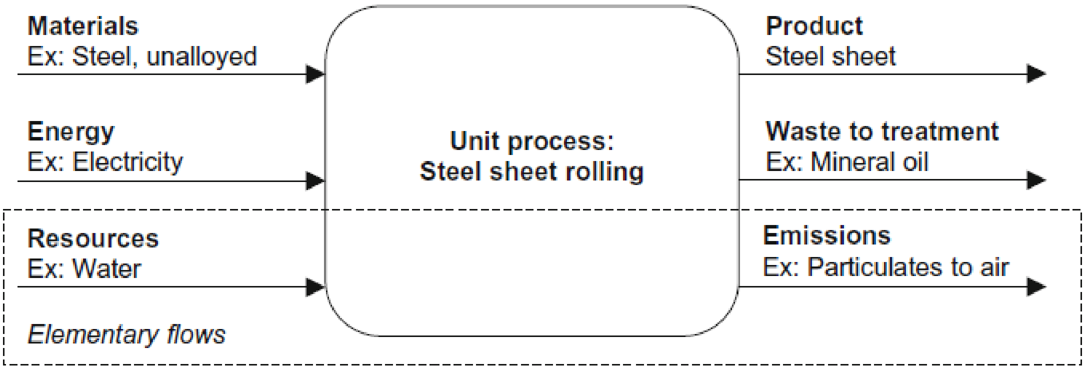
- Unit processes can be considered as the building blocks of a life cycle inventory model that are linked together by input and output data, which can be organized into six categories of physical flows:

- Input Flows:
  1. Materials
  2. Energy
  3. Resources

- Output Flows:
  1. Products
  2. Waste to treatment
  3. Emissions

Example:

- A simplified unit process of steel sheet rolling and examples of flows.

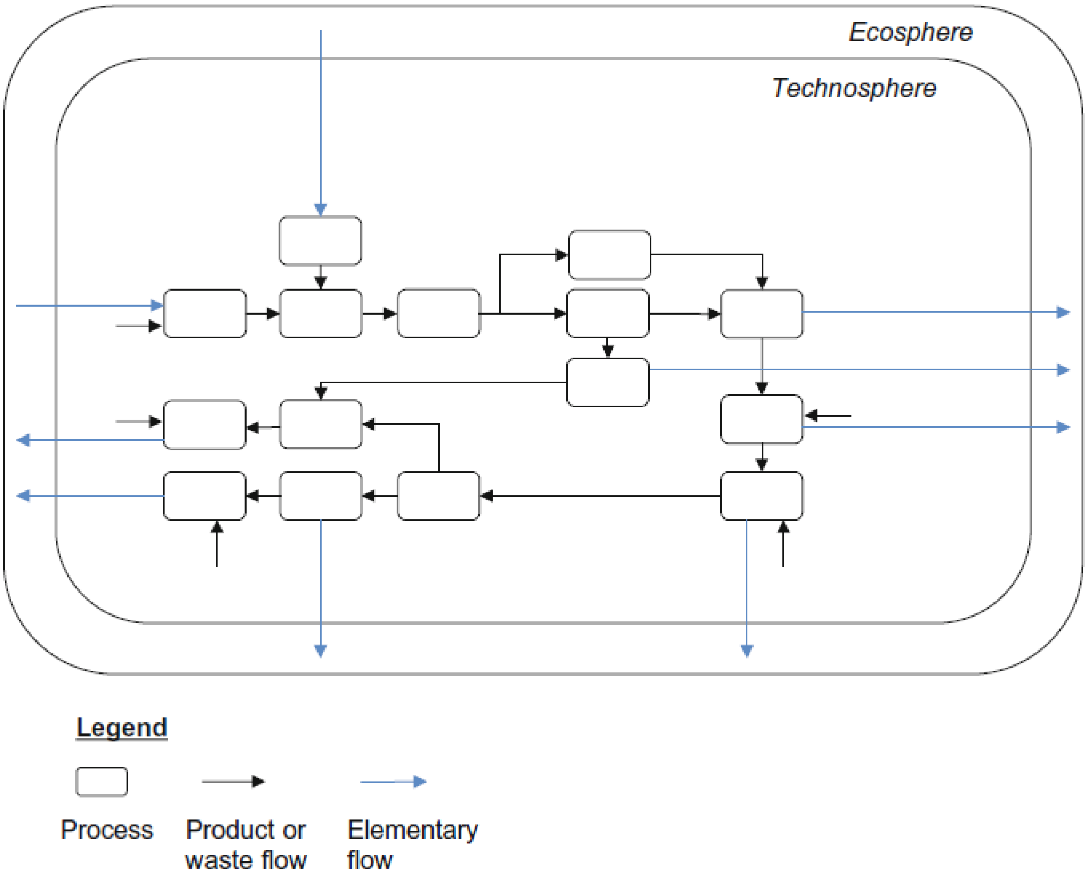


Technosphere and Ecosphere

LCA divides the world into a technosphere and an ecosphere:

- The technosphere is everything that is intentionally "manmade" and also includes processes that are natural in origin, but manipulated by humans, such as photosynthesis when part of an agricultural system. All unit processes of belong to the technosphere.

