Emerging Technologies for the Circular Economy

Lecture 3: Lifecycle Assessment (LCA)

Prof. Dr. Benjamin Leiding
M.Sc. Anant Sujatanagarjuna
M.Sc. Shohreh Kia

License

INTRODUCTION

LCA – Motivation

LCA – Motivation

Battery Electric Vehicles (EV)

Or

Internal Combustion Engine Vehicles

EV Break-Even Point?

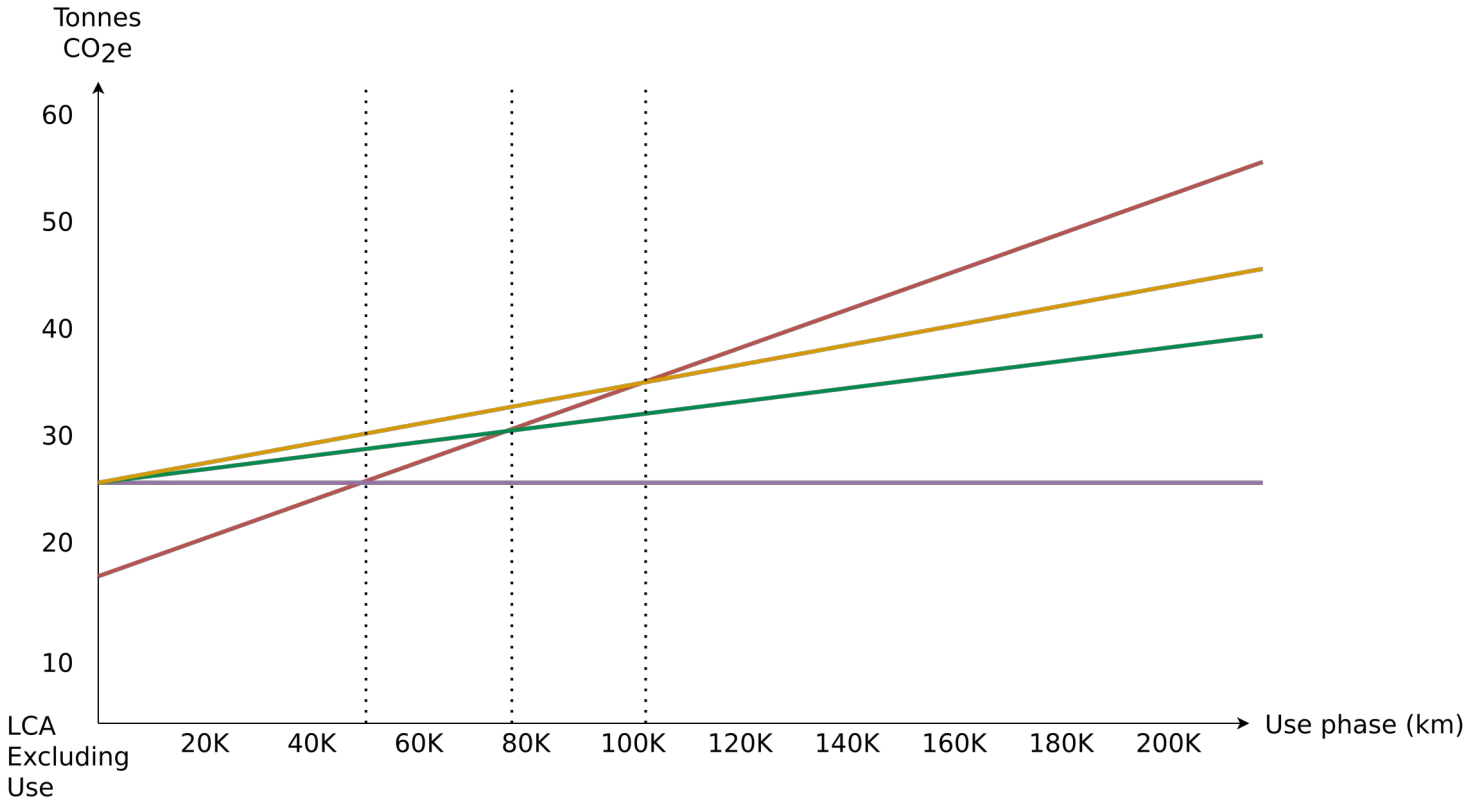
What is the **break-even** point (in km) after which an EV would have caused fewer emissions than an Internal Combustion Engine (ICE?)

a. 0 – 50.000km
b. 50.000 – 100.000km
c. 100.000 – 150.000km
d. 150.000 – 200.000km
e. After 200.000km

Life Cycle Assessment – Polestar 2

Cumulative amount of GHGs emitted depending on total km driven, from Polestar 2 (with different electricity mixes)

- XC40 ICE
- Polestar 2 -- Global electricity Mix
- Polestar 2 -- European (EU28) electricity Mix
- Polestar 2 -- Wind Power



Number of kilometers driven at break-even between Polestar 2 with different electricity mixes in the use phase of XC40 ICE (petrol)

Electric mix	Break-even (km)
Polestar 2 -- Global electricity Mix	112,000
Polestar 2 -- European (EU28) electricity Mix	78,000
Polestar 2 -- Wind Power	50,000

Polestar (2020) – Life Cycle Assessment – Carbon Footprint of Polestar 2.

LIFECYCLE ASSESSMENT (LCA)

Lifecycle Assessment (LCA)

Definition

“LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product’s lifecycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave).” -- ISO 14040

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Lifecycle Assessment (LCA)
ISO 14040 & ISO 14044

- The ISO 14040/14044 (ISO14040, 2006) (ISO14044, 2006) together provide a *loose* methodology for conducting LCA studies.
- ISO 14040 defines the *principles and framework* of the standard
- ISO 14044 provides *requirements and guidelines* for LCA practitioners.

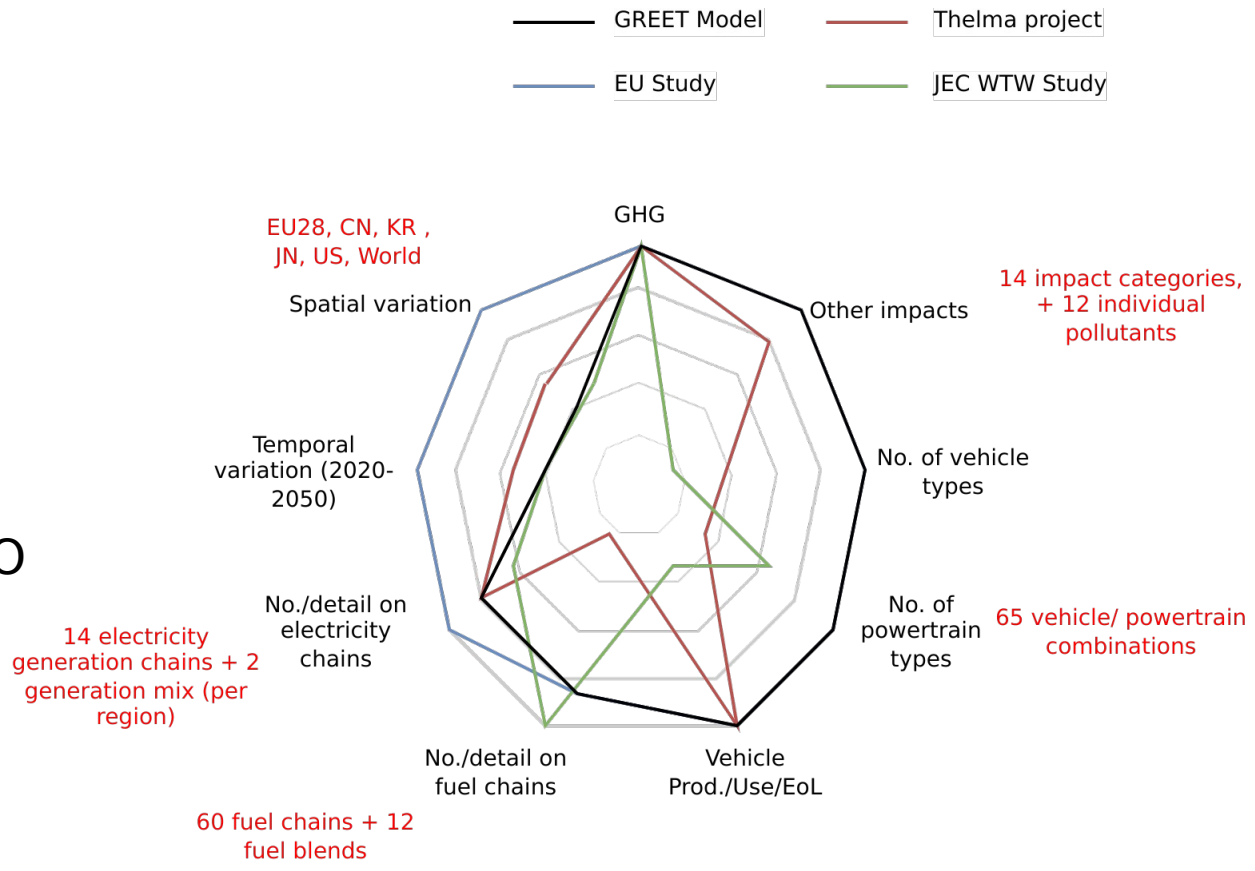
- Their scope is very broad, hence requiring LCA practitioners to further refine the methodology for their specific needs.

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)
ISO 14044 Environmental management — Life cycle assessment — Requirements and guidelines, International standards organisation (https://www.iso.org/standard/38498.html)

Lifecycle Assessment (LCA)

2020 EU Commission Report

- *"Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA"*
  - Prepared by *Ricardo Energy and Environment*
  - Generally follows the ISO 14040 and ISO 14044 standards.

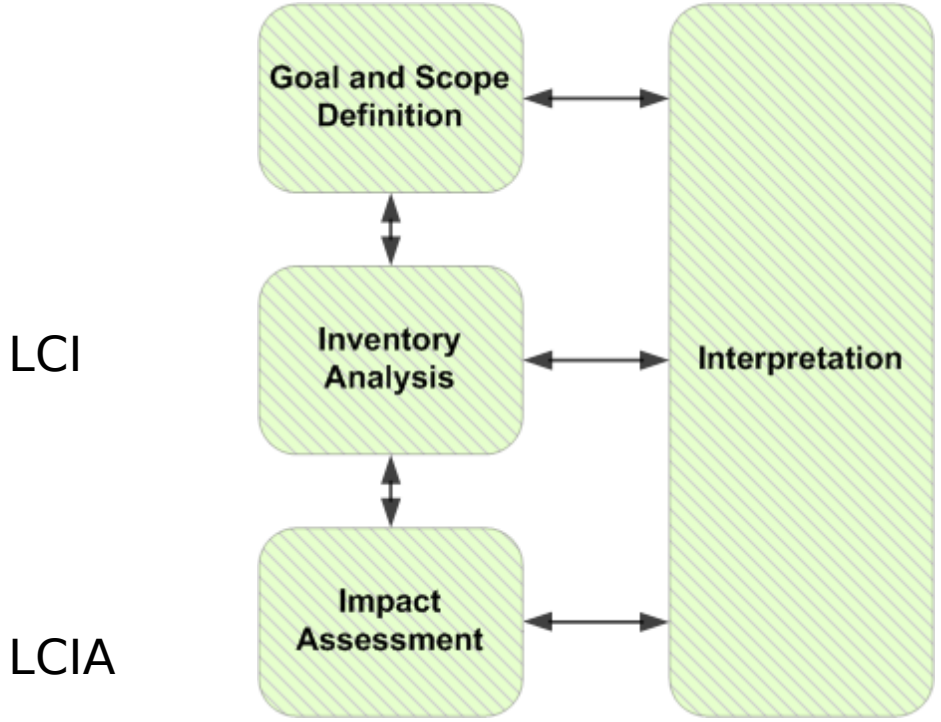


Overview of the LCA Application framework and key data flows, in comparison with other studies

Image adapted from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Lifecycle Assessment (LCA)

The four main stages



GOAL AND SCOPE DEFINITION

Goal and Scope Definition

Goal of an LCA study

- **ISO 14040 definition**
- The goal of an LCA states:
  - The intended application
  - The reasons for carrying out the study
  - The intended audience
  - Whether the results are intended to be used in comparitive assertions released publicly

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Goal and Scope Definition

Goal of an LCA study

- **2020 EU Study:**
  - The intended application: A representative selection of road vehicle configurations.
  - Aims to enhance the Commission's understanding of environmental impacts and of suitable methodologies to assess them in the mid- to long-term time frame (until 2050).
  - Target audience: European Commission and decision-makers.

