Introduction to Life Cycle Analysis

2022 NC Environmental Stewardship Initiative

October 25, 2022

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- Elis-Signe Olsson Professorship in Pulp and Paper Science and Technology, January 2018-
- PhD Chemical Engineering, Princeton, BS Pulp and Paper, NCSU, BS Chemical Engineering NCSU
- Research Areas: Paper Recycling, Bioproducts and Biofuels, Paper Science, Environmental LCA, Biopolymer Aquatic Biodegradation, Sustainability

- Courses Taught:
  - Process Control in Pulp and Paper
  - Unit Operations in Pulp and Paper
  - Environmental Life Cycle Analysis
  - Director and Teacher: Hands On Workshop for Pulp and Paper Basics
- Selected Current Research Grants:
  - Recycled Board: Products with Obvious Recycled Content
  - Training students for the Bioeconomy
  - The production and fate in the environment of microfibers
  - Aquatic Biodegradation of Paper Fibers and Biopolymers
  - LCA and Carbon footprinting of Paper Products

Tragedy of the Commons

Hardin, Garret. (1968). “The Tragedy of the Commons”. *Science, 12(3859): 1243-1248.*

A situation where in a shared-resource system, individual users acting independently according to their own self-interest instead of common good of all users by depleting or spoiling that resource through their collective action.

“Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all.”

Sustainability

- **Sustainable:** The ability to supply societies needs without harming the environment or future generations' ability to meet their needs

- We have many options to meet our demands, but how can we choose the "best" option?

Sustainability/Success Indicators for Bio-products

SAFI

#	Environmental	#	Economic	#	Social	#	Technical
1	GHG emissions	1	Market potential	1	Acceptance of biobased materials	1	Strength properties
2	Raw material efficiency	2	Raw materials cost	2	Product transparency	2	Cleanliness
3	End of life options	3	Product innovation	3	Job creation	3	Color
4	Ecotoxicity	4	Process innovation	4	Human toxicity	4	Softness
5	Waste generation	5	Technical risks	5	Income levels	5	Water absorptivity
6	Energy efficiency	6	Capital productivity	6	Workplace accidents and illnesses	6	Chemical structure
7	Natural land transformation	7	Energy cost	7	Education and training	7	Others....
8	Abiotic fossil depletion	8	Land productivity	8	Community support and involvement		
9	Eutrophication	9	Product efficiency	9	Fatal work injuries		
10	Agricultural land occupation	10	Labour productivity	10	Security measures		
11	Water consumption	11	Subsidies	11	Social security		
12	Organic carbon depletion	12	Waste disposal cost	12	Child labor		
13	Management practices	13	Transportation cost	13	Working hours		
14	Soil erosion			14	Discrimination		
15	Acidification			15	Cultural heritage		
16	Particular matter formation						
17	Abiotic mineral depletion						
18	Stratospheric ozone depletion						
19	Photo-oxidant formation						
20	Ionising radiation						

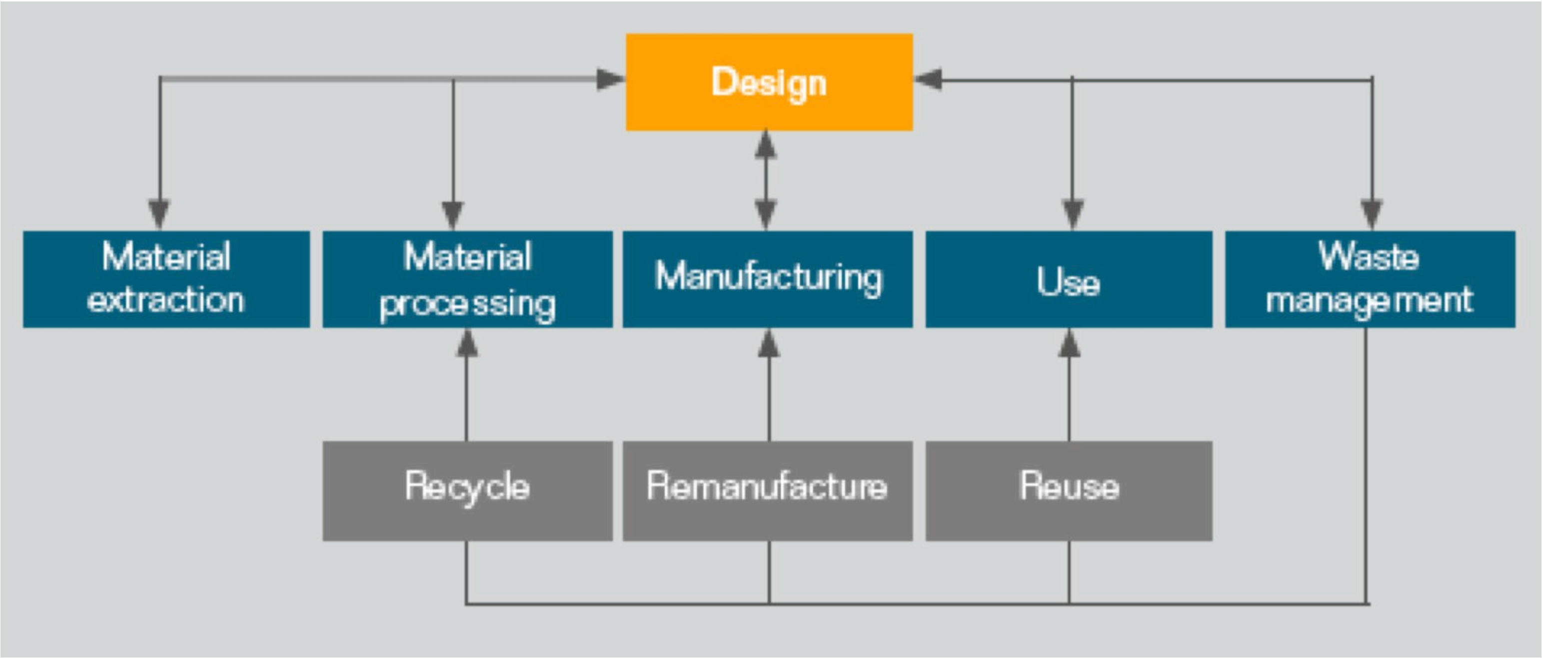
Sophie Van Schoubroeck, et al., 2019.

Life Cycle Assessment (LCA)

A concept and methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity (U.S. EPA, 1993).

Definitions

- A life cycle of a product (e.g., "cradle to grave") begins with raw materials production and extends to manufacture, use, transport, and waste management