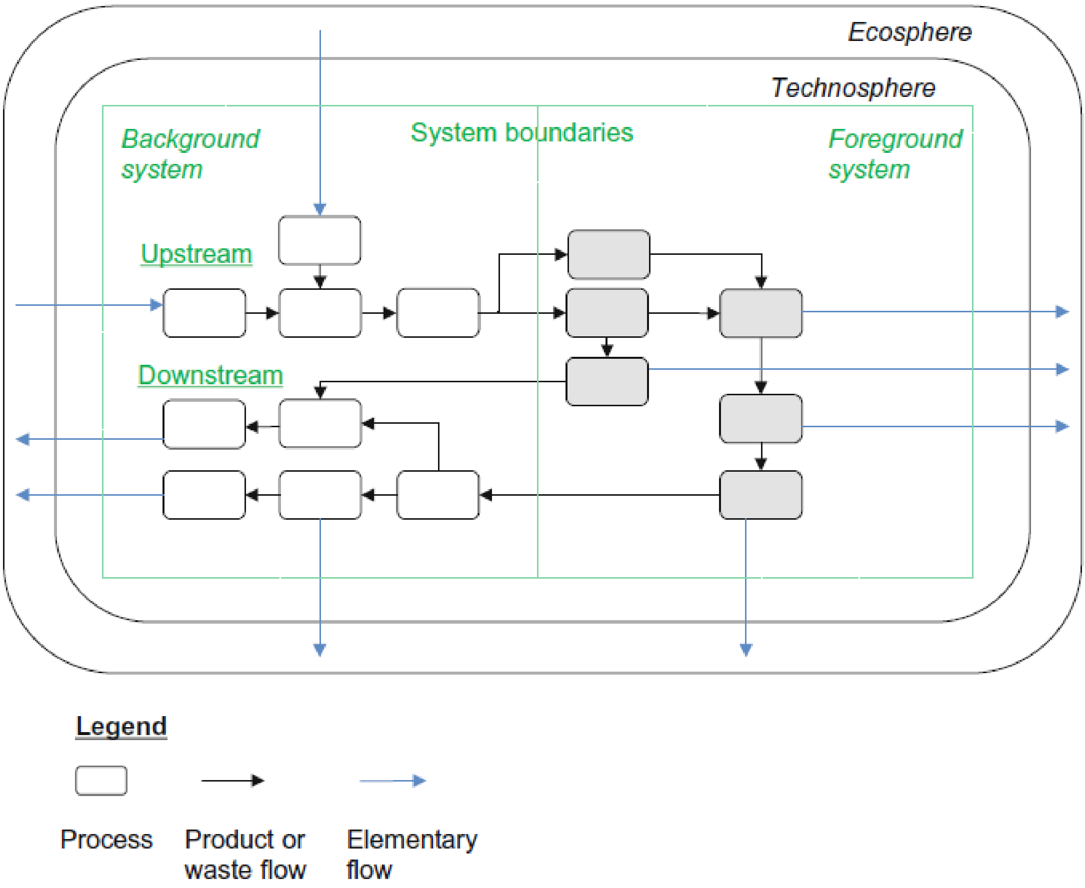
- The ecosphere is sometimes referred to as "the environment". It is everything which is not intentionally "man-made" and contains those qualities that LCA has been designed to protect, i.e. ecosystems, human health and resource availability.



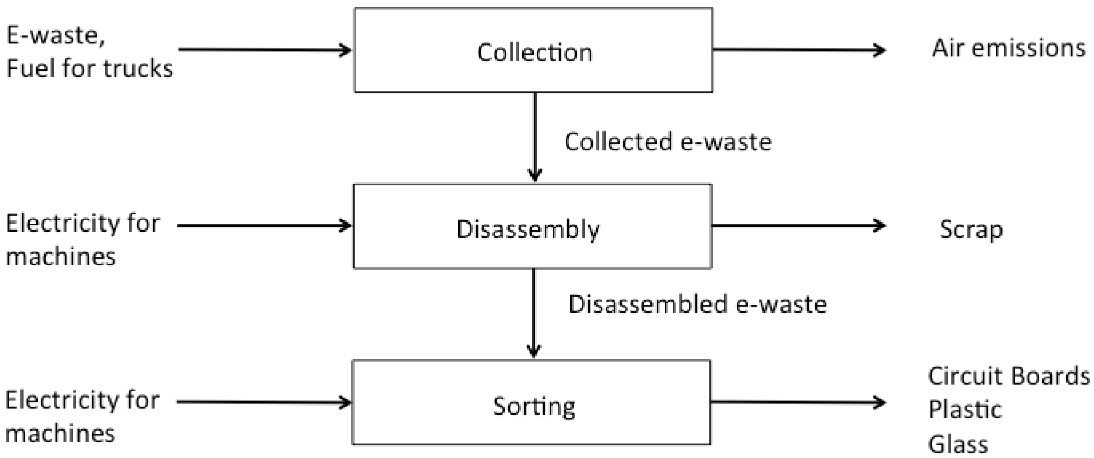
Foreground and Background System

- The foreground system is commonly defined as comprising those processes of a product system that are specific to it.

- The background system, in contrast, is commonly defined as those processes of a system that are not specific to it. Such processes take part in numerous product systems besides the one studied.



Example: Waste Treatment Process



Key Summary on Importance of System Boundary Definition

- System boundary greatly influence the scope of the calculations.
- System boundary can significantly change the LCA results.
- LCA calculation require identification of different types of flows.

Selection of Impact Categories

- Identify the environmental impact categories that will be assessed. Some common categories are:

1. **Climate change**: Assessing impacts related to greenhouse gas emissions (e.g., CO2, CH4) and their contribution to global warming and climate change.

2. **Ozone depletion**: Evaluating impacts on the ozone layer caused by substances like chlorofluorocarbons (CFCs) and their effect on stratospheric ozone.

3. **Acidification**: Measuring the contribution to acid rain through emissions of acidifying substances like sulfur dioxide (SO2) and nitrogen oxides (NOx).

4. **Eutrophication**: Assessing impacts related to excessive nutrient inputs (e.g., nitrogen and phosphorus) into ecosystems, leading to algal blooms, oxygen depletion, and ecosystem degradation.

5. **Ecotoxicity**: Evaluating the potential for substances to harm ecosystems and wildlife, including acute and chronic effects on organisms.

6. **Photochemical ozone formation**: Assessing contributions to the formation of ground-level ozone through chemical reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOCs).

7. **Depletion of resources**: Measuring the depletion of non-renewable resources such as minerals and fossil fuels, or the use of resources at rates exceeding their regeneration.

8. **Water depletion**: Evaluating impacts related to the withdrawal of water resources from rivers, lakes, or aquifers, affecting water availability and ecosystems.

9. **Land use**: Assessing impacts related to changes in land cover and land use patterns, including habitat loss, fragmentation, and degradation.

10. **Human toxicity**: Evaluating impacts on human health through exposure to toxic substances, considering both carcinogenic and non-carcinogenic effects.

- Choose impact categories based on the goals of the study, stakeholder interests, and relevance to the product or process being analysed.

Data Availability and Resources

- Specify the data needed and their requirements for the study.