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Goal and Scope Definition

Scope of an LCA study

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- The scope of an LCA should describe:
  - The functional unit(s) of the system(s)
  - Reference flow(s)
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  - *Limitations*
  - *Data quality requirements*
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quantified performance of a product system for use as a reference unit, e.g 1 million holes drilled

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measure of the outputs from processes in a given product system required to deliver the performace defined by the functional unit

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- **2020 EU Study**
- Functional units and reference flows
  - Based on vehicle size and utility

Body Type	Passenger Car	Van	Rigid Lorry	Artic Lorry	Urban bus	Coach
Default reference flow	Vehicle-km (vkm)	Vehicle-km (vkm)	Tonne-km (tkm)	Tonne-km (tkm)	Vehicle-km (vkm)	Vehicle-km (vkm)

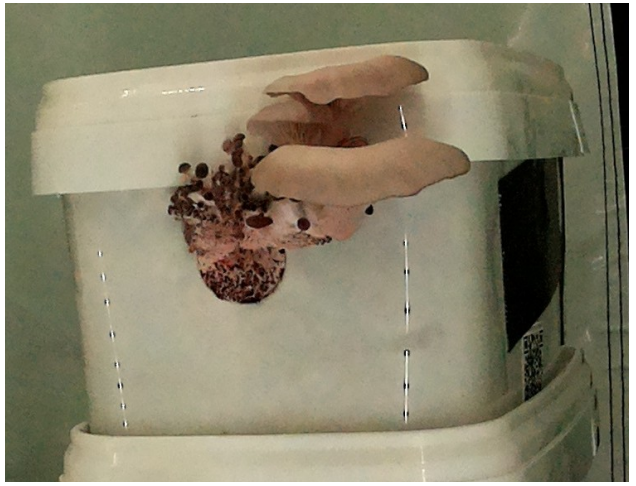
ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

MushR: A Short Detour

Mushroom production

- **Substrate:**
  - The medium from which the mushrooms grow.



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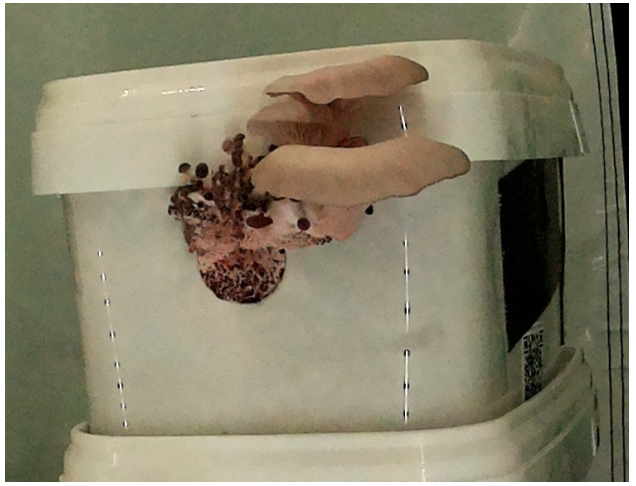
Mushroom production

- **Substrate:**
  - The medium from which the mushrooms grow.
- **Substrate Container:**
  - Contains the substrate throughout the entirity of the substrate's "lifespan".
  - After innoculation:
    - Small ventilation holes (filtered) that fascilitate incubation.



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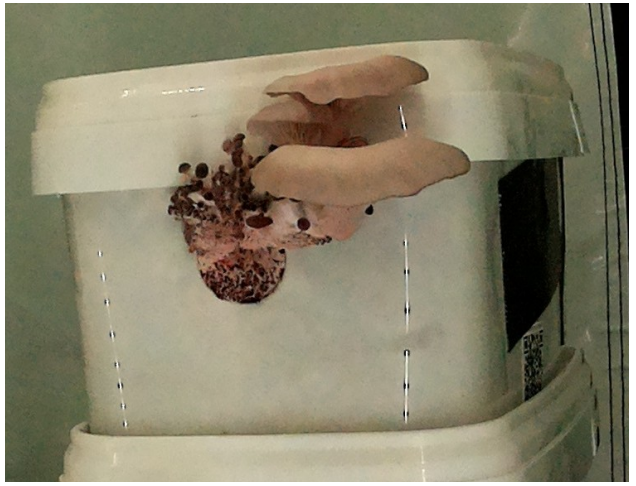
  - After incubation period:
    - Fruiting holes are opened.
    - Contained substrate is exposed to fresh air and high humidity allowing mushrooms to grow through the holes.



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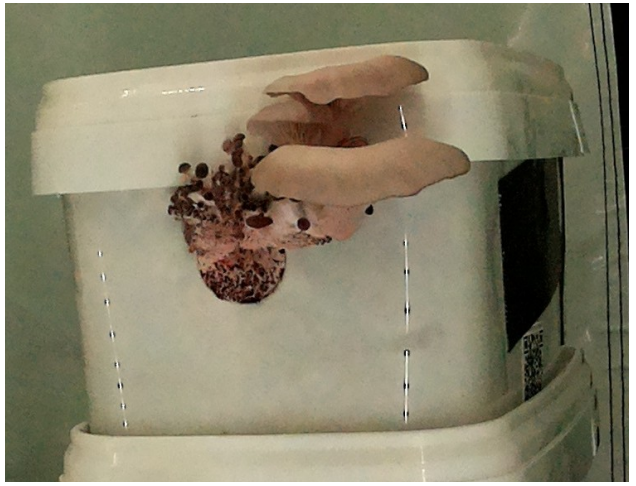
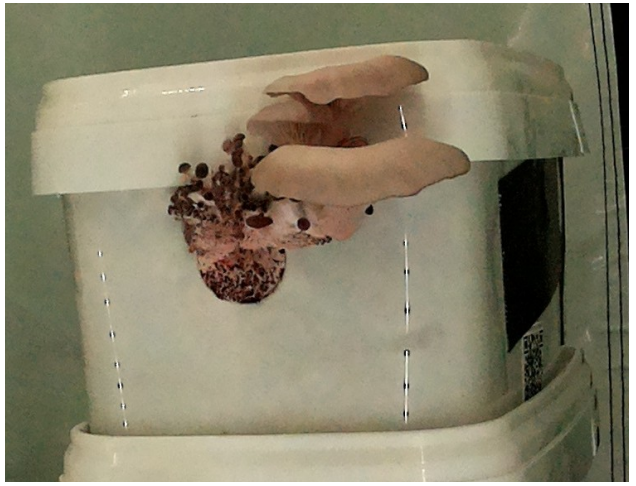
  - After incubation period:
    - Fruiting holes are opened.
    - Contained substrate is exposed to fresh air and high humidity allowing mushrooms to grow through the holes.
  - After some fruiting cycles:
    - Substrate is discarded/composted.



MushR: A Short Detour

Mushroom Substrate Containers

- **Traditional Substrate Containers:**
  - Plastic (polypropylene) bags
  - Usually sealed by folding the opening several times, then sealing it with tape/clips.
    - Can be tricky to seal.
    - Need to be re-opened for innoculation.



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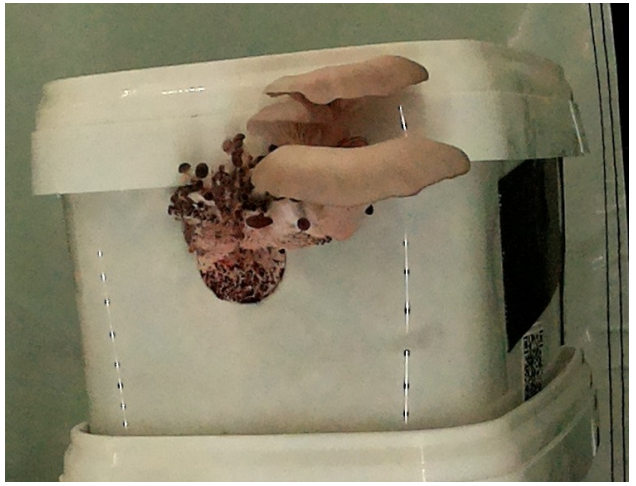
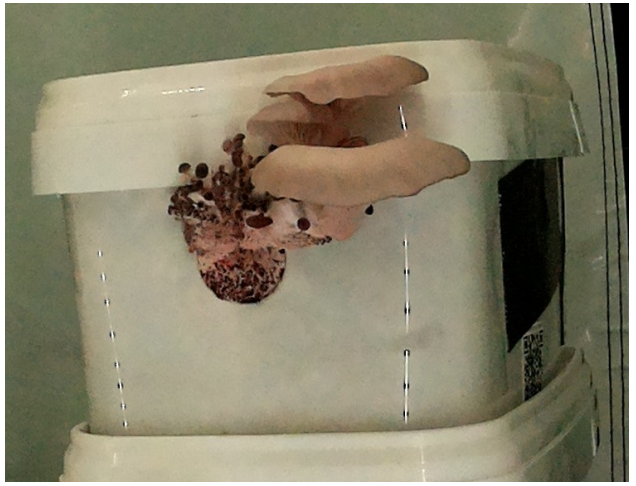
    - Need to be re-opened for innoculation.
  - Fruiting holes are permanent; basically made by cutting through the bags → Cannot be reused
  - Single-use only.



MushR: A Short Detour

Mushroom Substrate Containers

- **MushR Substrate Pods:**
  - Plastic (polypropylene) buckets.
  - Sealed by a plastic lid.
    - Trivial to seal/unseal.
  - Fruiting holes are still permanent; drilled into the bucket
    - Sealed with micro-porous tape during incubation.
    - Tape is removed for fruiting mushrooms → Can be reused.