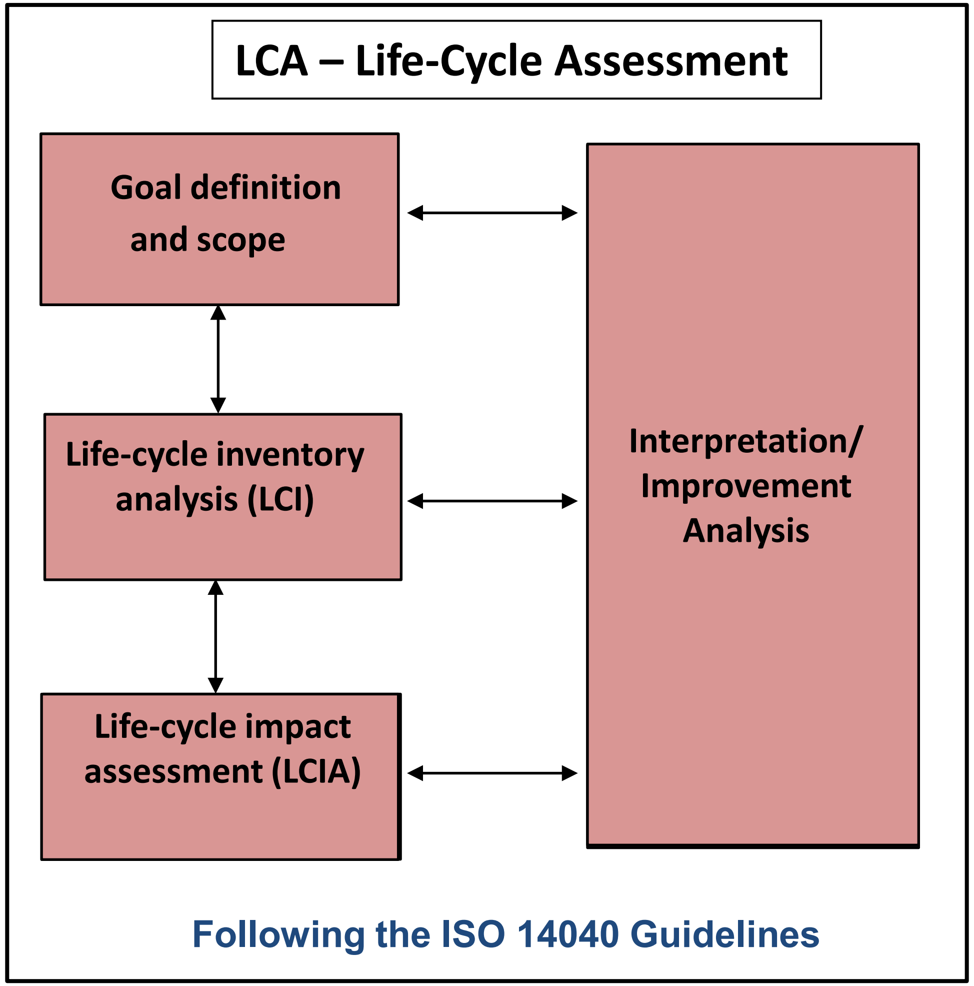


History of LCA

Initial LCA work was focused on energy

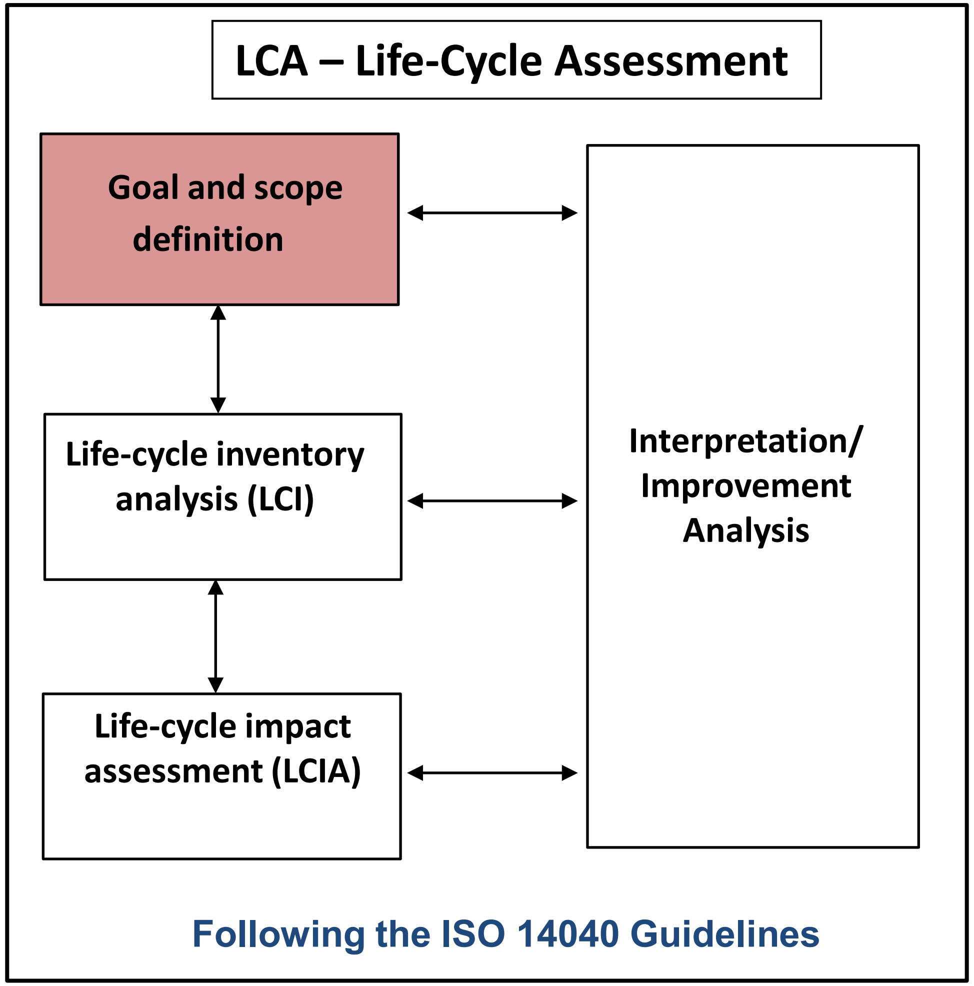
- 1969 - first multi-criteria study for Coca-Cola
  - Choice between glass and plastic for container
  - Choice between internal / external container production
  - End of life options (recycling or one-way)
  - Result: plastic bottle was best, contrary to expectations.
  - Study was never published
  - Questions of validity then occurred (a running theme!)
  - Led to calls by scientific community for a standardization process

LCA Framework



- LCA methodology is standardized internationally by the ISO 14040 series of guidelines
- These guidelines represent generally-accepted principles for sound LCA

LCA Framework



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Goal Definition

- Purpose is to make explicit:
  - Purpose of the LCA study (i.e., need statement)
    - Design alternative analysis
    - Product comparison
    - Hot spot analysis, identifying how important is a life cycle stage, sub-operation, or flow on the overall result
    - Documentation of an impact
    - Others
  - Intended audience and uses for results (e.g., internal design improvement, marketing, public policy)
    - Purpose of the study and its audience are inextricably linked!
    - Ensures results are used within limitations of study
    - Examples: influence policy of government or non-government, company strategic planning, marketing to the public
  - **Environmental impacts included and excluded and rationale**
    - Product comparison?
    - Water? Carbon? Energy?

Refs: ISO 14044: 2006E

Scope

- Project Scope "The work that needs to be accomplished to deliver a product, service, or result with the specified features and functions."

A Guide to the Project Management Body of Knowledge (PMBOK Guide) - Fourth Edition. Project Management Institute, 2008. ISBN 978-1-933890-51-7

Defining Scope

- Define functional unit of a product
  - Define the reference flows
- Establish system boundaries for the LCA
  - What stages and operations are included?
- Determine data collection methods
  - Literature
  - Measurements
  - Interviews
  - Other…

Function and Functional Unit

- What is the function of the system studied
  - What does it do?
  - What type of service does it provide?
- Functional unit "quantifies the function"
  - May be arbitrary
  - Is the quantitative basis for which your inputs and outputs relate
  - Explicit unit for comparisons within study and for future studies

Functional Unit and Reference Flows

- **Reference flow**: measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit

- The reference flows translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution.

Example: defining a reference flows

- There is a need to define a reference flow for containers that people can drink coffee from. The two alternatives considered are paper cups and a porcelain cup. Identify an appropriate reference flow for each.
- Assume the functional unit is to deliver 8000 cups of coffee each with 200 ml volume
- Assume the ceramic cup can be re-used 200 times before it wears out, volume of the cup is 200 ml
- Assume that the paper cup has a volume of 200 ml, only used once.

- Reference flow for the **paper** cup: 8000 paper cups
- Reference flow for the **ceramic** mug: 40 ceramic mugs

System Boundary

The ISO 14044 standard details the selection of a system boundary for LCA studies.

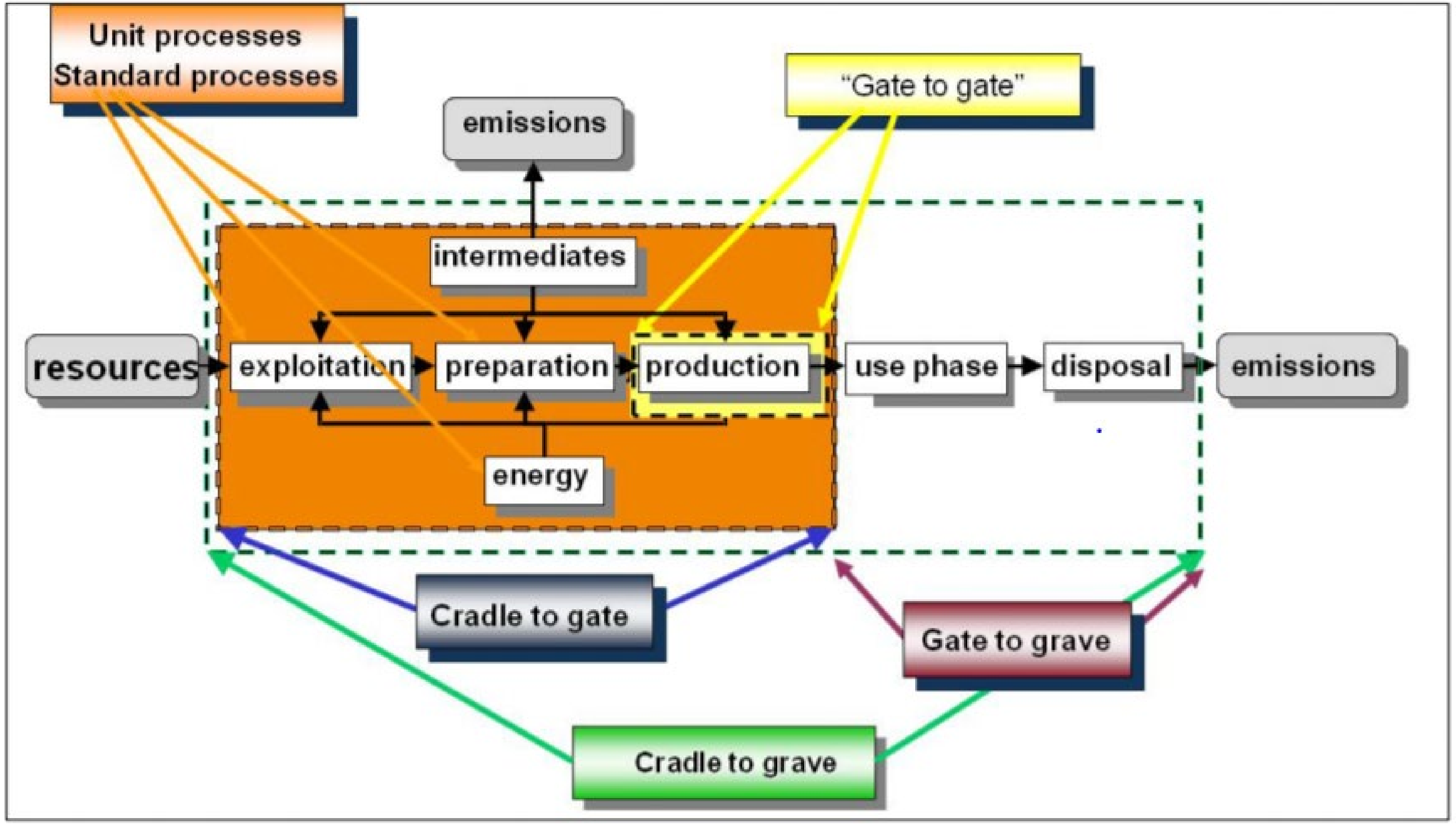
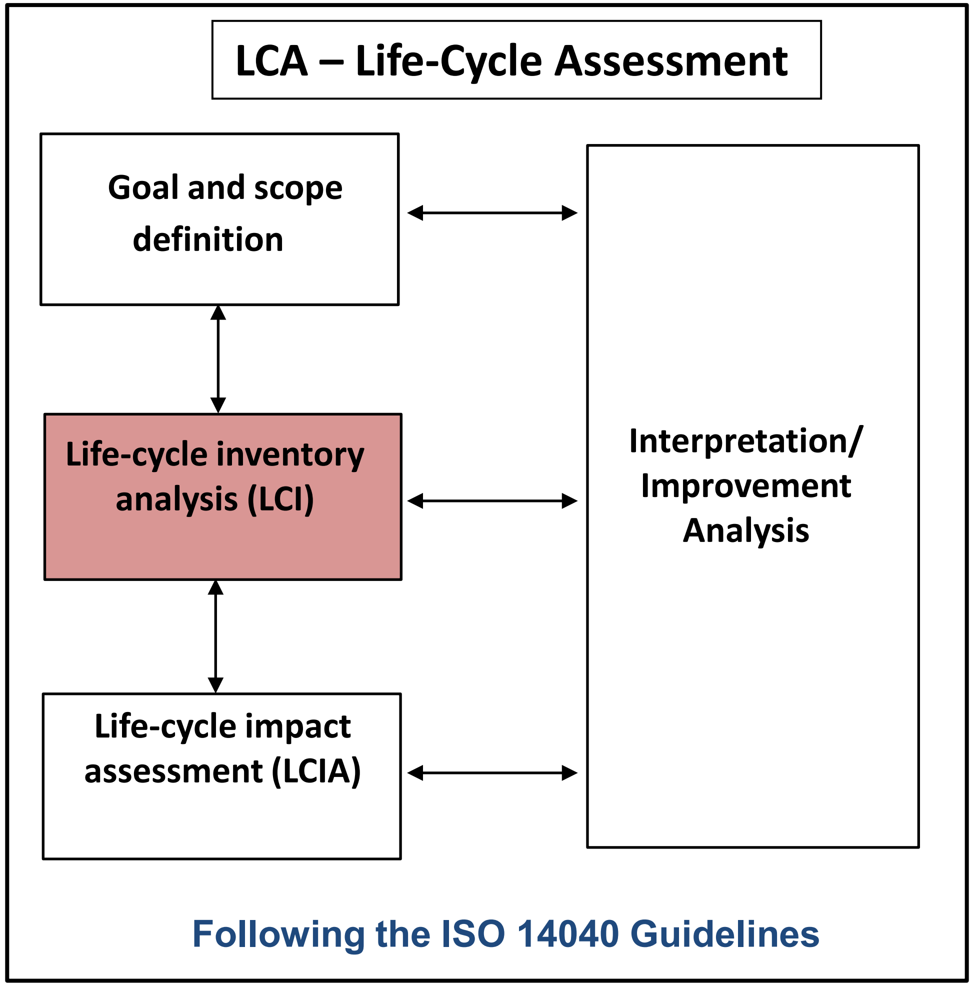