- Assess the availability of the data and resources needed to conduct the LCA within the defined scope.

- Consider the time, expertise, and budget required to collect data, perform analyses, and interpret results.

- If certain data are unavailable or uncertain, consider sensitivity analysis or assumptions to address gaps in the data information uncertainty.

State Major Assumptions and Limitations

- Clearly state any assumptions made and limitations of the LCA, including data uncertainties, methodological choices, and constraints imposed by the scope.

- Transparency about assumptions and limitations helps ensure the credibility and reliability of the study results.

Stakeholders Consulted

- Consult with relevant stakeholders, including internal team members, industry experts, regulators, and end-users, to ensure that the scope of the LCA aligns with their interests and concerns.

- Stakeholder engagement can provide valuable insights, improve the relevance of the study, and enhance the credibility of the results.

4.2 Phase 2: Inventory Analysis

- The following steps can be used to conduct a thorough inventory analysis that provides valuable insights into the environmental impacts of a product, service, or process throughout its life cycle.

1. **Identify Life Cycle Stages**

   - Break down the life cycle of the product, service, or process into distinct stages.
   - These stages typically include raw material extraction, manufacturing, distribution, use, and disposal.
   - Determine the boundaries of your analysis, including what activities and inputs/outputs will be included in each stage.

2. **Collect Data**

   - Gather data on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with each stage of the life cycle.
   - This may involve conducting surveys, consulting with experts, reviewing literature, or using databases.

3. **Quantify Inputs and Outputs**

   - Convert the collected data into quantitative measures.
   - For example, express raw material inputs in terms of mass or volume, energy consumption in kilowatt-hours, emissions in kilograms of CO_2 equivalent, etc.
   - Ensure consistency in units across different types of inputs and outputs.

4. **Compile Inventory Table**

   - Organize the quantified data into an inventory table.

   - Create a worksheet or database where each row represents a specific input or output, and each column represents a different life cycle stage.

   - This table should provide a comprehensive overview of the inputs and outputs associated with the entire life cycle.

5. **Normalization and Aggregation**

   - Normalize the inventory data to facilitate comparison between different life cycle stages or between different products/services.

   - This may involve expressing the data per unit of functional output (e.g., per kilogram of product, per unit of energy delivered) or per unit of time.

   - Aggregate the normalized data to calculate total impacts for each life cycle stage.

6. **Quality Assurance**

   - Ensure the accuracy and reliability of the inventory data.

   - Verify the sources of data, check for errors or inconsistencies, and document any assumptions or uncertainties associated with the data collection process.

7. **Sensitivity Analysis**

   - Conduct sensitivity analysis to assess the influence of uncertain or variable parameters on the results of the inventory analysis.

   - This helps identify which input parameters have the greatest impact on the overall environmental performance.

8. **Documentation**

   - Document the inventory analysis methodology, including data sources, assumptions, and calculations performed.

   - This documentation is essential for transparency and reproducibility and provides context for interpreting the results.

9. **Peer Review**

   - Consider having the inventory analysis reviewed by peers or experts in the field to ensure its accuracy and robustness.

   - Incorporate feedback and suggestions for improvement as necessary.

10. Iterative Process

- Inventory analysis is often an iterative process.

- As new data becomes available or as the scope of the analysis evolves, update the inventory accordingly and refine the analysis to improve accuracy and relevance.

4.3 Phase 3: Life Cycle Impact Assessment

- The Life Cycle Impact Assessment (LCIA) phase is concern with the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI.

- Impact assessment addresses
  1. Ecological impacts
  2. Human health effects
  3. Resource depletion.

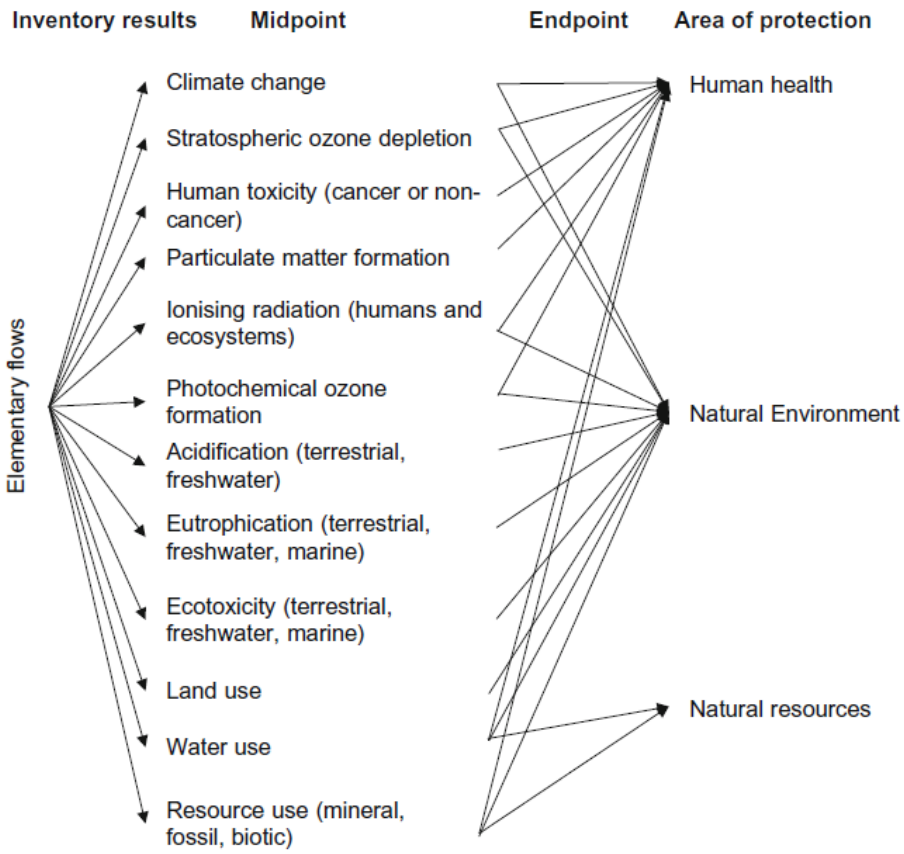
- A life cycle impact assessment attempts to establish a linkage between the product or process and its potential environmental impacts.