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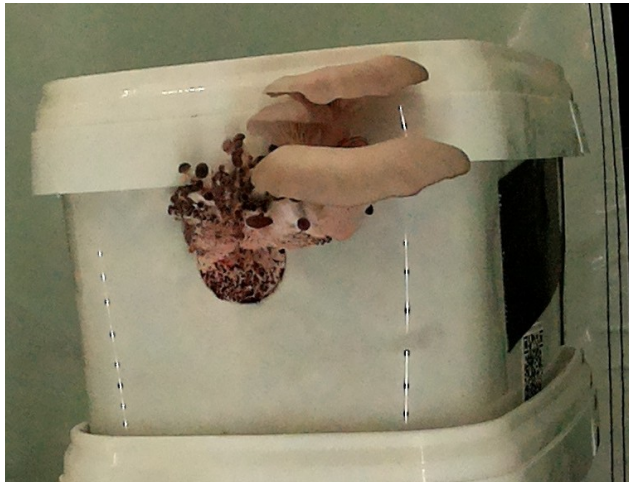
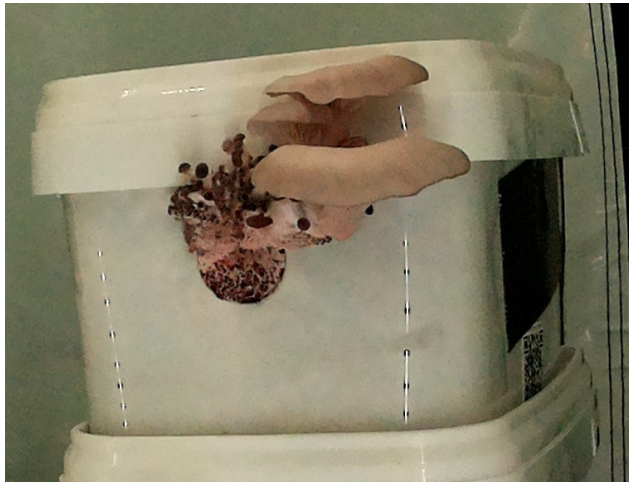
  - Fruiting holes are still permanent; drilled into the bucket
    - Sealed with micro-porous tape during incubation.
    - Tape is removed for fruiting mushrooms → Can be reused.
  - But:
    - Higher resource consumption required for production.
    - More complicated manufacturing process.



MushR: A Short Detour

LCA on Substrate Containers?



- **Goal**
  - Compare the environmental impact of the developed mushroom pods with non-reusable substrate bags by running lifecycle assessment calculations.

Goal and Scope Definition

Functional Unit VS Reference Flow

Functional Unit

quantified performance of a product system for use as a reference unit, e.g 1 million holes drilled

Reference Flow

a measure of the product(s) or product parts required to deliver the performance defined by the functional unit.

- How can you define the functional unit for a mushroom substrate container?

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- How can you define the functional unit for a mushroom substrate container?
  - In terms of “Colonizable volume of the container”: 3L colonizable volume

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- How can you define the reference flow?

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- How can you define the functional unit for a mushroom substrate container?
  - In terms of “Colonizable volume of the container”: 3L colonizable volume
- How can you define the reference flow?
  - In terms of the “Amount of polypropylene (g)” (weight of the container)

Goal and Scope Definition

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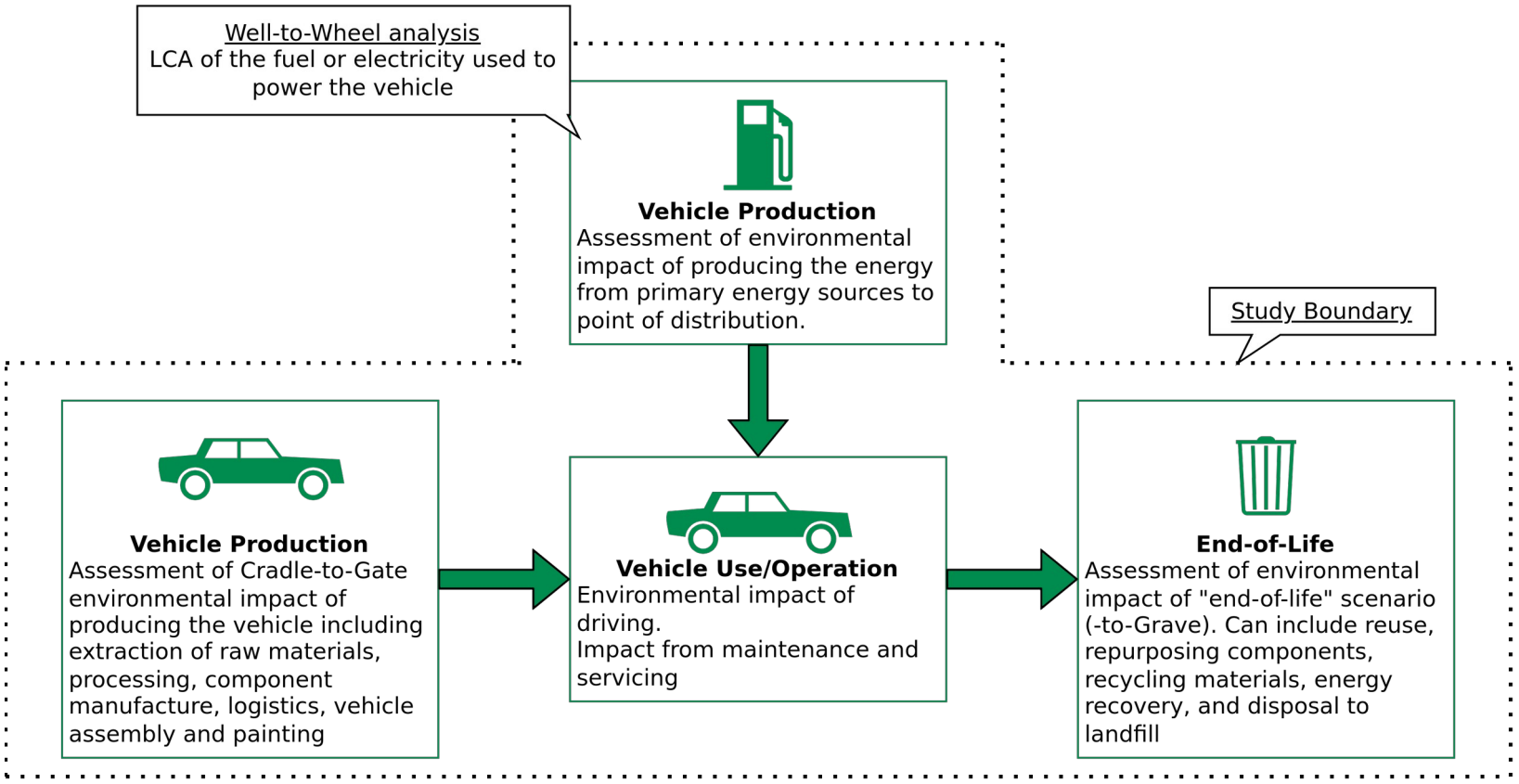
determines which processes are included in the LCA in accordance with it's goal

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Image recreated from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Goal and Scope Definition

System Boundary of 2020 EU Study



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- **MushR reusable mushroom pods**
  - (Theoretical) Manufacturing process
  - (Theoretical) End-of-life recycling process

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Goal and Scope Definition

Quantitative definition of system boundaries – the Cut-off criteria

- In general, all processes and flows that are attributable to the analysed system are to be included in the system boundaries.
- **However, not all of them are quantitatively “relevant”**.
- For less relevant ones, data of lower quality (estimates) can be used, limiting the effort for collecting high quality data.
- Irrelevant ones, can be entirely “Cut-off”

ILCD Handbook – General guide for Life Cycle Assessment – Detailed Guidance (Link)

Goal and Scope Definition

Quantitative definition of system boundaries – the Cut-off criteria

- “Cut-off” refers to the omission of not relevant life cycle stages, activity types (e.g. investment goods, storage, …), specific processes and products and *elementary flows* from the system model.
- Cut-offs are quantified in relation to the percentage of environmental impacts that is approximated to be excluded via the cut-off.
- e.g., "95 %" relates to cutting off about 5 % of the total environmental impact (or of a selected impact category)

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- Cut-offs are quantified in relation to the percentage of environmental impacts that is approximated to be excluded via the cut-off.
- e.g., "95 %" relates to cutting off about 5 % of the total environmental impact (or of a selected impact category)
- **BUT,** this would require an approximation of 100% of the impact, because if we already knew what 100% impact is, we wouldn’t be doing the study anyway.
- **IMPORTANT:** Cut-off should not be so big, or you can risk having incomplete data (meaning lower environmental impacts) and also overall uncertainity.

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- **2020 EU Study**

Impact Category	Indicator and unit
Climate change	Greenhouse gas emissions GWP100 in CO_2 eq (including carbon feedbacks)
Energy consumption	Cumulative energy demand in MJ: non-renewable (fossil and nuclear) and renewable
Acidification	Acidification potential in SO_2 eq
Eutrophication	Eutrophication potential in PO_4^{3-} eq
Photochemical ozone formation	Photochemical Ozone Creation Potential POCP in NMVOC eq
Ozone depletion	ODP in R11 eq
Ionising radiation	Ionising radiation potentials in U235 eq
Particulate matter	Particulate matter formation in PM2.5 eq
Human toxicity, cancer and non-cancer	Comparative Toxic Unit for Human Health in CTUh
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems in CTUe
Resource depletion – minerals and metals	ADP ultimate reserves in Sb eq
Resource depletion – fossil energy carriers	ADP fossil in MJ
Land use	Land occupation in m^2 * a
Water scarcity	Scarcity-adjusted water use in m^3

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Table recreated from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

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  - ***Limitations***
  - ***Data quality requirements***
  - …

- **MushR reusable mushroom pods**
  - Limitations
    - No data calculations on the performance of the substrate container
      - Amount of mushrooms harvested?
      - Contaimination rate?
    - Generic manufacturing and recycling data

ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

LIFECYCLE INVENTORY ANALYSIS (LCI)

Lifecycle Inventory Analysis (LCI)

Definitions

LCI is the phase of lifecycle assessment involving the compilation and quantification of *inputs* and *outputs* for a product throughout it's lifecycle.

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Inputs and *outputs* are product, material or energy flows that enter or leave a unit process.

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A *Unit Process* is the smallest element considered in the life-cycle inventory analyis for which input and output data are quantified.