Figure 4: System Boundaries.

LCA Framework



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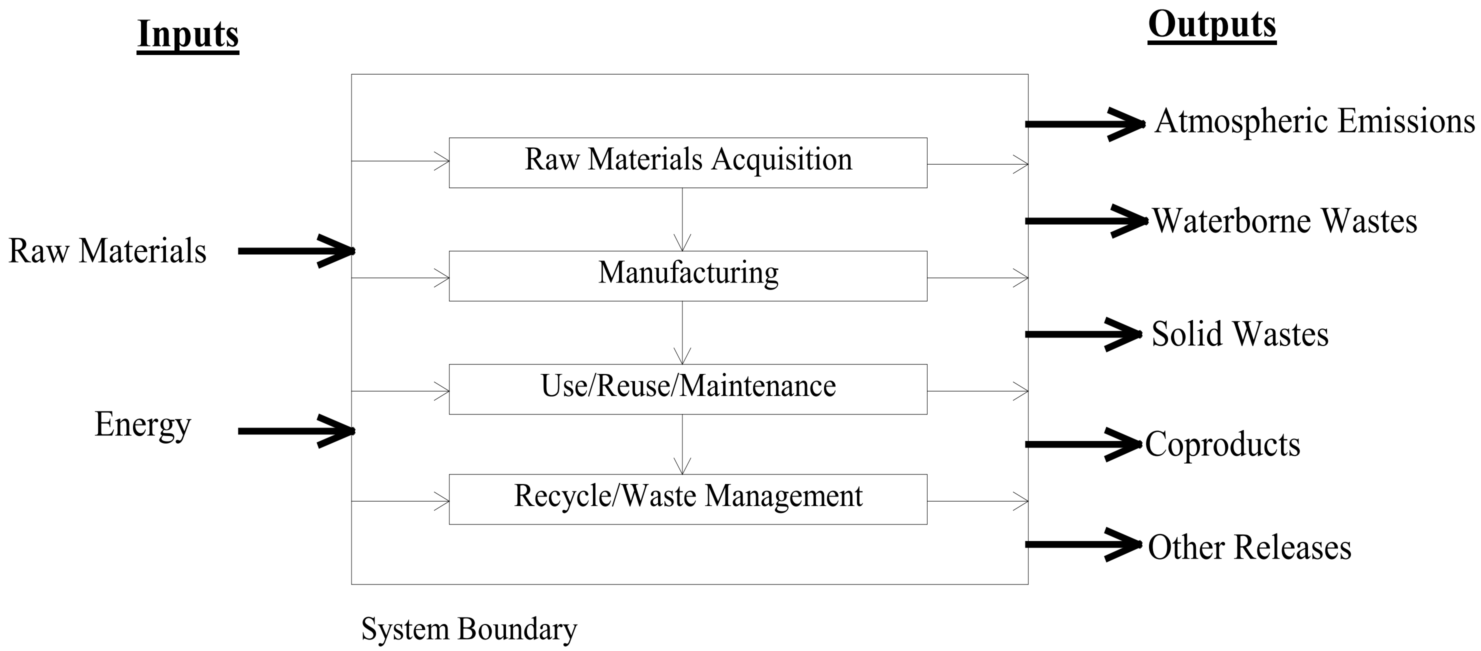
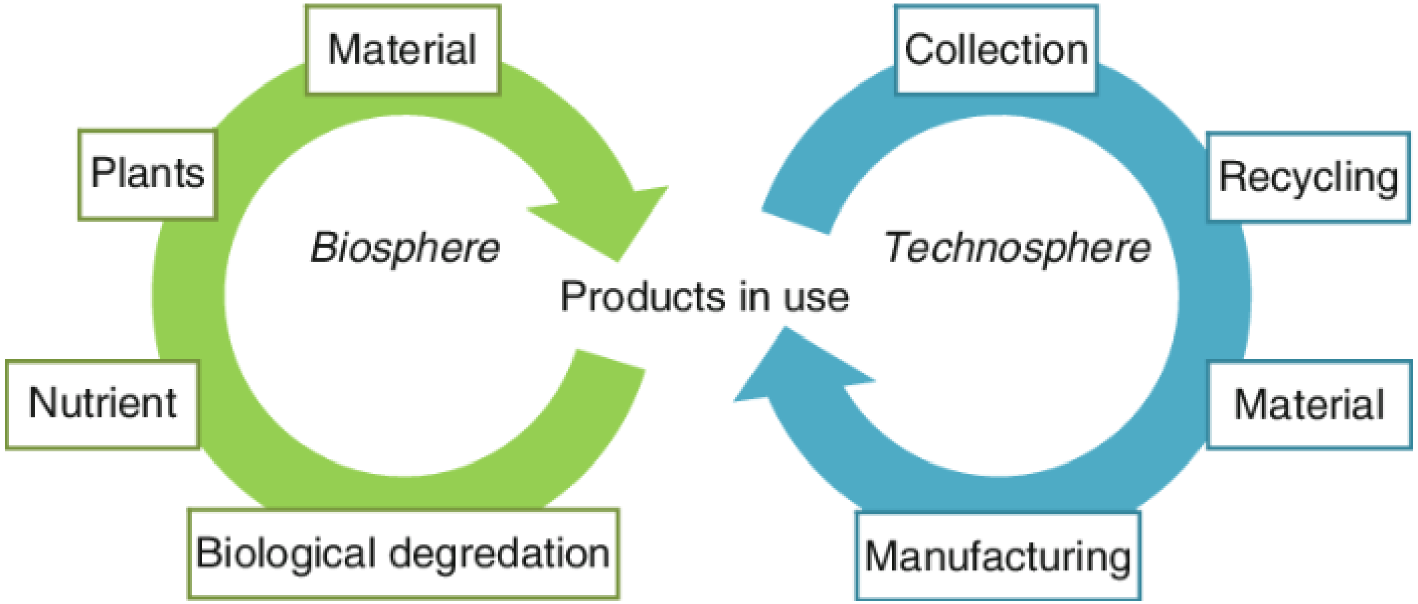
Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) Analysis:
Involves the compilation and quantification of inputs and outputs for a product throughout its life cycle [ISO 14044:2006E]. (Mass and Energy Balances)