Example

- What are the impacts of 9,000 tons of carbon dioxide or 5,000 tons of methane emissions released into the atmosphere? Which is worse? What are their potential impacts on smog? On global warming?

Midpoint versus Endpoint Modeling

- Midpoint impact assessment models reflect the relative potency of the stressors at a common midpoint within the cause-effect chain. It reduces the complexity of the modeling and simplify communication.



- Mid-Point Impact Indicators:

    1. Global warming potential (Climate change)
    2. Stratospheric ozone depletion
    3. Acidification (terrestrial, freshwater)
    4. Eutrophication (terrestrial, freshwater, marine)
    5. Photochemical ozone formation
    6. Ecotoxicity (terrestrial, freshwater, marine)
    7. Human toxicity (cancer, non-cancer)
    8. Particulate matter formation
    9. Ionising radiation (human health, aquatic and terrestrial ecosystems)
    10. Land Use (biotic productivity, aquifer recharge, carbon sequestration, albedo, erosion, mechanical and chemical filtration capacity, biodiversity)
    11. Water use (human health, aquatic ecosystems, terrestrial ecosystems, ecosystem services)
    12. Abiotic resource use (fossil and mineral)
    13. Biotic resource use (e.g. fishing or wood logging)
    14. Noise
    15. Pathogens

- **Endpoint Impact Indicators**

    1. Human health
    2. Ecosystem quality or natural environment
    3. Natural resources and ecosystem services

- The following can be used to conduct impact assessment to evaluate the potential environmental impacts of a product, service, or process:

1. Select Impact Categories

- Choose the environmental impact categories that you want to assess based on the goals of the study, stakeholder interests, and relevance to the product, service, or process being analysed.

- Common impact categories include:
    1. Global warming potential (climate change)
    2. Acidification
    3. Eutrophication
    4. Ozone depletion
    5. Human toxicity
    6. Ecotoxicity
    7. Resource depletion
    8. Land use

2. Characterization

- In this step, all elementary flows in the LCI are assessed according to the degree to which they contribute to an impact.

- All elementary flows *E*, classified within a specific impact category c (representing an environmental issue of concern), are multiplied by their respective characterisation factor CF and summed over all relevant interventions *i* (emissions or resource extractions) resulting in an impact score IS for the environmental impact category.

- A characterisation factor (CF) represents the contribution per quantity of an elementary flow to a specific environmental impact (category).

- CF are calculated using models of the environmental mechanism representing as realistically as possible the cause–effect chain of events leading to effects (impacts) on the environment for all elementary flows which contribute to this impact.

3. Normalization (Optional step)

- Normalize the impact scores to facilitate comparison between different impact categories or between different products, services, or processes.

- Normalization involves expressing impact scores relative to a reference value, such as per unit of functional output (e.g., per kilogram of product, per megajoule of energy) or per capita.

4. Weighting (Optional step)

- Optionally, apply weighting factors to the normalized impact scores to reflect the relative importance of different impact categories based on stakeholder preferences or policy priorities.

- Weighting allows you to aggregate the impacts into a single score or indicator that represents overall environmental performance.

- However, weighting is a subjective process and should be used with caution. Proper use of MCDM methods can avoid this problem.

5. Impact Assessment Models

- Use impact assessment models or methods to calculate impact scores for each impact category based on the inventory data.

- There are several established impact assessment methods available, such as:
  1. ReCiPe (ReCiPe Endpoint and ReCiPe Midpoint)
  2. IMPACT 2002+
  3. CML (Center for Environmental Science, Leiden University)
  4. TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts)

6. Interpretation

- Interpret the results of the impact assessment to identify hotspots where the largest environmental impacts occur and to understand the relative contributions of different life cycle stages, processes, or inputs to each impact category.

- Consider trade-offs between different impact categories and stages of the life cycle.

7. Sensitivity Analysis

- Conduct sensitivity analysis to assess the influence of uncertainties or variations in input parameters on the results of the impact assessment.

- Identify key parameters that have the greatest impact on the outcomes and explore alternative scenarios or assumptions to understand their implications.

8. Documentation

- Document the impact assessment methodology, including the selection of impact categories, characterization factors, normalization and weighting methods (if applicable), and any assumptions or uncertainties associated with the analysis.

- Transparency about the methodology used in the impact assessment helps ensure the credibility and reliability of the study results.

4.4 Phase 4: Interpretation

- The following steps may be used to effectively interpret the results of a life cycle assessment and use the insights gained to drive environmental sustainability and continuous improvement within your organization or industry.

1. Review the Results

- Start by reviewing the quantitative results of the LCA, including the environmental impacts assessed in different impact categories (e.g., global warming potential, acidification, eutrophication) and their magnitudes across various life cycle stages.

2. Identify Hotspots

- Identify hotspots where the largest environmental impacts occur.
- These hotspots may represent specific processes, materials, or life cycle stages that contribute disproportionately to overall environmental burdens.
- Focus on addressing hotspots to achieve the greatest environmental improvements.

3. Compare Alternatives

- If comparing multiple products, services, or processes, compare their environmental performance across different impact categories and life cycle stages.
- Identify areas of relative strength and weakness for each alternative to inform decision-making and prioritize areas for improvement.

4. Consider Trade-offs

- Recognize that environmental improvements in one impact category or life cycle stage may lead to trade-offs in others.
- For example, reducing greenhouse gas emissions may increase water consumption or toxicity.
- Consider trade-offs carefully and strive for holistic solutions that minimize overall environmental impacts.

5. Contextualize Results

- Consider the context in which the LCA results are interpreted.
- Take into account factors such as the scale of production, geographic location, technological advancements, regulatory requirements, and stakeholder preferences.
- Contextualization ensures that the interpretation is relevant and actionable.

6. **Sensitivity Analysis**

   - Assess the sensitivity of the results to uncertainties or variations in input parameters.
   - Identify key parameters that have the greatest influence on the outcomes and explore alternative scenarios or assumptions to understand their implications.
   - Sensitivity analysis enhances the robustness and reliability of the interpretation.

7. **Engage Stakeholders**

   - Involve relevant stakeholders, including internal team members, industry partners, regulators, and consumers, in the interpretation process.
   - Seek input and feedback to ensure that the interpretation reflects diverse perspectives and priorities.
   - Stakeholder engagement fosters buy-in and support for implementing LCA recommendations.