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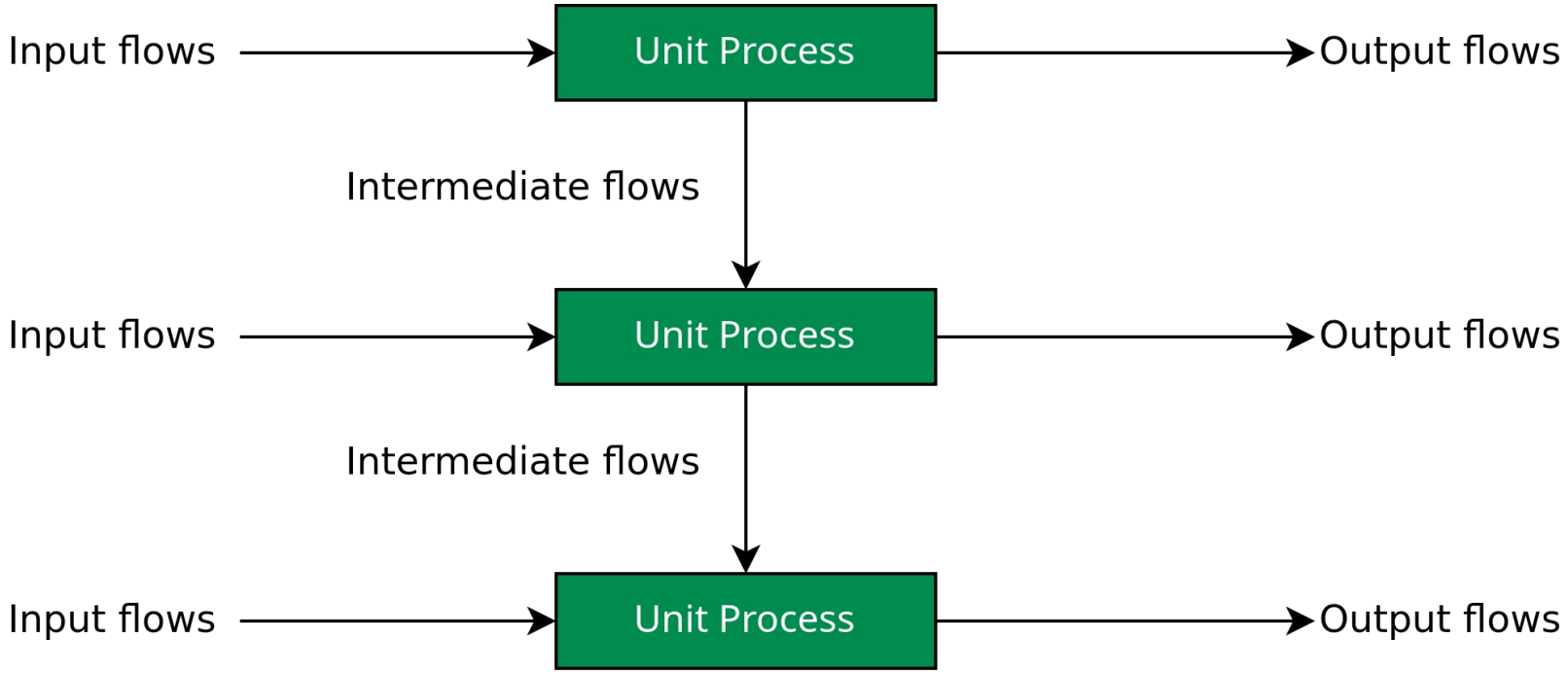
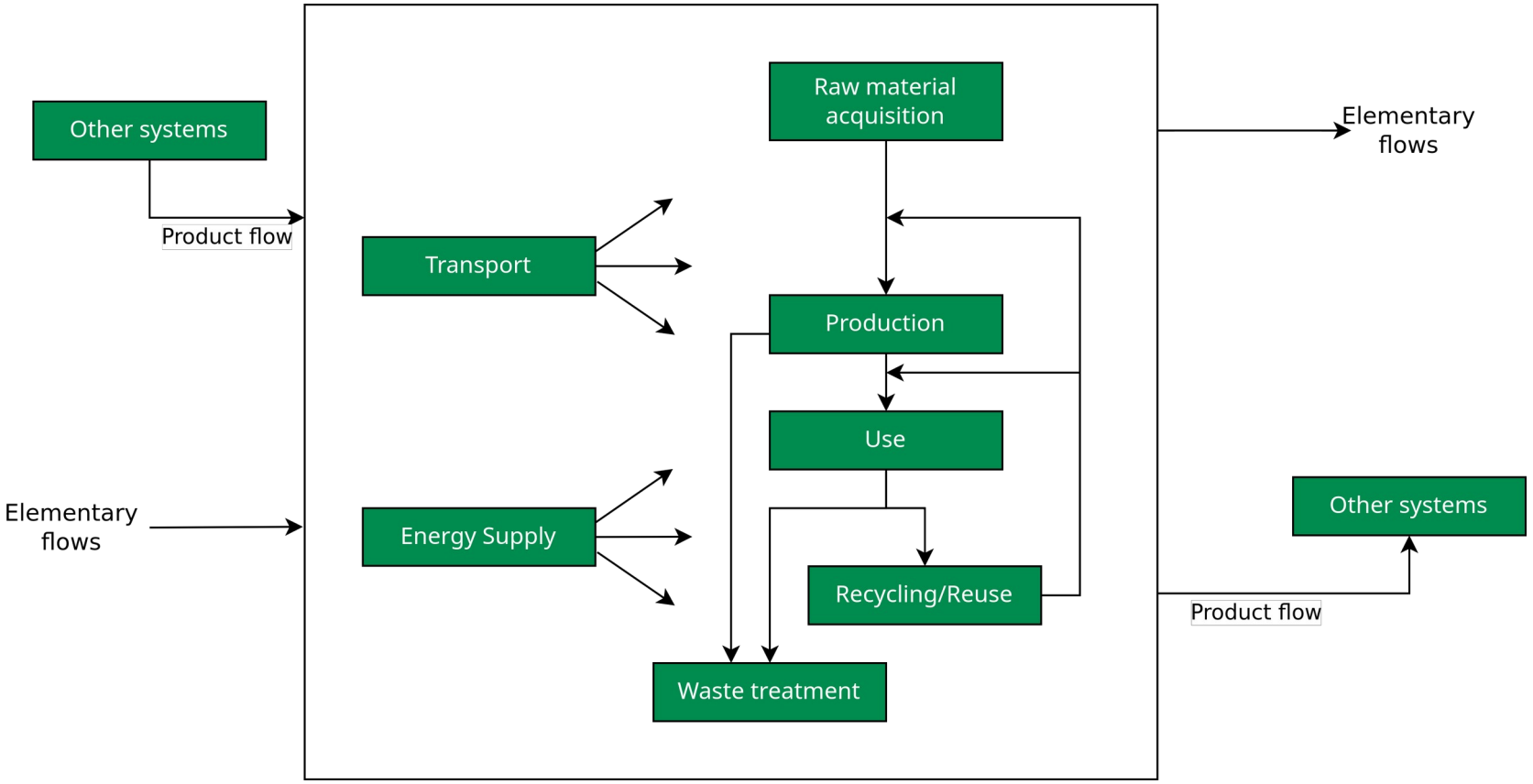
Lifecycle Inventory Analysis (LCI)



Example of a set of unit processes within a product system

Images recreated from ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Lifecycle Inventory Analysis (LCI)



Example of a product system

Images recreated from ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Lifecycle Inventory Analysis (LCI)

Preparing for data collection

Completed by:	Date of completion:			
Unit process identification:	Reporting location:			
Time period: Year	Starting month:	Ending month:		
Description of unit process:				
Material inputs	Units	Quantity	Description of sampling procedures	Origin
...	...	...	...	...
Water consumption	Units	Quantity		
...	...	...	...	...
Energy Inputs	Units	Quantity	Description of sampling procedures	Origin
...	...	...	...	...
Material outputs	Units	Quantity	Description of sampling procedures	Destination
...	...	...	...	...

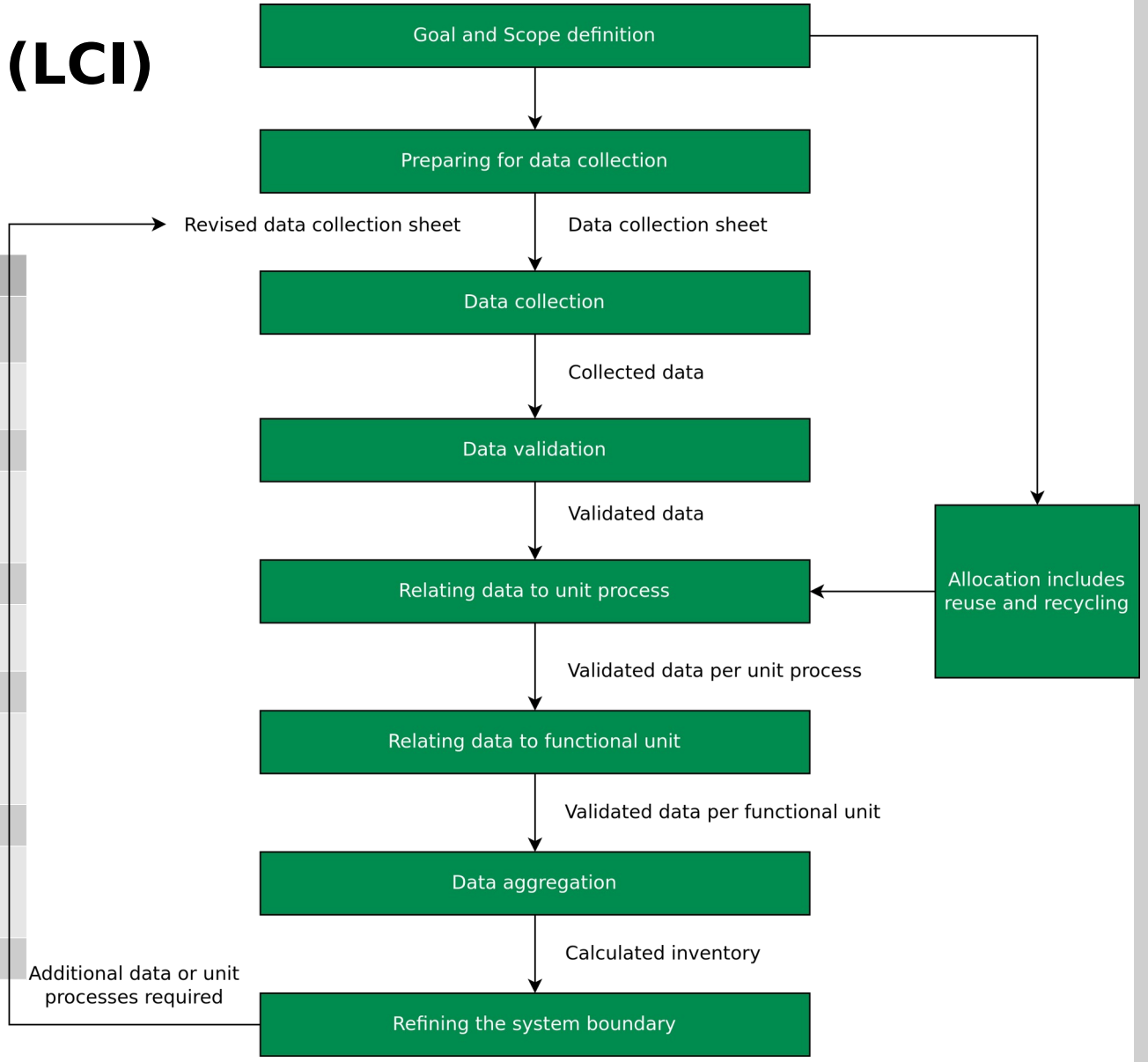
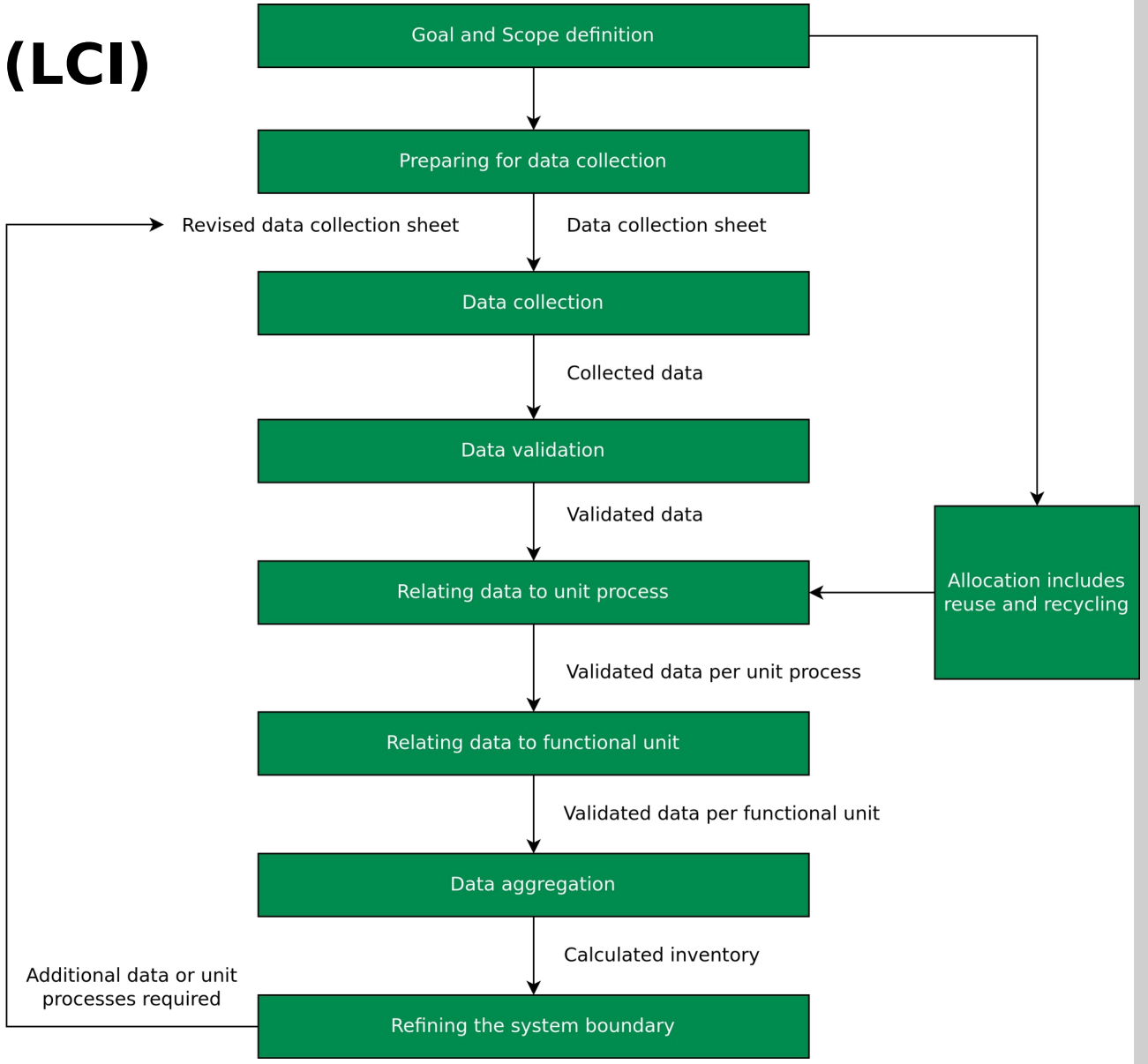