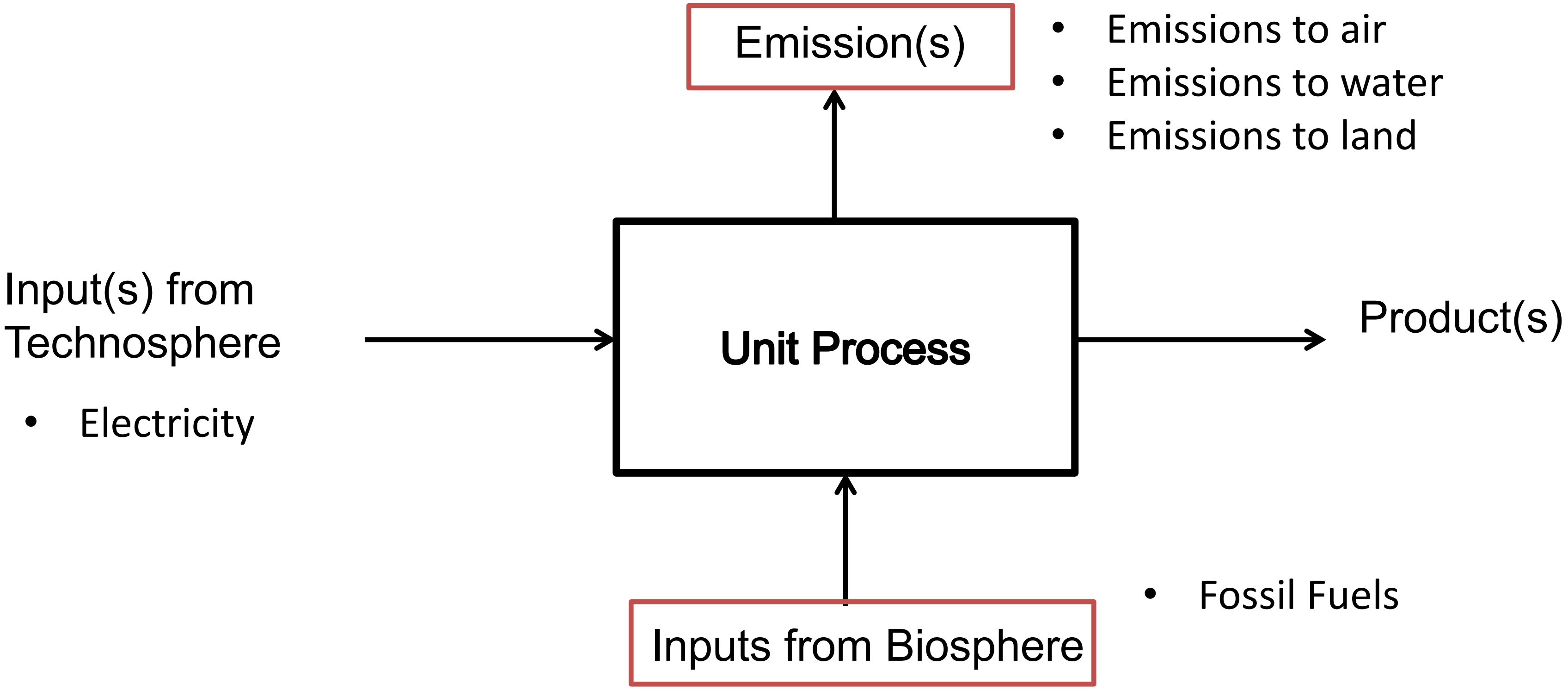
Life Cycle Inventory and Flows



Technosphere – Production/Economic Systems (human transformation involved)

Biosphere – Ecosphere, ecosystem (no human transformation), Environment

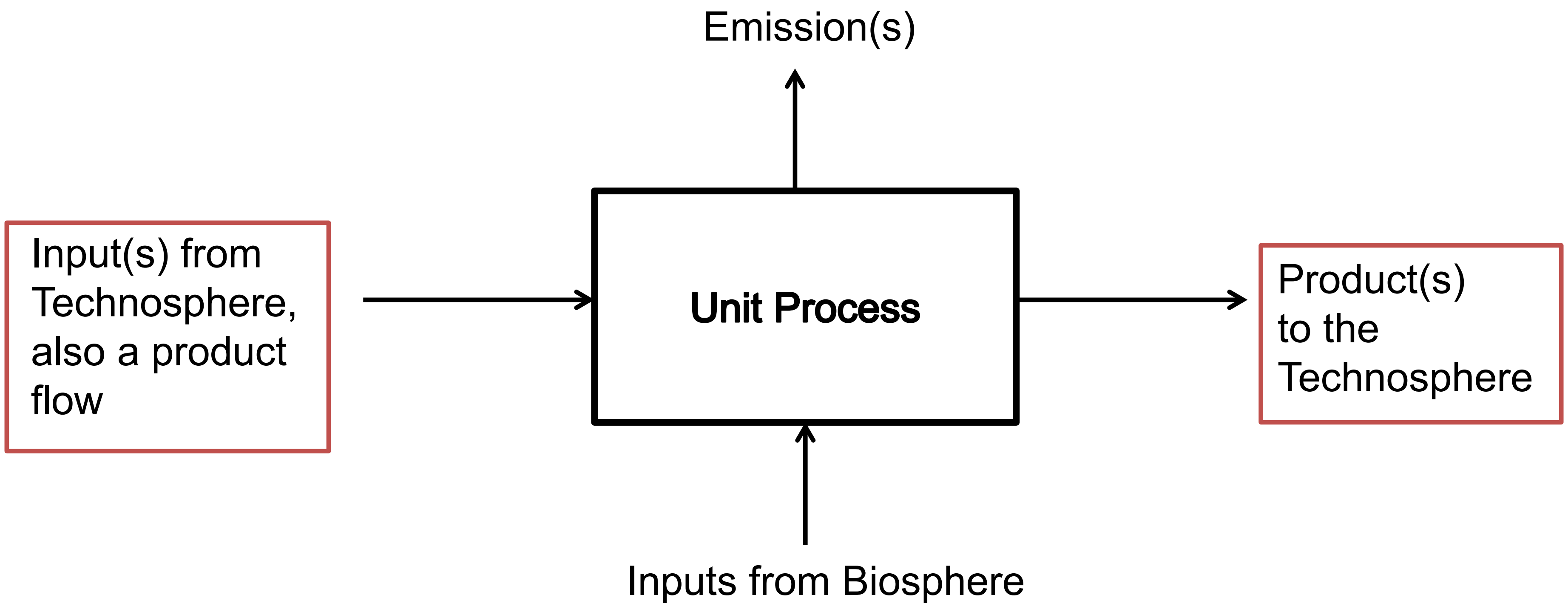
Life Cycle Inventory and Flows



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

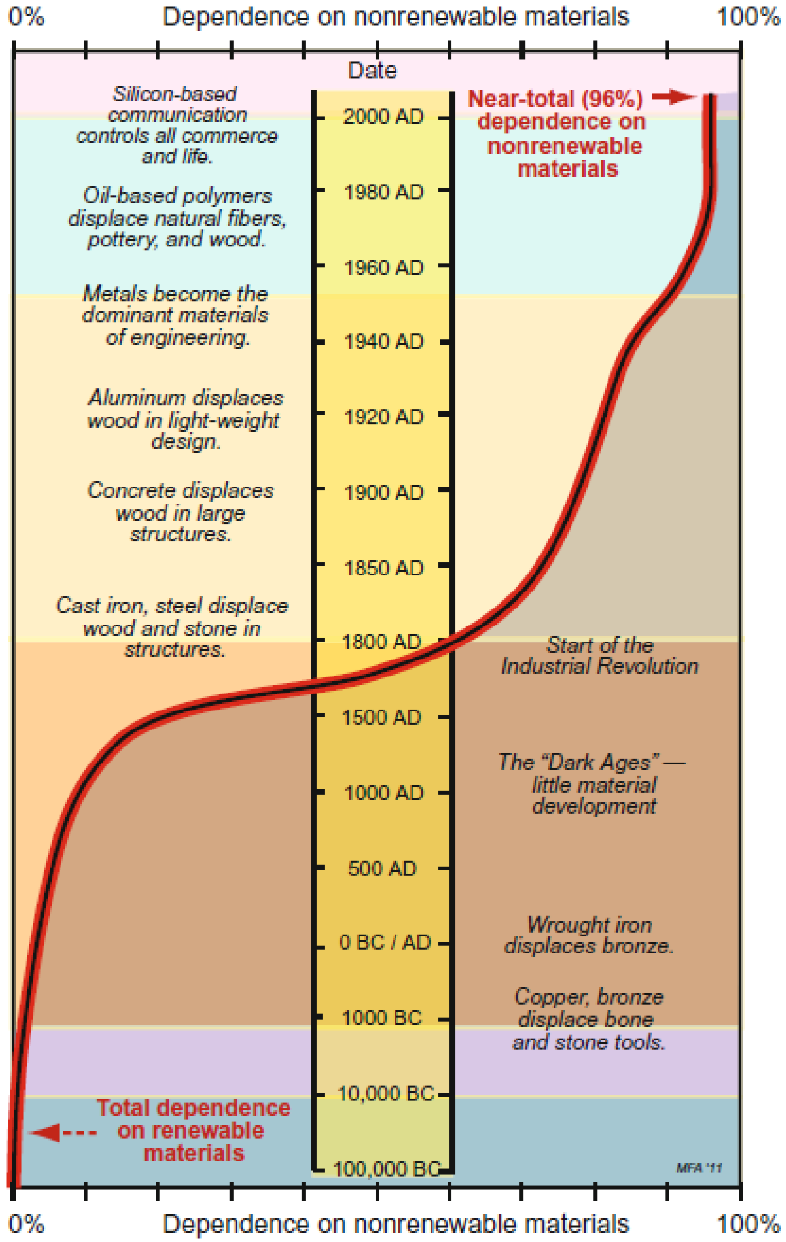
Source: ISO 14040:2006

Life Cycle Inventory and Flows



Product Flow
Products entering from or leaving to another product system (within the technosphere)

Source: ISO 14040:2006



Source: Michael F. Ashby, Materials and the Environment, 2013

Renewable vs Nonrenewable Materials

Renewable: a resource that can be replaced naturally in a short time.