8. **Set Priorities for Improvement**

   - Based on the interpretation of the LCA results, prioritize areas for improvement that offer the greatest potential for environmental benefits and align with organizational goals and objectives.
   - Develop action plans and strategies to address identified hotspots and capitalize on opportunities for innovation and optimization.

9. **Document Findings and Recommendations**

   - Document the interpretation of LCA results, including key findings, insights, recommendations, and decision-making criteria.
   - Communicate the implications of the LCA to stakeholders through reports, presentations, and discussions, ensuring transparency and accountability.

4.5 LCA Report Structure

- Summary or Abstract
- Introduction
    - Problem background and definition
    - Literature review
- Goal of the Study
    - Reasons for the study
    - Specific question to answer
    - Type of study: Comparative or stand-alone?
    - Intended application
    - Intended audience
- Scope of the Study
    - Functional unit
    - System boundaries
    - Assumptions and limitations
    - Impact categories and impact assessment method
    - Normalization and weighting (if any)
- Inventory Analysis
    - Process flowcharts
    - Data
- Impact Analysis
- Interpretation
- Conclusion and Recommendations
- References
- Appendix A
- Appendix B

References

5 Case Studies

5.1 Case Study 1: LCA study of a 1-Liter Polyethylene Plastic Bottle

- This study evaluates the environmental impacts associated with the production, use, and disposal of a 1-liter polyethylene (PE) plastic bottle.

- The analysis follows the ISO 14040 and ISO 14044 standards and uses the Cumulative Life Cycle Impact Assessment (CML) methodology to assess various environmental impact categories.

Phase 1: <u>Goal and Scope Definition</u>

- **Goal and Objectives**

  - To assess the environmental impacts of producing, using, and disposing of a 1-liter PE bottle.
  - The study also aims to identify hotspots in the life cycle and suggest improvements for reducing environmental impacts.

- **Scope**

  - **Functional Unit**:
    One 1-liter PE bottle.

  - **System Boundaries:** Cradle-to-Grave)
    1. Raw material extraction
    2. PE production
    3. Bottle manufacturing
    4. Transportation
    5. End-of-life.

  - **Geographical Coverage**:
    Region X.

  - **Temporal Coverage**:
    Current practices as of 2024.

- **Impact Categories and Characterization Factors**

  - These following impact categories were selected to provide a comprehensive assessment of the environmental impacts associated with the life cycle of the PE bottle based on the Cumulative Life Cycle Impact Assessment (CML) methodology

    1. Global Warming Potential (GWP)
    2. Acidification Potential (AP)
    3. Eutrophication Potential (EP)
    4. Photochemical Ozone Creation Potential (POCP).

1. **Global Warming Potential (GWP)**
   - Unit: kg CO_2 equivalent (kg CO_2 eq)
   - Description: Measures the potential contribution to climate change by greenhouse gases over a specific time period (usually 100 years). It includes emissions such as CO_2, CH_4, N_2O, etc.

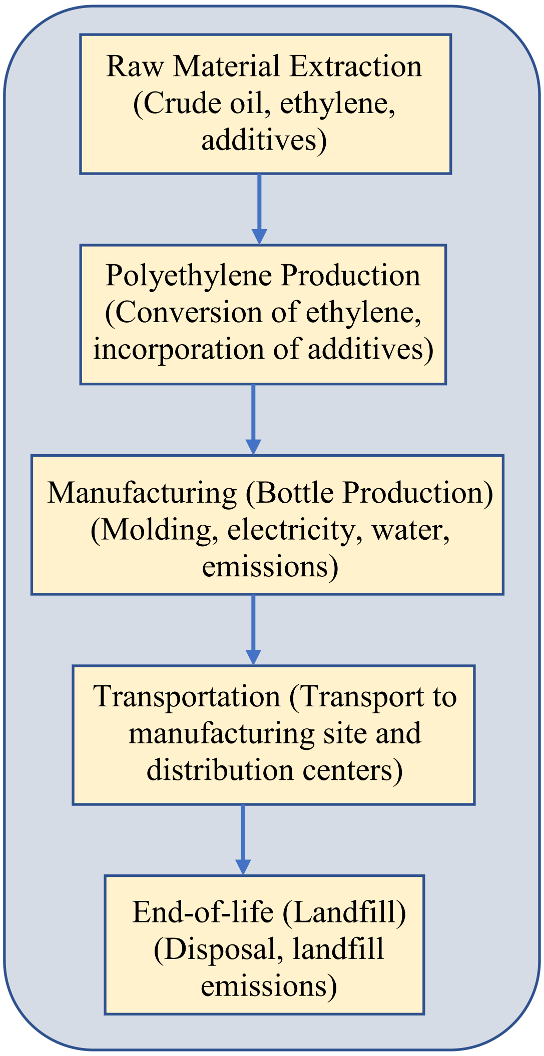
2. **Acidification Potential (AP)**
   - Unit: kg SO_2 equivalent (kg SO_2 eq)
   - Description: Measures the potential for acidifying effects on soil and water, primarily due to emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x).

3. **Eutrophication Potential (EP)**
   - Unit: kg PO_4 equivalent (kg PO_4 eq)
   - Description: Measures the potential for nutrient enrichment in aquatic and terrestrial environments, which can lead to excessive growth of algae and other plants, affecting water quality and biodiversity. Key contributors include phosphorus (P) and nitrogen (N) compounds.

4. **Photochemical Ozone Creation Potential (POCP)**
   - Unit: kg C_2H_4 equivalent (kg C_2H_4 eq)
   - Description: Measures the potential for formation of ground-level ozone (smog), which can affect human health and vegetation. It includes emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x).

- **Process Flow Diagram for a 1-Liter Polyethylene (PE) Plastic Bottle**

  The process flow diagrams for the life cycle of a 1-liter polyethylene (PE) plastic bottle is shown below.



Phase 2: Inventory Analysis (LCI)

- **Data Collection**

  Raw Material Extraction:
  - Ethylene: 1.05 kg per kg PE.
  - Additives: 0.002 kg per kg PE.
  - Energy: 2.5 kWh per kg PE.
  - Emissions: 1.6 kg CO2, 0.02 kg SO2, 0.01 kg NOx per kg PE.