Image and table recreated from ISO 14040 Environmental management — Life cycle assessment — Principles and framework, International standards organisation (https://www.iso.org/standard/37456.html)

Lifecycle Inventory Analysis (LCI)

Data collection and validation

- Data must be validated to confirm and provide evidence for data quality requirements, both during and after the data collection process.
- This can also involve establishing mass and energy balances.
- Obvious anomalies can necessitate collecting alternative data.



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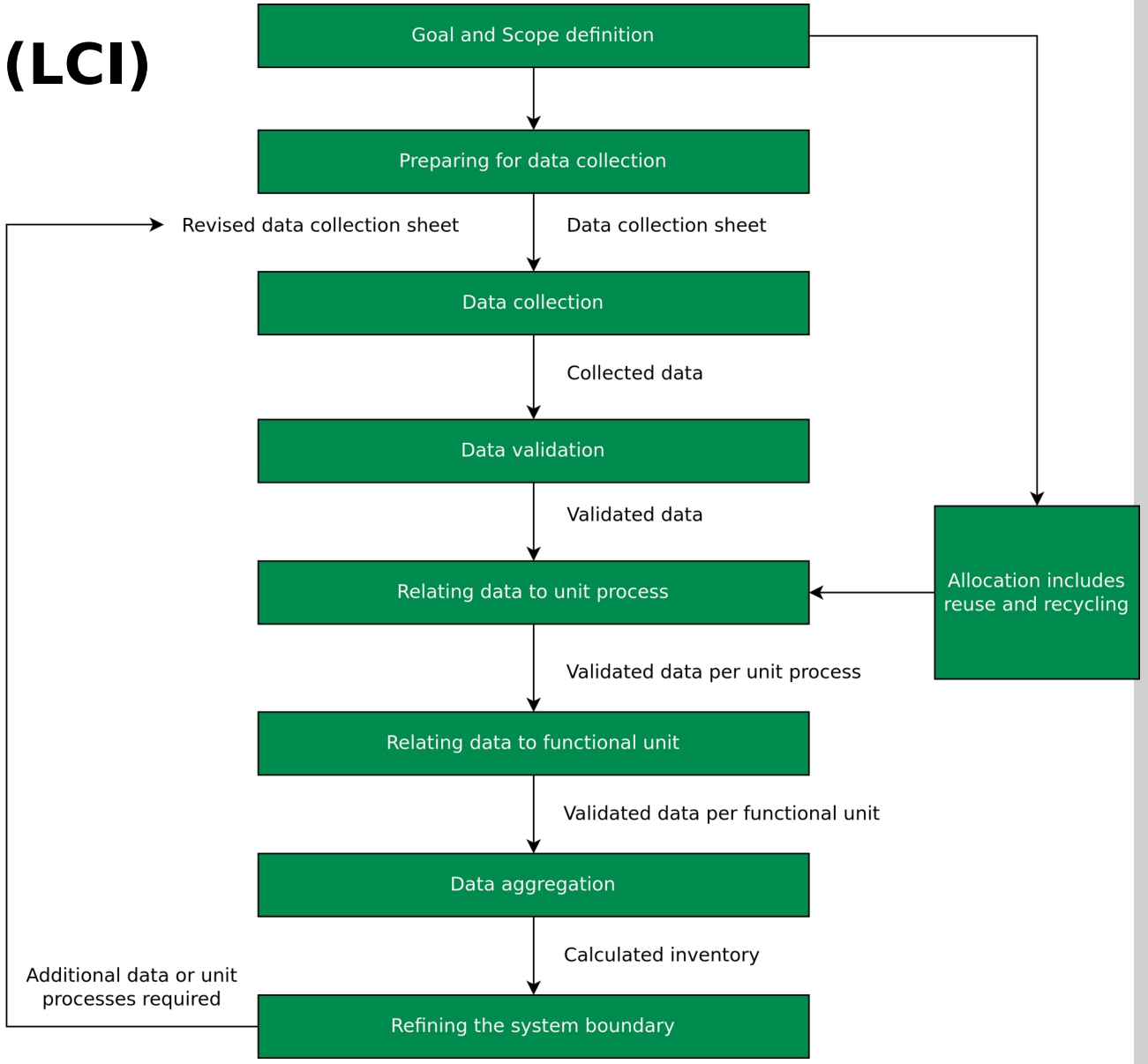
Lifecycle Inventory Analysis (LCI)

Relating data to unit process and functional unit

- Based on the flow chart and the flows between unit processes, the flows of all unit processes are related to the reference flow.
- The calculation should result in all system input and output data being referenced to the functional unit.
- Recall: a measure of the product(s) or product parts required to deliver the performance defined by the functional unit.



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Lifecycle Inventory Analysis (LCI)

Relating data to unit process and functional unit

- **MushR example**
  - Experimental estimation:
    - Colonizable volume of a 5L substrate bag weighing 30g = *3L*
      - *Since we have to fold the bag a couple times to seal it.*

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  - This allows us to scale and compare the two container types on similar terms, e.g:
    - 1000g of substrate bags, can contain (1000 × 3 / 30) = 100 Liters of substrate.
    - 1000g of substrate buckets, can contain (1000 × 3 / 90) = 33.333 Liters of substrate.

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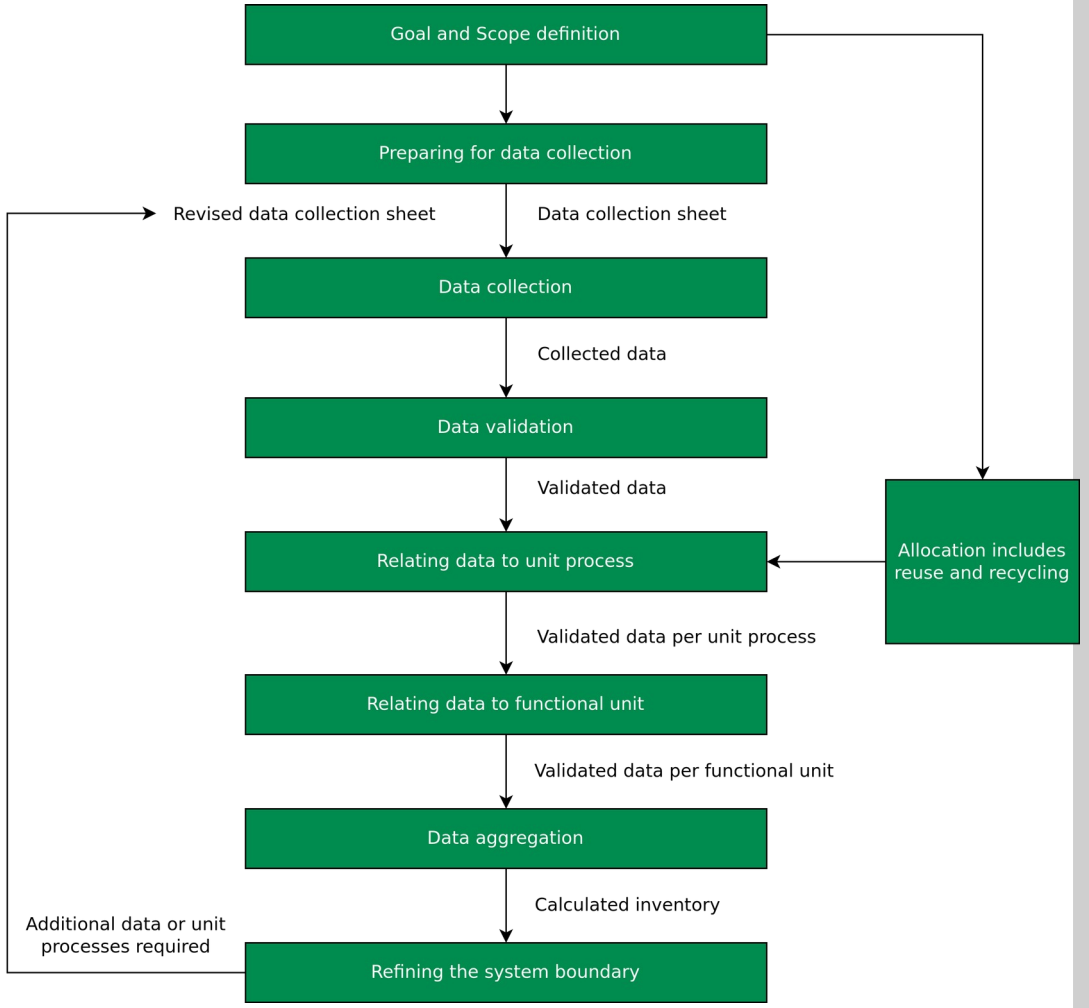
Lifecycle Inventory Analysis (LCI)

Refining the system boundary

- The initial system boundary is revised, in accordance with the cut-off criteria established before.
- Further analysis may result in:
  - Exclusion of life cycle stages or unit processes if they lack significance
  - Exclusion of inputs or outputs
  - Inclusion of new unit processes, inputs and outputs that are shown to be more significant than estimated before.