- Forest
- Plants
- Animals

https://forestry.ces.ncsu.edu/

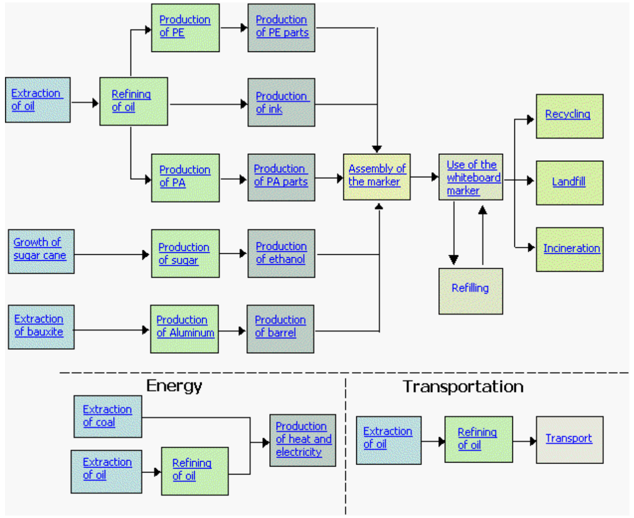
Non-renewable: a resource that cannot be replaced naturally in a meaningful human time-frame.

- Fossil fuels
- Metal ores
- Minerals

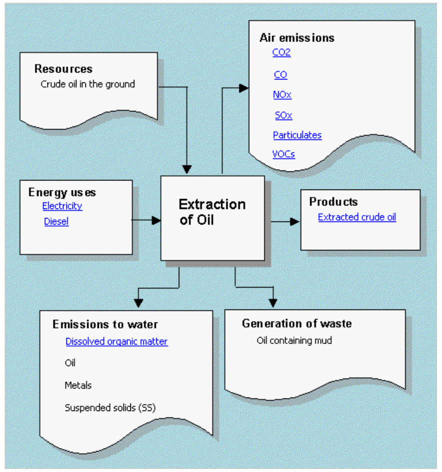
https://www.miningreview.com/water-impacts-coal-power-underestimated/

Visualization of Data Collection Steps

Process flow diagram



Process-level data collection



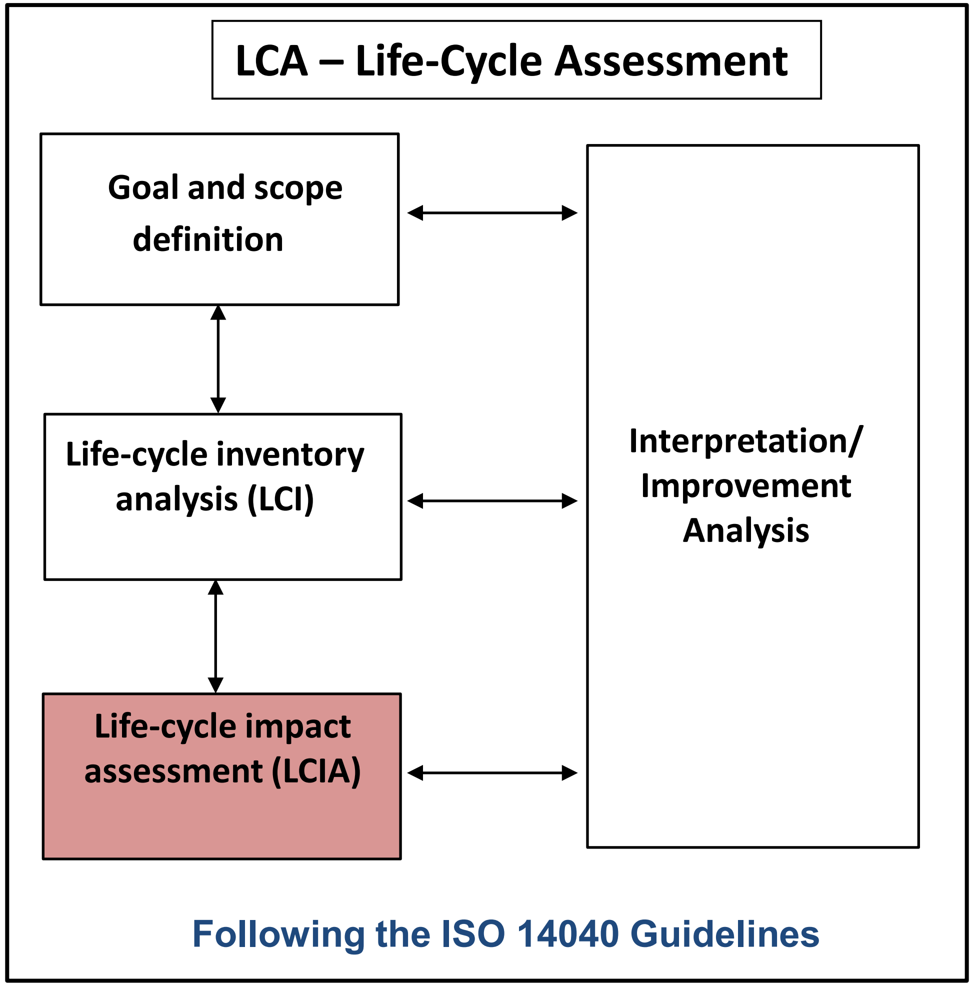
Life-cycle inventory

- Fuel inputs
- Solid waste generation
- Water inputs
- Air emissions
- Water emissions
- Hazardous waste generation
- Radioactive waste generation
- Etc.

Source: http://www.howproductsimpact.net/

LCI Data Sources for Manufacturing: US Life Cycle Inventory Database, www.nrel.gov/lci/

LCA Framework



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LCIA: From inventory to impacts

- In LCIA, the effects of the resource use and emissions generated are grouped and quantified into a limited number of environmental impact indicators, which are more intuitive and meaningful for interpretation, comparisons, and decision making

LCI Data

Glass/frit	
Barium	9.33E-10
Carbon dioxide	2.85E+00
Carbon monoxide	1.64E-04
Chromium	1.39E-07
Cobalt	1.43E-10
Copper	6.33E-10
Fluorides (F-)	2.93E-05
Lead	3.22E-07
Manganese	4.67E-10
Nickel	5.33E-10
Nitrogen oxides	4.47E-02
PM	1.10E-04
Sulfur oxides	5.08E-05
Zinc (elemental)	4.67E-09
Total	2.90E+00
PWB	
Formaldehyde	3.88E-05
Japanese grid	
1,1,1-Trichloroethane	6.46E-08
1,2-Dichloroethane	4.57E-08
2,3,7,8-TCDD	1.68E-14
2,3,7,8-TCDF	5.84E-14
2,4-Dinitrotoluene	3.19E-10
2-Chloroacetophenone	8.00E-09
2-Methylnaphthalene	2.38E-10
5-Methyl chrysene	2.51E-11
Acenaphthene	4.32E-09
Acenaphthylene	3.29E-10
Acetaldehyde	6.52E-07
Acetophenone	1.71E-08
Acrolein	3.31E-07
Anthracene	4.55E-10