  Manufacturing:
  - Electricity: 0.5 kWh per bottle.
  - Water: 10 liters per bottle.
  - Emissions: 0.2 kg CO2 per bottle.

  Transportation:
  - Distance: 500 km by truck.
  - Fuel consumption: 0.2 liters diesel per ton-km.
  - Emissions: 2.68 kg CO2/liter diesel, 0.02 kg SO2/liter diesel.

  End-of-life:
  - Methane emissions: 0.1 kg CH4 per kg PE.
  - Landfill space: 0.001 cubic meters per bottle.

- **Inventory Summary Table**

Life Cycle Stage	Input/Output	Quantity
Raw Material Extraction	Polyethylene (PE)	1 kg
	Ethylene	1.05 kg
	Additives	0.002 kg
	Energy	2.5 kWh
	CO2 emissions	1.6 kg
	SO2 emissions	0.02 kg
	NOx emissions	0.01 kg
Manufacturing	Electricity	0.5 kWh
	Water	10 liters
	CO2 emissions	0.2 kg
Transportation	Diesel fuel	100 liters
	CO2 emissions	268 kg
	SO2 emissions	2 kg
End-of-life	Methane emissions (landfill)	0.1 kg
	Landfill space	0.001 m^3

Phase 3: Impact Assessment (LCIA)

- Characterization Factors:

Impact Category	Characterization Factor	Unit
Global Warming Potential (GWP)	1 kg CO_2 eq per kg	kg CO_2 eq
Acidification Potential (AP)	1 kg SO_2 eq per kg	kg SO_2 eq
Eutrophication Potential (EP)	1 kg PO_4 eq per kg	kg PO_4 eq
Photochemical Ozone Creation Potential (POCP)	1 kg C_2H_4 eq per kg	kg C_2H_4 eq

1. **Global Warming Potential (GWP)**

   Relevant substances and their equivalent to CO_2 on GWP:

   1. CO_2: 1 kg CO_2 eq.
   2. CH_4: 1 kg of methane has 25 times the global warming potential of 1 kg of CO_2.
   3. N_2O: 1 kg of nitrous oxide has 298 times the global warming potential of 1 kg of CO_2.

Computations:

Raw Material Extraction:
CO_2: 1.6 kg * 1 = 1.6 kg CO_2 eq

Manufacturing:
CO_2: 0.2 kg * 1 = 0.2 kg CO_2 eq

Transportation:
CO_2: 268 kg * 1 = 268 kg CO_2 eq

End-of-life:
CH_4: 0.1 kg * 25 kg CO_2 eq/kg = 2.5 kg CO_2 eq

Total GWP = 1.6 + 0.2 + 268 + 2.5 = 272.3 kg CO_2 eq

2. Acidification Potential (AP)

Relevant substances and their equivalent to SO_2 on AP:

1. SO_2 (sulfur dioxide)**:** 1 kg SO_2 eq.
2. NOx (nitrogen oxides)**:** The acidification potential of 1 kg of NOx is equivalent to 2 kg of SO_2.
3. NH_3 (ammonia)**:** The acidification potential of 1 kg of NH_3 is equivalent to 1.88 kg of SO_2.

Computation:

Raw Material Extraction:
SO_2: 0.02 kg * 1 = 0.02 kg SO_2 eq

Manufacturing:
SO_2: 0 kg (negligible)

Transportation:
SO_2: 2 kg * 1 = 2 kg SO_2 eq

Total AP = 0.02 + 0 + 2 = 2.02 kg SO_2 eq

3. Eutrophication Potential (EP)

Relevant substances and their equivalent to

1. Phosphorus (PO_4): 1 kg PO_4 eq
2. Nitrogen (NOx): The eutrophication potential of 1 kg of NOx is equivalent to 1 kg of PO_4.

Computations:

Raw Material Extraction:
NOx: 0.01 kg * 1 = 0.01 kg PO_4 eq

Manufacturing:
NOx: 0 kg (negligible)

Transportation:
NOx: 0.01 kg * 1 = 0.01 kg PO_4 eq

Total EP = 0.01 + 0 + 0.01 = 0.02 kg PO_4 eq

4. Photochemical Ozone Creation Potential (POCP)

Relevant substances and their equivalent to Ethylene (C_2H_4)

1. Ethylene (C_2H_4): 1
2. Propylene (C_3H_6): 10
3. Toluene: 4
4. Benzene: 2
5. Xylene: 1.2

Computations:

Raw Material Extraction:
VOCs: 0.02 kg * 1 = 0.02 kg C_2H_4 eq

Manufacturing:
VOCs: 0 kg (negligible)

Transportation:
VOCs: 0.01 kg * 1 = 0.01 kg C_2H_4 eq

Total POCP = 0.02 + 0 + 0.01 = 0.03 kg C_2H_4 eq

	Impact Category	**Score**	**unit**
1	Global Warming Potential (GWP)	272.3	Kg CO_2 eq
2	Acidification Potential (AP)	2.02	Kg SO_2 eq
3	Eutrophication Potential (EP)	0.02	Kg PO_4 eq
4	Photochemical Ozone Creation Potential (POCP)	0.03	Kg C_2H_4 eq

5.5 Phase 4: Interpretation

- **Hotspots:**

  1. Global Warming Potential: The transportation stage contributes the most to GWP due to the high fuel consumption and CO_2 emissions.

  2. Acidification Potential: Transportation is the largest contributor due to SO_2 emissions from diesel fuel combustion.

  3. Eutrophication Potential: Both raw material extraction and transportation contribute to EP, with NO_x emissions playing a significant role.

  4. Photochemical Ozone Creation Potential: Raw material extraction is the main contributor due to VOC emissions.

- **Recommendations:**

  1. Transportation: Optimize logistics to reduce transportation distances and consider more efficient or alternative transport modes.

  2. Raw Material Sourcing: Investigate alternative sources or materials with lower environmental impacts.

  3. Energy Efficienc: Implement energy-saving measures in manufacturing to reduce electricity consumption and associated emissions.