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Lifecycle Impact Assessment (LCIA)

Definition

LCIA is the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

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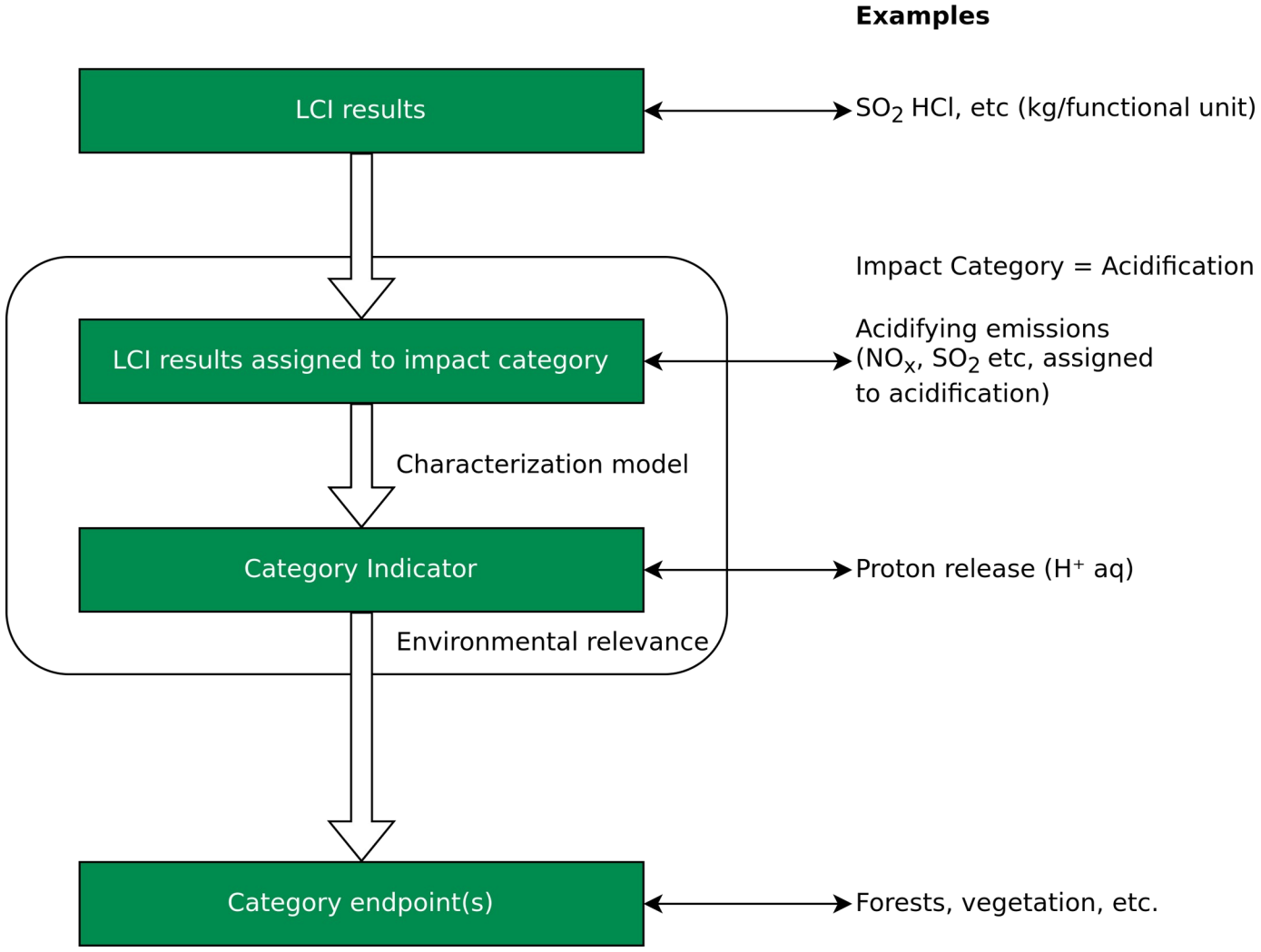
Lifecycle Impact Assessment (LCIA)

Oveview



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Lifecycle Impact Assessment (LCIA)

MushR Example

Impact category	Reference unit	Mushroom Substrate Bag	MushR Reusable Pods
Acidification	H+ mmole eq	11.21	40.15
Global warming	g CO2 eq	102.46	217.20
Ozone depletion	g CFC-11 eq	2.64E-07	1.49E-06
Water intake	liters	0.95	2.3

Tables recreated from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Lifecycle Impact Assessment (LCIA)

MushR Example

Impact category	Reference unit	Mushroom Substrate Bag	MushR Reusable Pods	MushR Pods Break-even point (reuse cycles)
Acidification	H+ mmole eq	11.21	40.15	3.6
Global warming	g CO2 eq	102.46	217.20	2.1
Ozone depletion	g CFC-11 eq	2.64E-07	1.49E-06	5.6
Water intake	liters	0.95	2.3	2.4

Tables recreated from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Lifecycle Impact Assessment (LCIA)

2020 EU Study Example

Impact Category	Indicator and unit
Climate change	Greenhouse gas emissions GWP100 in CO_2 eq (including carbon feedbacks)
Energy consumption	Cumulative energy demand in MJ: non-renewable (fossil and nuclear) and renewable
Acidification	Acidification potential in SO_2 eq
Eutrophication	Eutrophication potential in PO_4^{3-} eq
Photochemical ozone formation	Photochemical Ozone Creation Potential POCP in NMVOC eq
Ozone depletion	ODP in R11 eq
Ionising radiation	Ionising radiation potentials in U235 eq
Particulate matter	Particulate matter formation in PM2.5 eq
Human toxicity, cancer and non-cancer	Comparative Toxic Unit for Human Health in CTUh
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems in CTUe
Resource depletion – minerals and metals	ADP ultimate reserves in Sb eq
Resource depletion – fossil energy carriers	ADP fossil in MJ
Land use	Land occupation in m^2 * a
Water scarcity	Scarcity-adjusted water use in m^3

Pollutant	Acidification	Eutrophication	POCP	Particulate matter formation (PMF)
CO	0	• 0	0.0456	0
NH_3	1.6	0.35	0	0.64
NO_x	0.5	0.13	1	0.88
$PM_{2.5}$	0	0	0	1
SO_x	1	0	0.0811	0.54
NMVOC	0	0	1	0.012

Non-methane volatile organic compoind

Tables recreated from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Lifecycle Impact Assessment (LCIA)

2020 EU Study Example

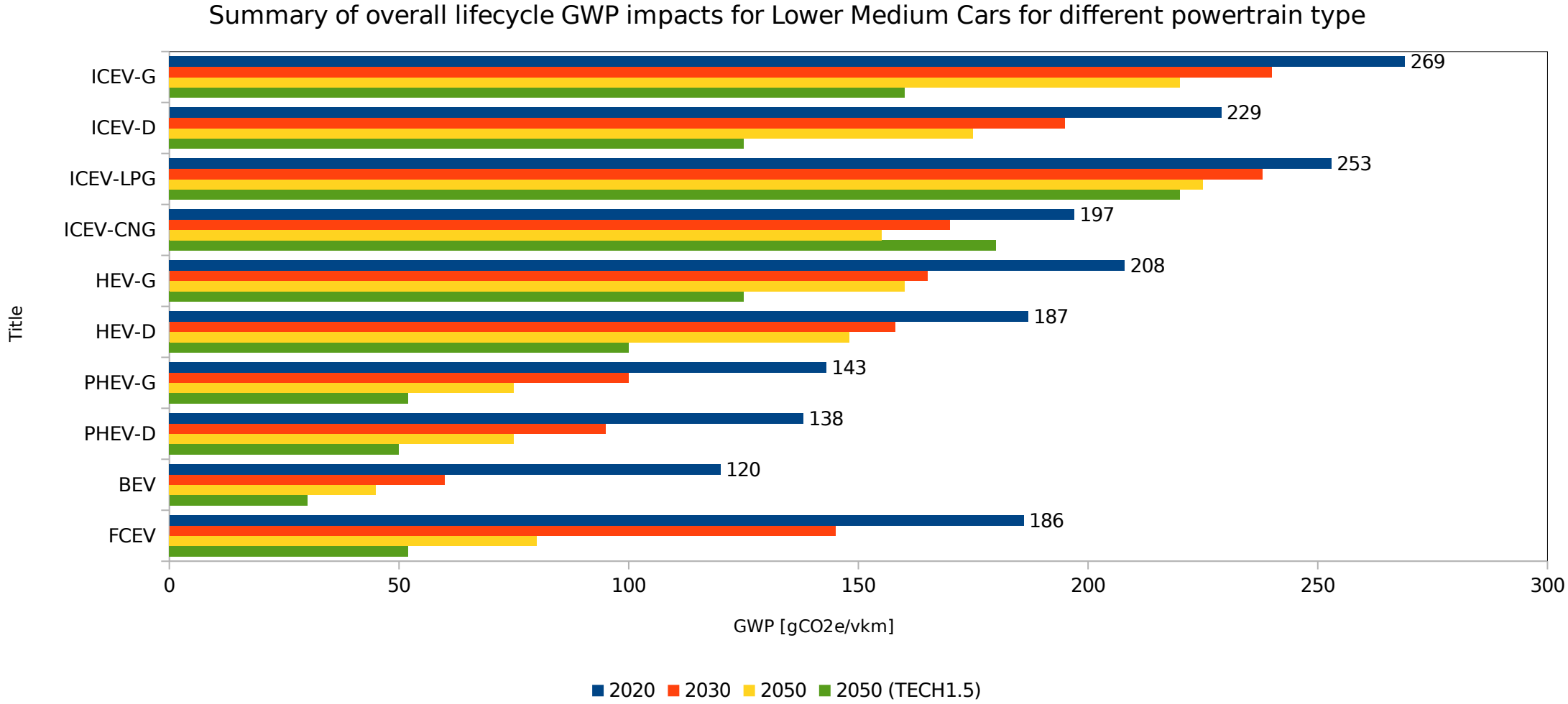

Chart adapted from Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Ricardo Energy and Environment (Link)

Lifecycle Interpretation

Definition

Lifecycle Interpretatopm is the phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