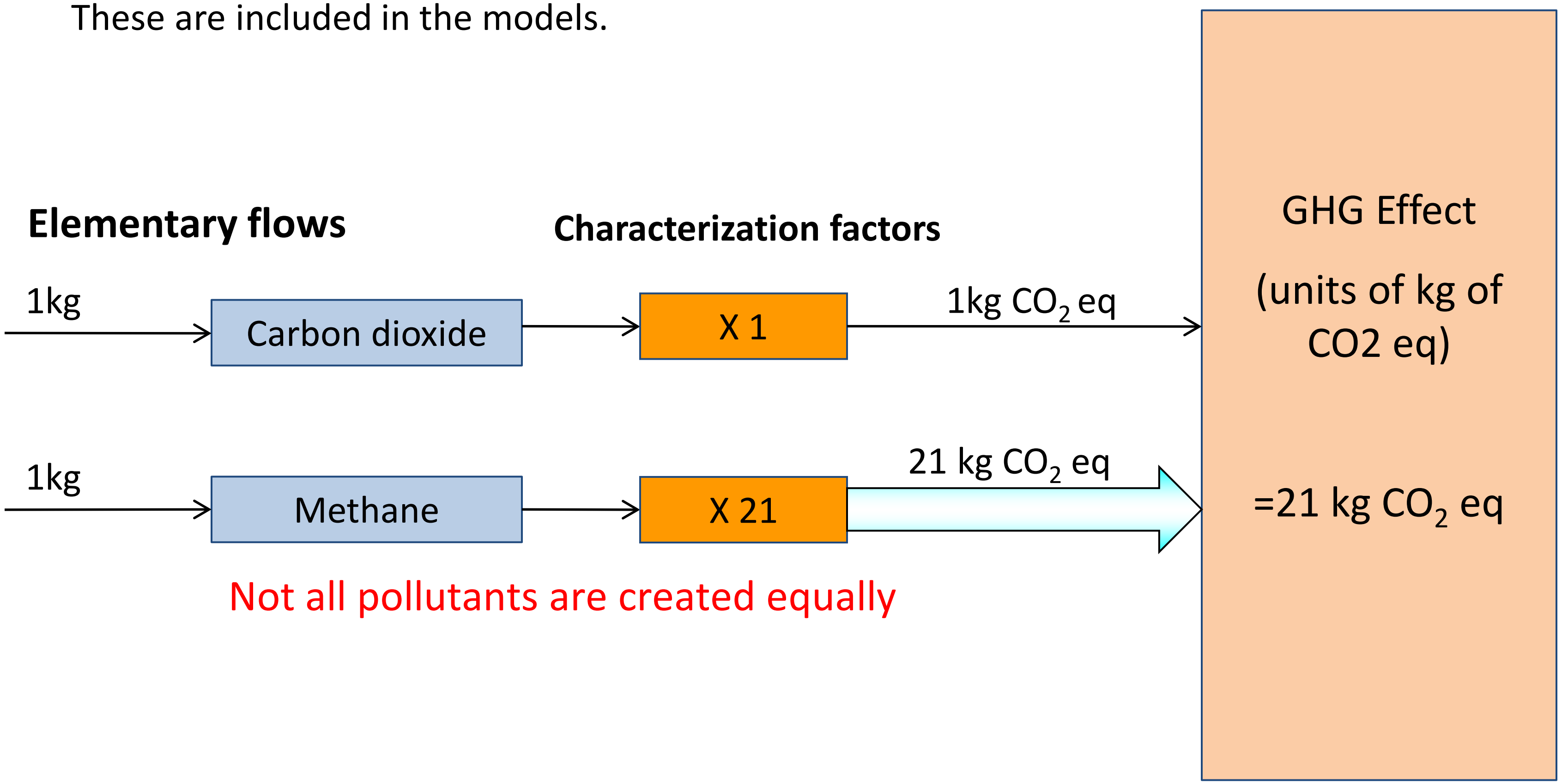
Environmental Impact Indicators

- Resource depletion
- Land use
- Global warming potential
- Ozone depletion potential
- Acidification
- Solid waste generation
- etc.

Impact Assessment Models: Characterization

Characterization factor: factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result (elementary flow) to category indicators and to category endpoints [ISO 14044:2006E]

These are included in the models.



Reference: http://www.epa.gov/RDEE/energy-resources/calculator.html#results

Life Cycle Impact Assessment
Mandatory elements

1. Selection (choose impact categories and characterization models)

- LCIA impact characterization models are still limited and are a focus of current research

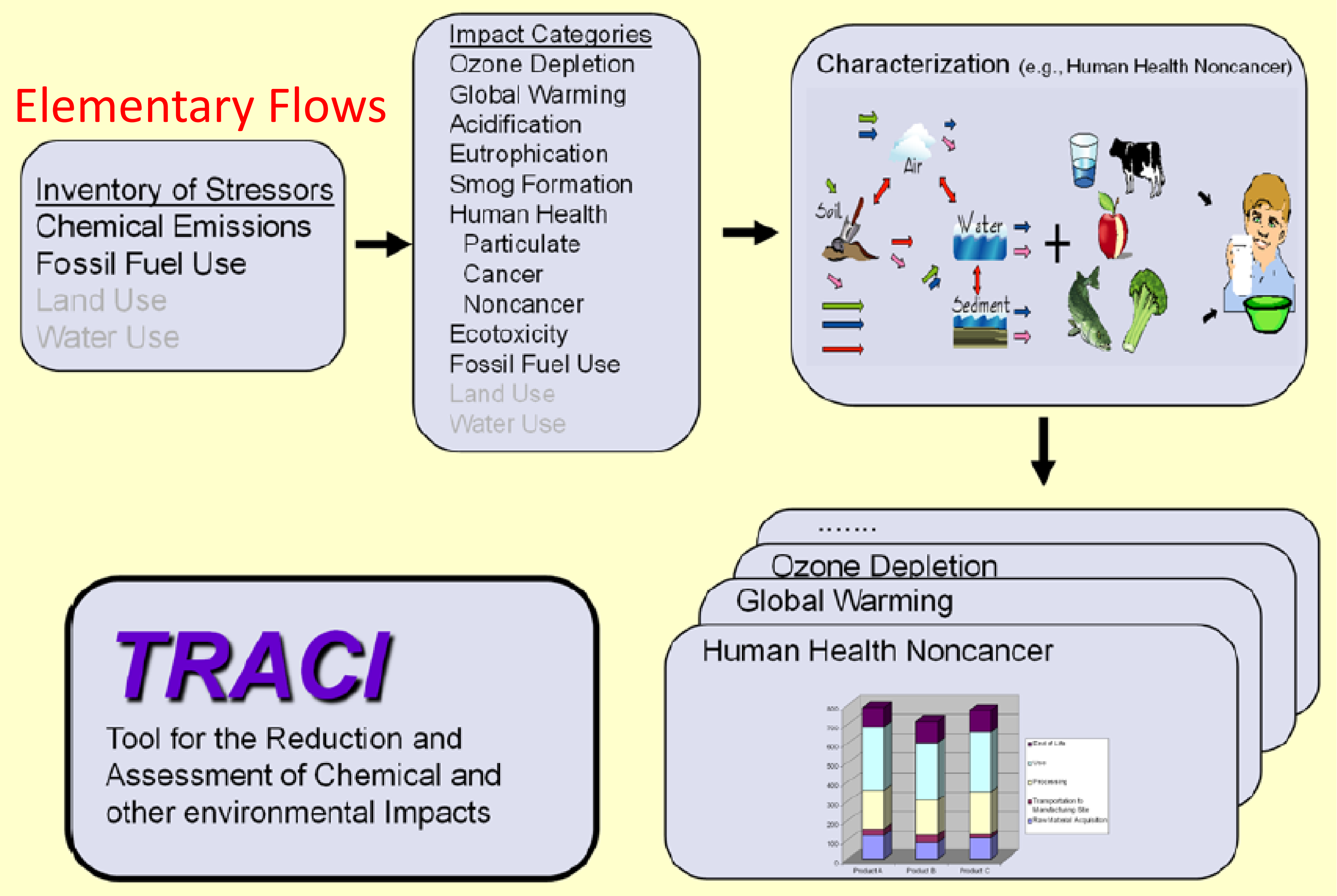
2. Classification (assign LCI results to impact categories)

- E.g., SO_2 can lead to both acidification and human health effects (respiratory problems)

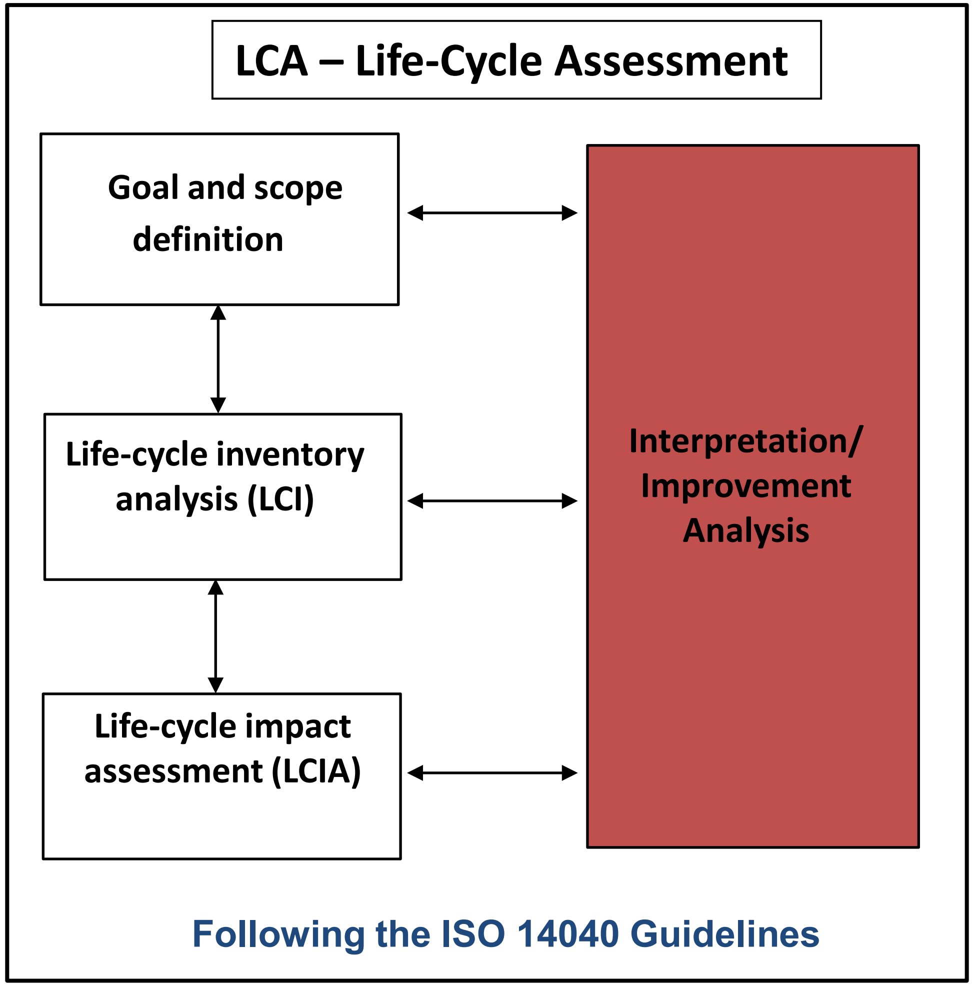
3. Characterization (calculate category results based on equivalency factors)

- Equivalency factors equate all emissions in a given impact category to a common reference unit (e.g., CO_2 equivalents for global warming potential)

Elementary Flows



LCA Framework



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Life Cycle Interpretation (ISO 14044)

1. **Identification** of significant issues
2. **Evaluation**
    a. completeness check
    b. sensitivity check
    c. consistency check
3. **Conclusions**, recommendations and reporting
    1. critical review

Identification of significant issues

- Objective - to structure the results from LCI or LCIA to help determine the significant issues:
  - inventory data categories: energy, emissions, waste, …
  - significant contributions from life cycle stages: individual unit processes or groups of processes, …
  - impact categories: resource use, global warming, …
  - Implications of the methods used and assumptions made (e.g., allocation methods and cut-off decisions)

Life Cycle Interpretation (ISO 14044) Evaluation

- Objective - to enhance the confidence in and the reliability of the results:
  - completeness check
    - to ensure that all relevant (with respect to the Goal and scope) information and data are available and complete
    - **If a flow should be there but is not….use engineering calculations or literature values**
    - **In some cases might have to adjust the goal and scope**

Life Cycle Interpretation (ISO 14044) Evaluation

- Objective - to enhance the confidence in and the reliability of the results:
  - sensitivity check
    - to assess the reliability of the final results and conclusions
    - issues predetermined by the goal and scope; results from all other phases of the study; expert judgments and previous experiences
    - If used for comparative assertions to be disclosed to the public, interpretative statements should be made based on the detailed sensitivity analysis.