- **Reporting and Critical Review**

  1. Documentation: The results, assumptions, data sources, and methodologies used in this LCA study are documented comprehensively in this report.

  2. Critical Review: An independent expert review will be conducted to ensure the credibility, accuracy, and transparency of the study.

Conclusion

- This LCA study provides a detailed analysis of the environmental impacts associated with the life cycle of a 1-liter PE plastic bottle.

- By identifying the key contributors to environmental impacts, the study offers actionable insights for improving the sustainability of plastic bottle production and usage.

5.2 Case Study 2: Comparative LCA study on using LED and Incandescent Lamps

- This case study shows how to conduct a comparative Life Cycle Assessment (LCA) of using LED and incandescent lamps for home lighting.

- Some of the data used here are only representative values for illustrative purposes only.

Phase 1: <u>Goal and Scope Definition</u>

- **Goal:**

  - To compare the environmental impacts of LED and incandescent lamps used for home lighting over their complete life cycles.

  - The results of this assessment will inform stakeholders including consumers, manufacturers, and policymakers, about the sustainability of each lighting option, enabling more environmentally conscious decisions.

- **Scope:**

  - **Functional Unit:**

    - Provide 10,000 hours of home lighting.

    - This ensures that the comparison between the two lamps is based on delivering the same lighting service, allowing for a fair assessment of their environmental impacts over a comparable duration of use.

  - **Lamp Specifications:**

    LED Lamp:
    - Power: 10W
    - Lifespan: 25,000 hours
    - Number of lamps needed for 10,000 hours:
      = 10,000 hours / 25,000 hours per lamp = 0.4 lamps

    Incandescent Lamp:
    - Power: 60W
    - Lifespan: 1,000 hours
    - Number of lamps needed for 10,000 hours:
      = 10,000 hours / 1,000 hours per lamp =10 lamps

- **System Boundaries:**
  - Cradle-to-Grave analysis includes the following stages:
    1. Raw Material Extraction and Processing: Extraction and processing of raw materials used in manufacturing the lamps.
    2. Manufacturing: Production processes for both LED and incandescent lamps, including energy and material inputs.
    3. Transportation: Distribution of lamps from manufacturing sites to retail locations and ultimately to the consumer.
    4. Use Phase: Energy consumption during the operation of the lamps over 10,000 hours.
    5. End-of-Life: Disposal, recycling, or landfilling of lamps after their use phase.
- **Major Assumptions**
  - The electricity mix for the use phase is based on an average grid mix with an emission factor of 0.5 kg CO_2e/kWh.
  - Manufacturing energy and materials data are based on industry averages.
  - Transportation impacts are averaged for typical distribution distances.
  - End-of-life scenarios assume 80% recycling for LEDs and 100% landfill for incandescent lamps.
- **Impact Categories:**
  1. Global Warming Potential (GWP)
     - This category measures the greenhouse gas emissions, expressed in kilograms of CO_2 equivalents (kg CO_2e), that contribute to global warming.
  2. Energy Consumption
     - This category assesses the total energy used throughout the life cycle of the lamps, measured in kilowatt-hours (kWh).
  3. Resource Depletion
     - This category evaluates the depletion of natural resources, expressed in kilograms of antimony equivalents (kg Sb eq.).
  4. Human Toxicity
     - This category measures the potential harm to human health from toxic substances, expressed in kilograms of 1,4-dichlorobenzene equivalents (kg 1,4-DB eq.)
  5. Eutrophication
     - This category assesses the potential for nutrient pollution in aquatic ecosystems, which can lead to excessive growth of algae and other problems, expressed in kilograms of phosphate equivalents (kg PO_4 eq.).

- **Characterization Factors:**

  1. GWP: kg CO_2e
  2. Energy Consumption: kWh
  3. Resource Depletion: kg Sb eq.
  4. Human Toxicity: kg 1,4-DB eq.
  5. Eutrophication: kg PO_4 eq.

- **Data Sources:**

  - Inventory data are obtained from industry reports, life cycle databases and scientific literature.
  - Impact characterization factors are sourced from established LCIA methodologies such as TRACI, ReCiPe, or CML.

Phase 2: <u>Life Cycle Inventory (LCI)</u>

- **LED Lamp:**

  - Raw Materials:
    - Aluminum heat sink: 120g
    - Plastic components: 30g
    - Electronic components: 10g
    - LED chips: 5g

  - Manufacturing Energy:
    - 5 kWh per lamp

  - Transportation:
    - 0.5 kg CO2e per lamp

  - Electricity Consumption
    - Use phase: 10W x 10,000 hours = 100 kWh

  - End-of-Life:
    - Recycling: 80%
    - Landfill: 20%

- **Incandescent Lamp:**

  - Raw Materials:
    - Glass: 25g
    - Tungsten filament: 1g
    - Aluminum base: 5g

  - Manufacturing Energy:
    - 1 kWh per lamp

  - Transportation:
    - 0.2 kg CO2e per lamp

  - Electricity Consumption:
    - Use phase: 60W x 10,000 hours = 600 kWh

  - End-of-Life:
    - Landfill: 100%

Phase 3: **<u>Impact Assessment</u>.**

- **Calculation of Impact Categories**

  1. Global Warming Potential (GWP):

  - LED Lamp:

    - Manufacturing:
      5 kWh x 0.5 kg CO_2e/kWh = 2.5 kg CO_2e
    - Transportation:
      0.5 kg CO_2e
    - Use phase:
      100 kWh x 0.5 kg CO_2e/kWh = 50 kg CO_2e
    - End-of-Life:
      Negligible (recycling)

    Total: 2.5 + 0.5 + 50 = 53 kg CO_2e

  - Incandescent Lamp:

    - Manufacturing:
      1 kWh x 0.5 kg CO_2e/kWh = 0.5 kg CO_2e
    - Transportation:
      0.2 kg CO_2e
    - Use phase:
      600 kWh x 0.5 kg CO_2e/kWh = 300 kg CO_2e
    - End-of-Life: Negligible

    Total: 0.5 + 0.2 + 300 = 300.7 kg CO_2e

2 Energy Consumption:

- LED Lamp:

  - Manufacturing:
    5 kWh
  - Use phase:
    105 kWh

  Total: 5 + 105 = 110 kWh

- Incandescent Lamp:

  - Manufacturing:
    600 kWh
  - Use phase:
    601 kWh

  Total: 600 + 601 = 121 kWh

3. Resource Depletion:

- LED Lamp:
  - Raw materials extraction:
    approx. 0.001 kg Sb eq.