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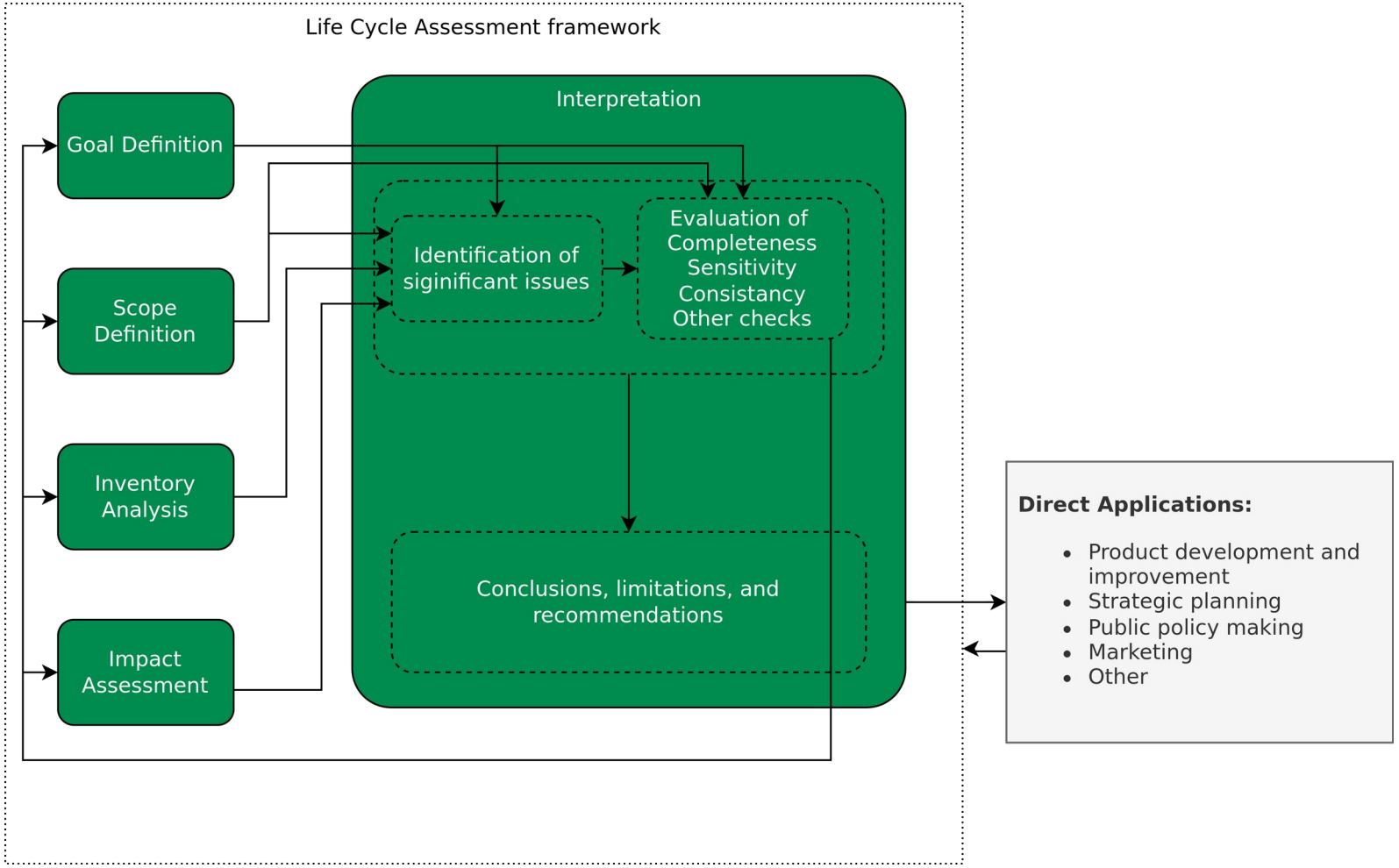
Lifecycle Interpretation

Overview



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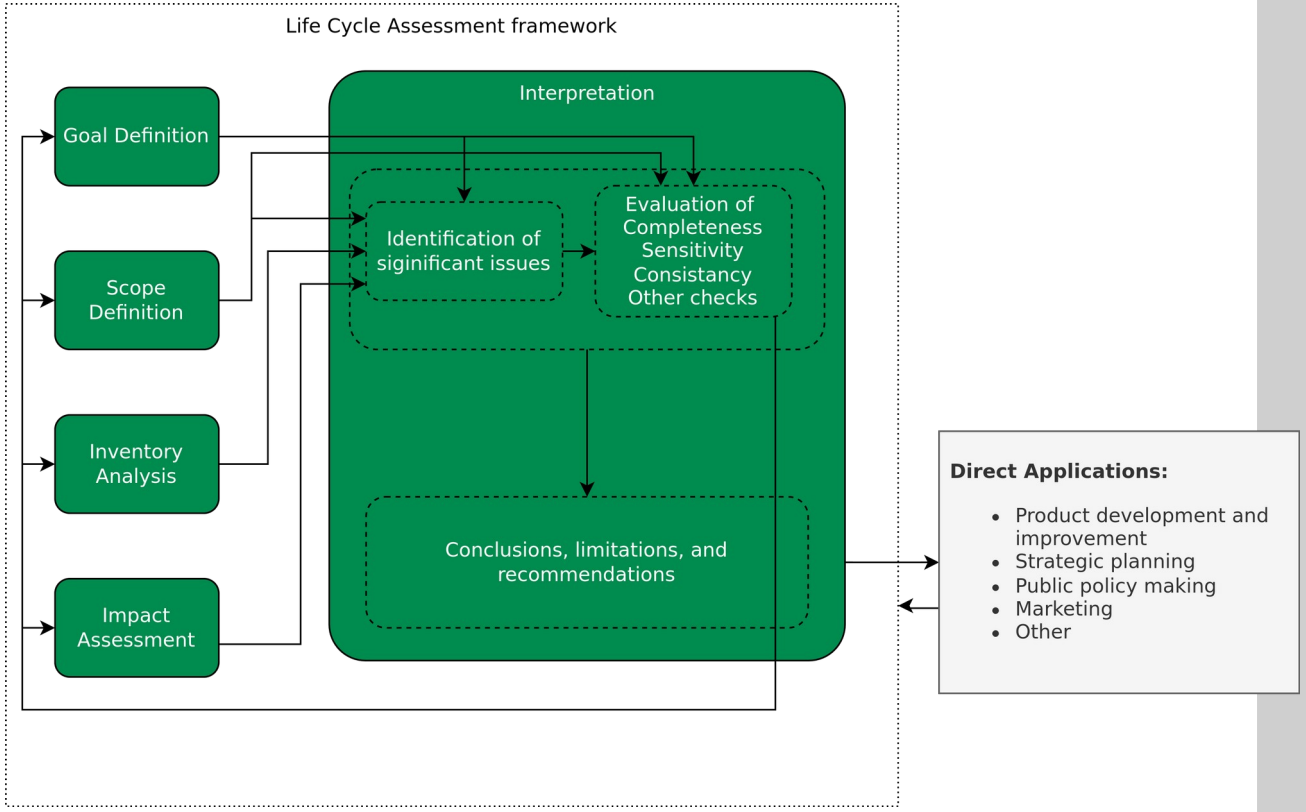
Lifecycle Interpretation

Identification of significant issues

- Two interrelated aspects of significant issues:
  - The main contributors to environmental impacts, like most important lifecycle stages, processes and elementary flows.



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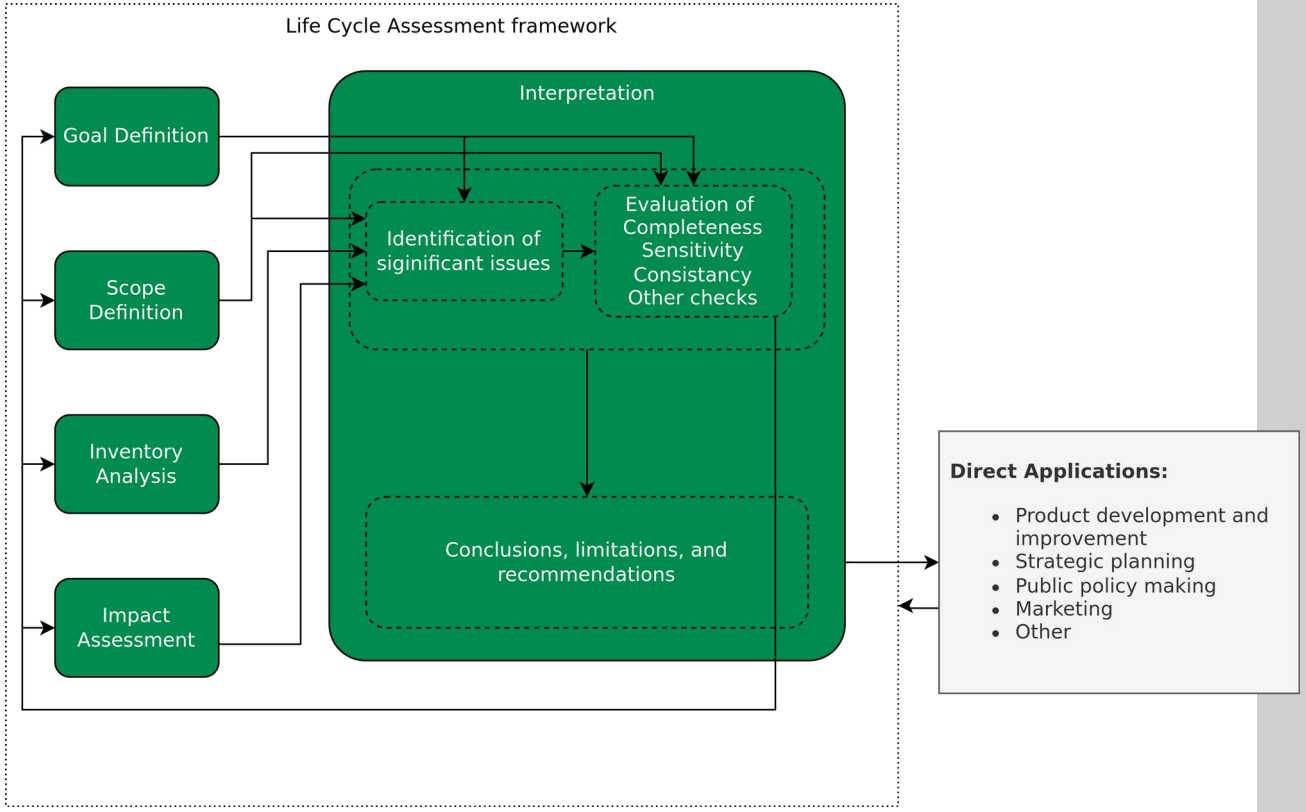
Lifecycle Interpretation

Identification of significant issues

- Two interrelated aspects of significant issues:
  - The main contributors to environmental impacts, like most important lifecycle stages, processes and elementary flows.
  - The main choices that have the potential to influence the precision of the final results of the LCA, like methodological choices (e.g., cut-offs), assumptions, data, LCIA methods.