Uncertainty and Variability

- **Uncertainty**, epistemic uncertainty, in LCA exists as a result of using inputs or methods that imperfectly capture the characteristics of the product system. The data itself could be unavailable, or of questionable quality. The methods may similarly be imperfect.
  - Additional research/data to improve the model to better reflect reality

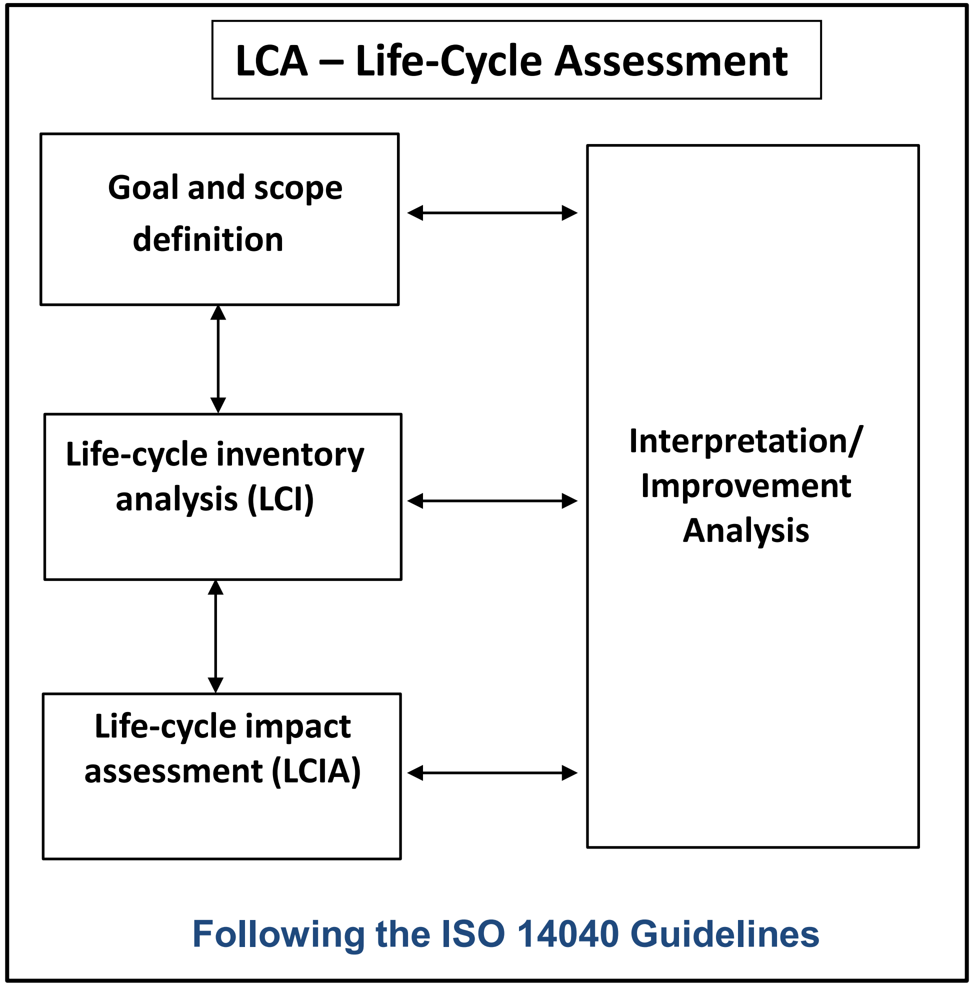
- **Variability**, aleatory (random) uncertainty, in LCA occurs as a result of randomness in the data (or potentially the methods). There are different values of data, even from technically identical processes.
  - More work to evaluate the distribution of the data
  - Example, mining for gold, variability in the concentration of gold in the excavation, impacts the environmentally efficiency of the process….

Source: Prof. Scott Matthews, Carnegie Mellon University

Life Cycle Interpretation (ISO 14044) Evaluation

- Objective - to enhance the confidence in and the reliability of the results:
  - consistency check
    - to determine whether the assumptions, methods and data are consistent with the goal and scope
      1. Are differences in data quality along a product system life cycle and between different product systems consistent with the goal and scope?
      2. Have regional and/or temporal differences, if any, been consistently applied?
      3. Have allocation rules and the system boundary been consistently applied to all product systems?
      4. Have the elements of impact assessment been consistently applied?

LCA Framework



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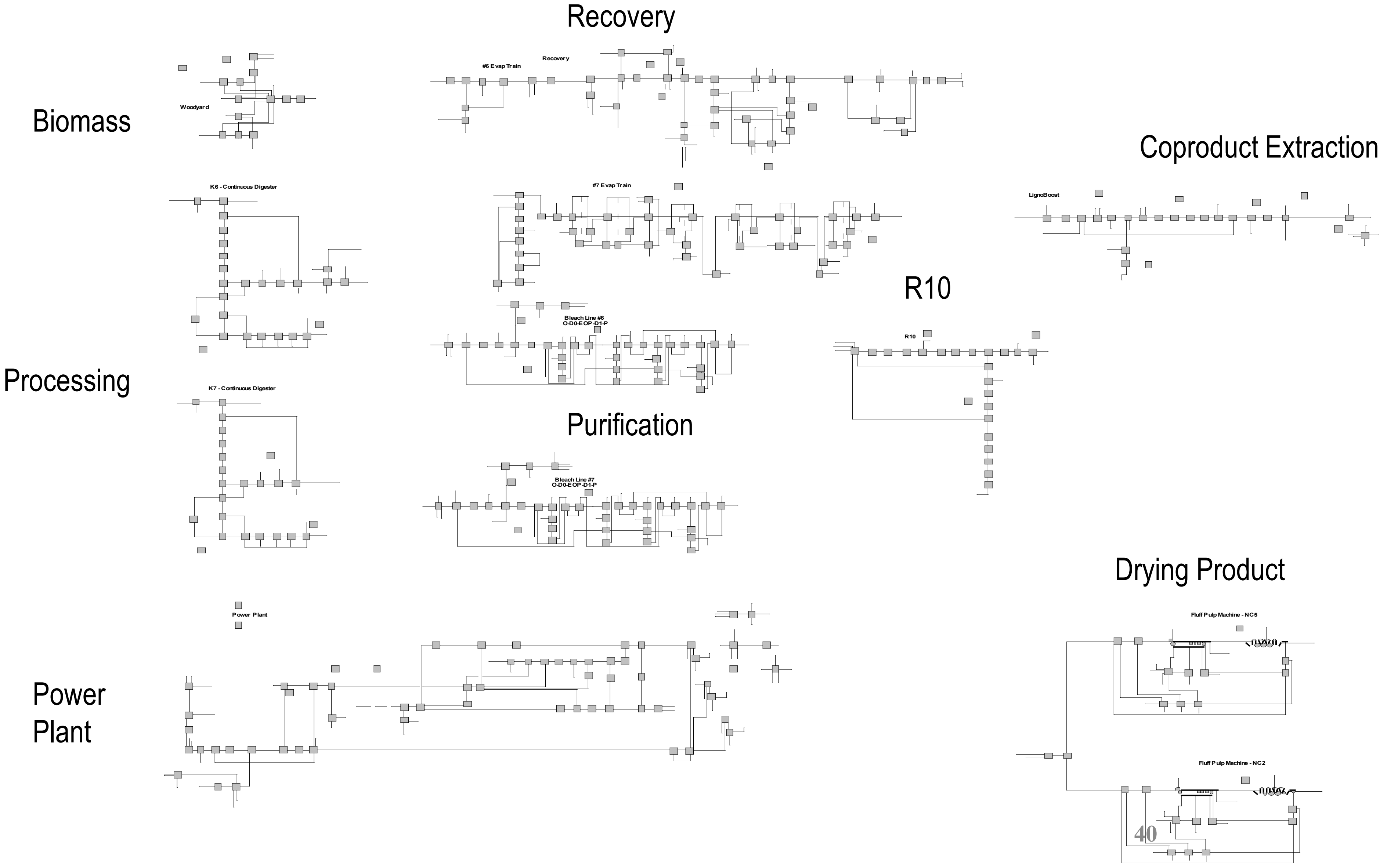
Goal: Identify Hot Spots in a Biorefinery