- Incandescent Lamp:
  - Raw materials extraction:
    approx. 0.0001 kg Sb eq.

4. Human Toxicity:

- LED Lamp:

  - Production of electronic components and metals:
    approx. 0.01 kg 1,4-DB eq.

- Incandescent Lamp:
  - Production of tungsten filament and glass:
    approx. 0.001 kg 1,4-DB eq.

5. Eutrophication:

- LED Lamp:
  - Manufacturing processes:
    approx. 0.0001 kg PO4 eq.

- Incandescent Lamp:
  - Manufacturing processes:
    approx. 0.00005 kg PO4 eq.

- **Observations:**

  - LED lamps have significantly lower global warming potential and energy consumption compared to incandescent lamps.

  - Despite slightly higher resource depletion and human toxicity impacts due to the production of electronic components, LEDs are a more environmentally friendly choice for home lighting when considering overall impacts.

Normalization of Impacts

- Normalization involves expressing the impact results relative to a reference value.

- The reference values typically represent the total annual environmental impact of a region, country, or the world per capita.

- This process helps to understand the significance of the results in a broader context.

- **Normalization Reference Values**
  (*Representative values as examples only. Check with real data bases in real applications*)

  1. Global Warming Potential (GWP):
     7.2 × 10^9 kg CO2e per capita per year

  2. Energy Consumption:
     8.0 × 10^3 kWh per capita per year

  3. Resource Depletion:
     0.5 kg Sb eq. per capita per year

  4. Human Toxicity:
     2.5 × 10^2 kg 1,4-DB eq. per capita per year

  5. Eutrophication:
     2.0 kg PO4 eq. per capita per year

- **Normalized Impact Values**

  1. Global Warming Potential (GWP):

     LED: $53 / (7.2\times10^{9}) = 7.361\times 10^{-9}$

     Incandescent: $300.7 / (7.2\times10^{9}) = 4.176\times 10^{-8}$

  2. Energy Consumption:

     LED: 110 / 8000 = 0.01375

     Incandescent: 601 / 8000 = 0.075125

3. Resource Depletion:

   LED: 0.001/0.5 = 0.0020

   Incandescent: 0.0001/0.5 = 0.0002

4. Human Toxicity:

   LED: 0.01 / 250 = 0.000040

   Incandescent: 0.001 / 250 = 0.0000040

5. Eutrophication:

   LED: = 0.0001 / 2 = 0.00005

   Incandescent: 0.00005 / 2 = 0.000025

Phase 4: Interpretation

- **Summary of Results**

  - LED Lamp:

	Impact	Absolute value	Normalized value
1	GWP	53 kg CO2e	7.361×10^{-9}
2	Energy Consumption	105 kWh	0.01375
3	Resource Depletion	0.001 kg Sb eq.	0.0020
4	Human Toxicity	0.01 kg 1,4-DB eq.	0.000040
5	Eutrophication	0.0001 kg PO4 eq	0.00005

  - **Incandescent Lamp:**

	Impact	Absolute value	Normalized value
1	GWP	300.7 kg CO2e	4.176×10^{-8}
2	Energy Consumption	601 kWh	0.075125
3	Resource Depletion	0.0001 kg Sb eq.	0.0002
4	Human Toxicity	0.001 kg 1,4-DB eq.	0.0000040
5	Eutrophication	0.00005 kg PO4 eq.	0.000025

- **Weighting**

  - Weighting assigns a relative importance to each normalized impact category based on societal, environmental, or economic considerations.

  - The values of weighs should be accessed from stakeholder preferences, policy goals, or expert judgment.

  - Multiple Criteria Decision Making (MCDM) methods may be used in this step.

  - Suppose that in consultation with the stakeholders and decision makers, the following weights were assessed:

    1. Global Warming Potential (GWP): 0.4
    2. Energy Consumption: 0.3
    3. Resource Depletion: 0.1
    4. Human Toxicity: 0.1
    5. Eutrophication: 0.1

  - Weighted Normalized Impact Values

    LED:

    $= 0.4\,(7.361\times10^{-09}) + 0.3\,(0.01375) + 0.1\,(0.0020) + 0.1\,(0.000040) + 0.1\,(0.000050)$
    $= 0.00433$

Incandescent Lamps:

$= 0.4\ (4.176\times10^{-08}) + 0.3\ (0.075125) + 0.1\ (0.0002) + 0.1\ (0.000004) + 0.1\ (0.000025)$
$= 0.02256$

- Observation: From the weighted scores, it's clear that the LED lamp has a significantly lower overall environmental impact compared to the incandescent lamp.

- **Observations:**

  - The normalized and weighted results show that the LED lamp has a significantly lower overall environmental impact compared to the incandescent lamp.

  - This conclusion is supported by lower normalized impacts in global warming potential, energy consumption, and other categories.

  - The total weighted score for the LED lamp (0.00433) is much lower than that for the incandescent lamp (0.02256), indicating that LED lamps are more environmentally friendly for home lighting over their life cycle.

Conclusion

- Environmental Impacts Comparison:
  1. Global Warming Potential (GWP):
     - o LED lamps have significantly lower GWP compared to incandescent lamps (53 kg CO2e vs. 300.7 kg CO2e).

  2. Energy Consumption:
     - o LED lamps consume much less energy over their lifetime (105 kWh vs. 601 kWh).

  3. Resource Depletion:
     - Both types have low impacts, but LEDs use more resources due to electronic components.

  4. Human Toxicity:
     - LED lamps have higher toxicity due to the production of electronic components.

  5. Eutrophication:
     - Both types have negligible impacts, with LEDs being slightly higher.

- **Overall Summary**

  - LED lamps are more environmentally friendly in terms of GWP and energy consumption, despite slightly higher impacts in resource depletion and human toxicity.

  - The advantages of reduced energy use and lower GWP make LEDs a better choice for sustainable home lighting.

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