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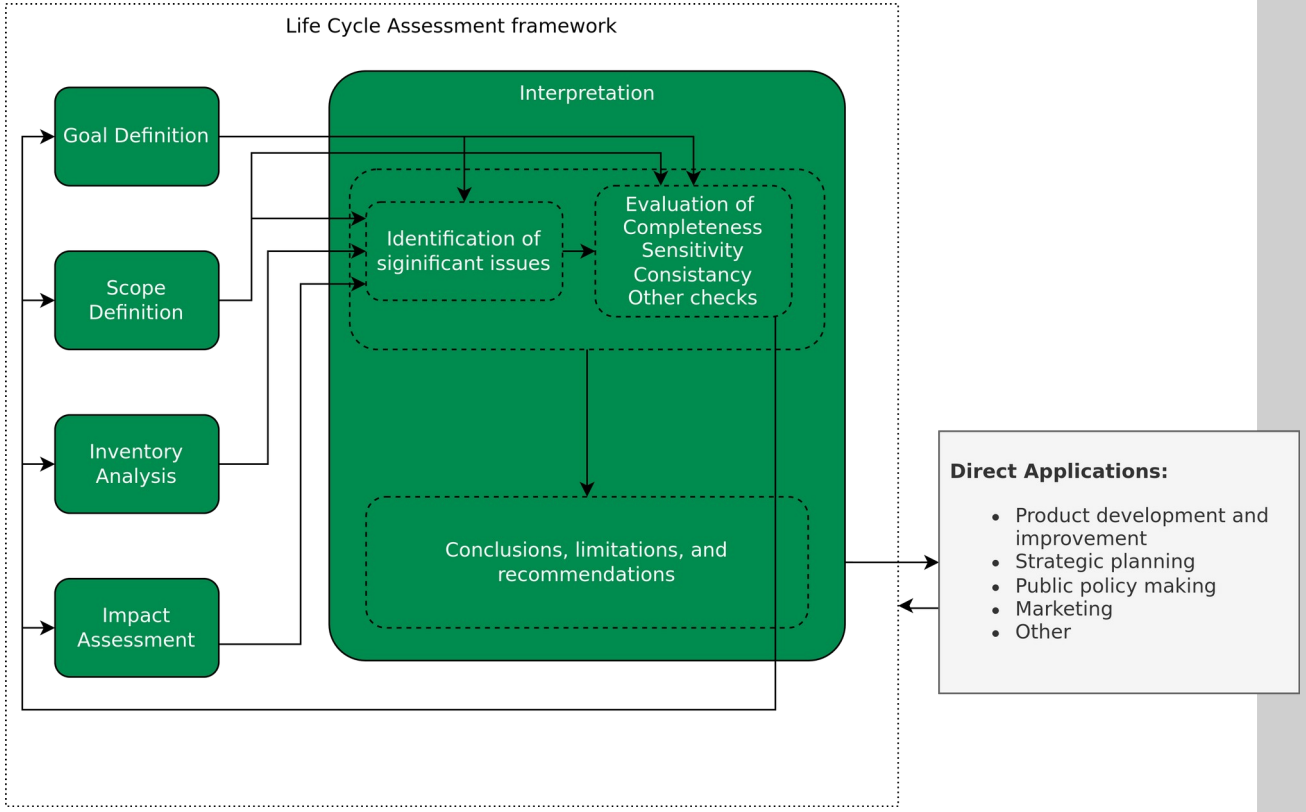
Lifecycle Interpretation

Evaluation

- Evaluation is performed to establish the foundation for subsequently drawing the conclusions and provide reccommendations during the interpretation of the study results.



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Lifecycle Interpretation

Evaluation

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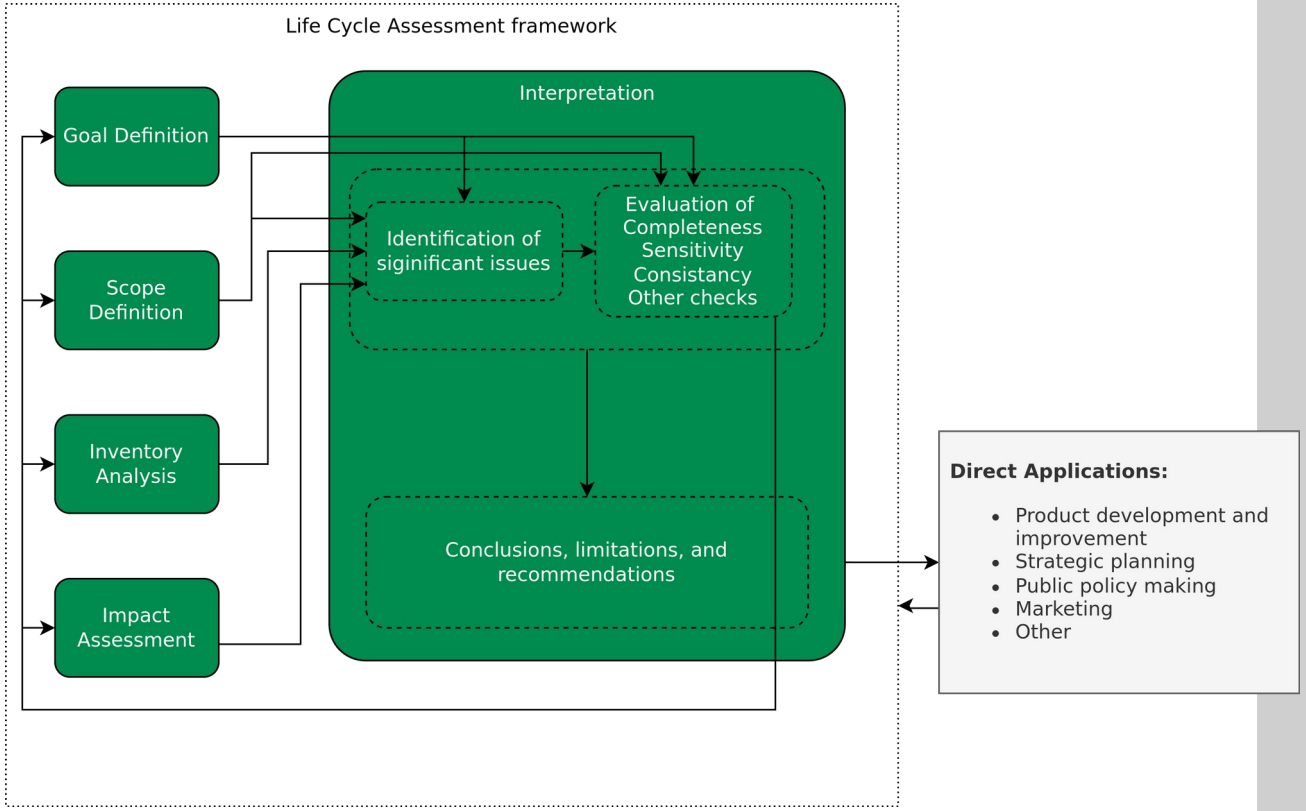
- This involves:
  - Completeness checks
  - Sensitivity checks in combination with scenario analysis and potentially uncertainity analysis
  - Consistancy checks



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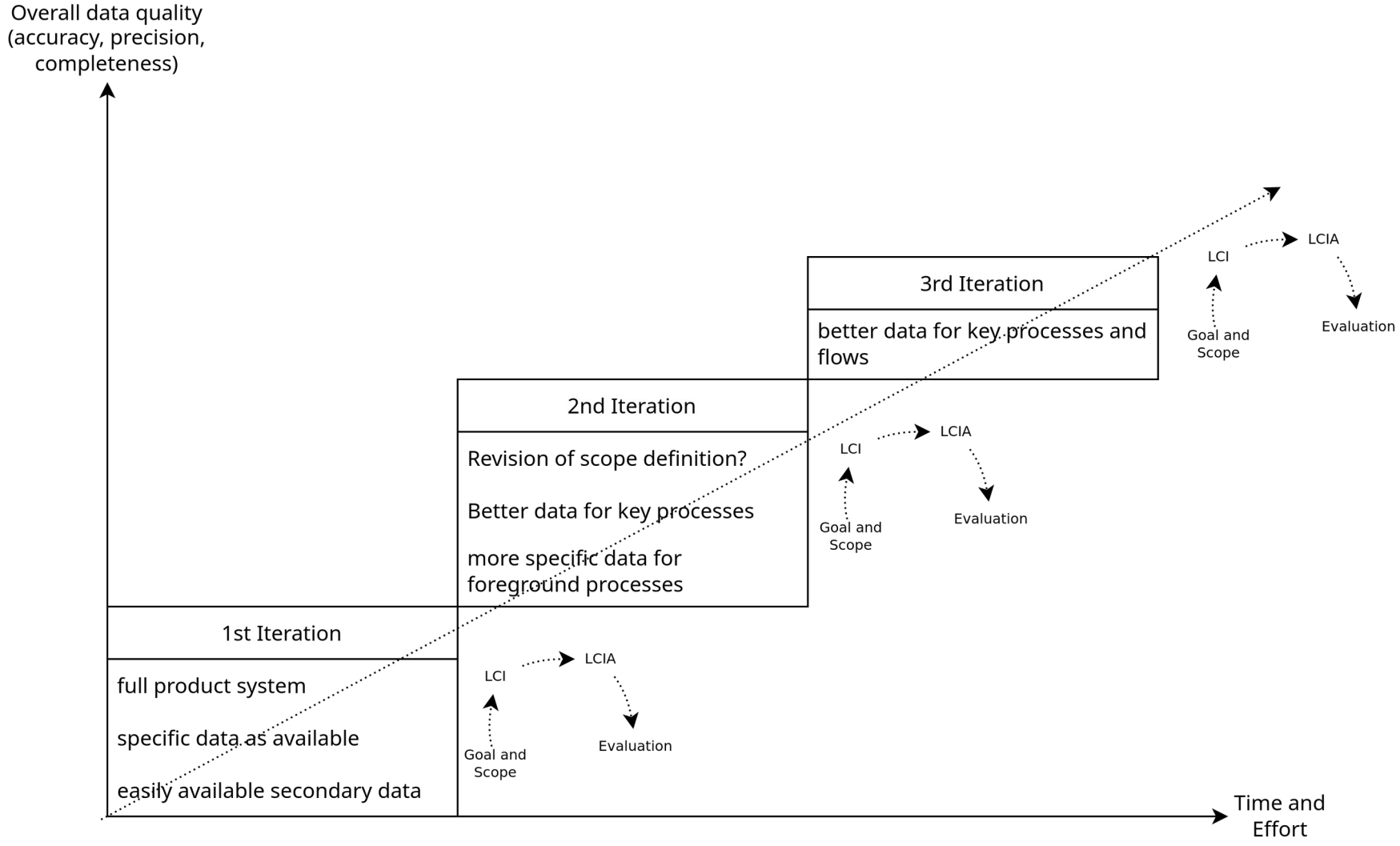
Iterative Approach to LCA



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Reporting and Critical Review

- A reporting strategy is an integral part of an LCA.
- A report should:
  - contain the results and conclusions of the LCA in an adequate form to the intended audience
  - address the data, methods and assumptions applied in the study, and the limitations thereof.

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  - address the data, methods and assumptions applied in the study, and the limitations thereof.
- A critical review will fascilitate understanding and enhance the credibility of the LCA.
- Critical reviews verify whether the LCA has met the requirements for methodology, data, interpretation and reporting and whether it is consistant with it’s principles.
  - Carried out by an internal or external expert, or by a panel of interested parties.

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CONCLUSION

Conclusion

- A high-level overview and guide to Life Cycle Assessment
  - Goal and Scope definition
  - Life Cycle Inventory analysis
    - Unit Processes and Process flows
  - Life Cycle Impact Assessment
    - Impact categories, classification, characterization, weighting, etc.
  - Life Cycle Interpretation
    - Evaluation
    - Reporting and Critical review
- Examples from Polestar, 2020 EU Commission report, MushR project

Questions?