ADM wheat, World-grain.com

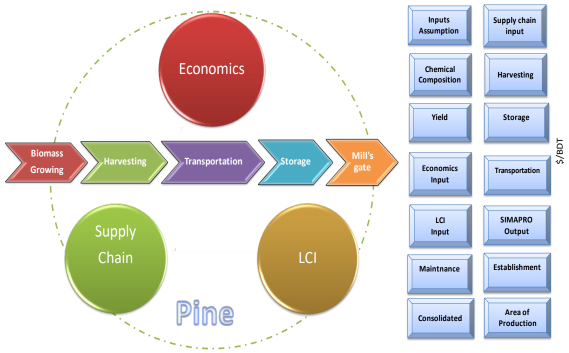
Life Cycle Inventory: Biorefinery Modelling



- 12 Unit Operations
- 371 Blocks
- 632 Streams

Life Cycle Inventory

Feedstock Supply Chain Models



Fuel Combustion Data

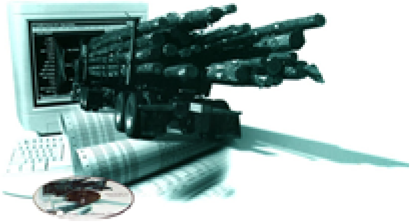
Databases

ecoinvent Centre

U.S. Life Cycle Inventory Database

MASS and ENERGY Balance Simulators

aspentech



WinGEMS™

Example of Life Cycle Inventory for Biorefinery

Mill mill	Mill A @35%	Mill B @ 50%
Inputs	**Case 1**	**Case 2**
Raw Materials		
Biomass feed (mt/mt)	2.91	2.85
Chips to process (mt/mt)	2.68	2.72
Sawdust (kg/mt)	-	0.13
Bleaching Chemicals		
Sodium hydroxide 50% solution (kg/mt)	64.7	49.7
Sulfuric acid 98% solution (kg/mt)	7.0	6.8
Sodium hypochlorite (kg/mt)	-	5.8
Hydrogen peroxide 50% solution (kg/mt)	14.2	-
CLO_2 gen R-10		
Sodium chlorate (kg/mt)	15.2	36.4
Methanol (kg/mt)	1.8	4.3
Sulfuric acid 98% solution (kg/mt)	11.8	28.7
Recovery chemicals		
Sodium sulfate makeup (kg/mt)	16.1	20.4
Lime (CaO) makeup (kg/mt)	29.3	20.0
Sodium hydroxide 50% solution makeup (kg/mt)	62.0	62.3
Sodium hydroxide 50% solution from CCE (kg/mt)	-	23.4
Freshwater (m^3/mt)	36.0	121.6
Energy (MWh/mt)		
Electricity demand	0.95	1.43
Electricity generation (on-site)	1.49	1.07
Power surplus (Mill A)/Purchased (Mill B)	0.55	0.36
Fuels (Mcal/mt)		
Natural gas to power boiler	-	2,832
Natural gas to limekiln	39.5	27.0

Mill mill	Mill A @ 35%	Mill B @ 50%
Outputs	**Case 1**	**Case 2**
Bleached pulp AD (6.5%mois mt)	1	1
Sodium sulfate (kg/mt)	0.15	-
Tall oil (mt/mt)	-	-
Turpentine (mt/mt)	-	-
Waste wood	0.13	-
Emissions to air		
CO_2, fossil (kg/mt)	227	740
CO_2, biogenic (kg/mt)	3,070	3,061
SO_2, (kg/mt)	-	0.13
CH_4, (mg/mt)	45.4	38.2
N_2O, (mg/mt)	10.0	8.45
Emissions to water		
AOX (kg/mt)	0.17	0.45
Water effluent (m^3/mt)	33.5	117.3
COD[37] (kg/mt)	-	22
BOD (kg/mt)	5.3	-
Waste to treatment		
Ashes (kg/mt)	-	0.73
Dregs & grits (kg/mt)	25.9	22.1
Mud inert (kg/mt)	7.67	5.74
Dust losses (kg/mt)	0.61	0.44

Life Cycle Impact Assessment

Life Cycle Inventory:

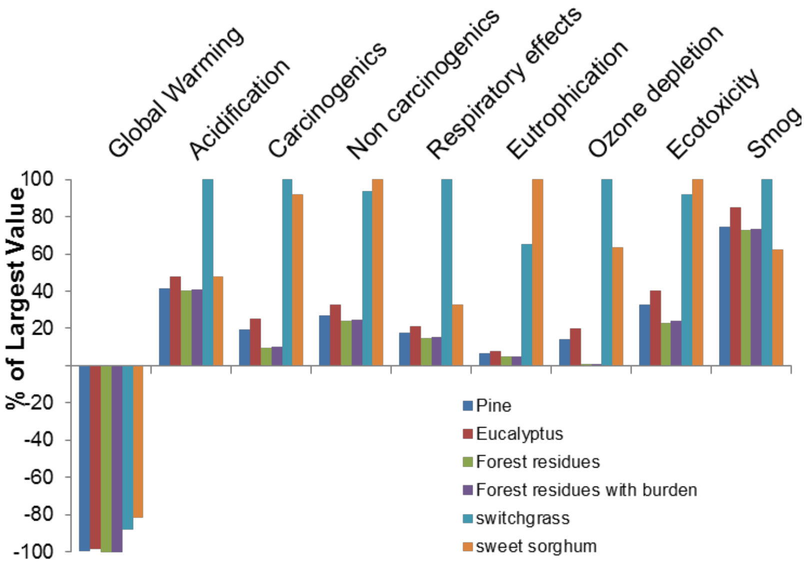
Mass and Energy Balances

Flows in and out of environment

Life Cycle Impact Assessment Software

openLCA

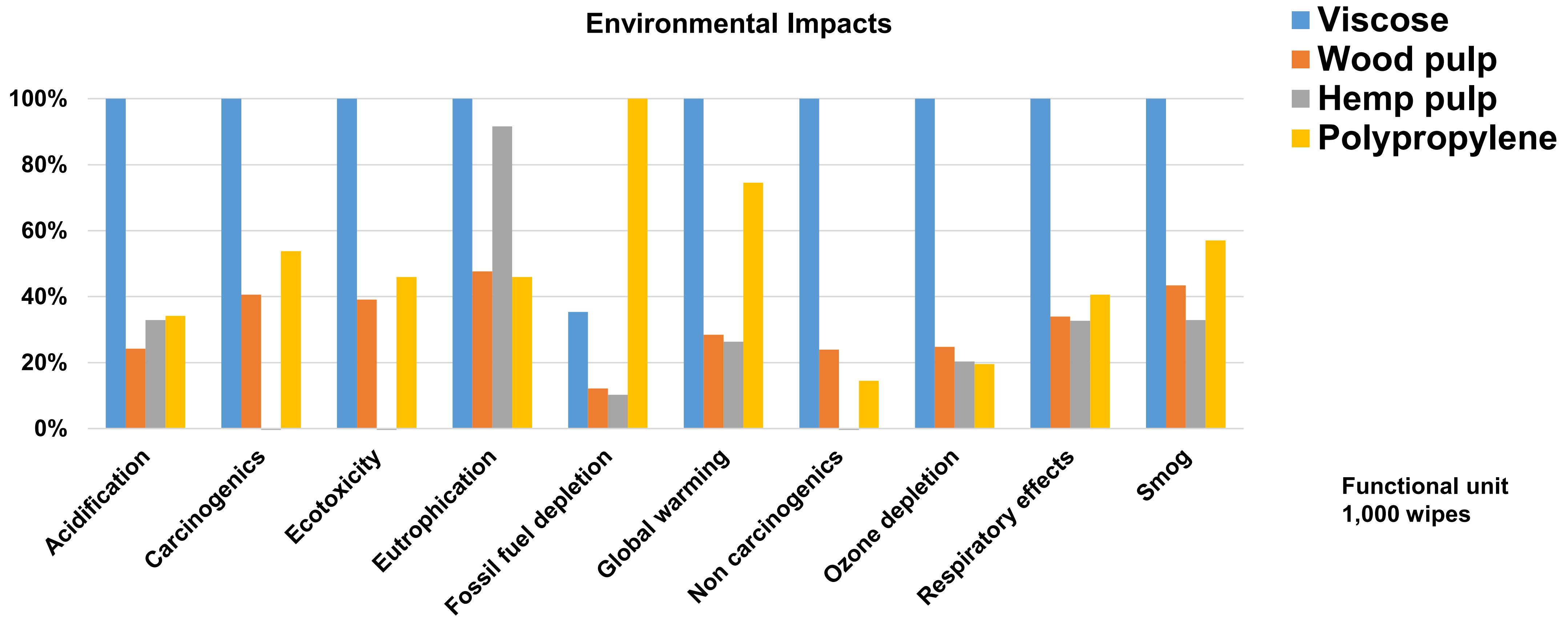
Environmental Impacts



Life Cycle Impact Assessment: Hot Spot Analysis to Identify Improvement Projects

	NaOH, 50%	CaO	H2O2, 50%	H2SO4	NaClO3	CH3OH	CO2 (gas)	Nat. Gas	Emissions	Soft.W.	Solid Residue	Transport	Transport, F.
Global Warming	6%	4%	2%	0%	16%	0%	0%	60%	567%	-562%	0%	1%	5%
Acidification	3%	0%	1%	5%	9%	1%	0%	59%	1%	17%	0%	1%	4%
Carcinogenics	7%	0%	5%	1%	42%	1%	0%	29%	0%	3%	11%	0%	1%
Non-carcinogenics	3%	0%	5%	1%	47%	1%	0%	42%	0%	1%	0%	0%	0%
Respiratory effects	5%	1%	1%	6%	13%	1%	0%	65%	0%	5%	0%	0%	3%
Eutrophication	8%	1%	2%	2%	18%	0%	0%	14%	0%	15%	36%	1%	4%
Ozone depletion	7%	6%	4%	1%	18%	1%	0%	45%	0%	0%	1%	2%	16%
Ecotoxicity	15%	1%	13%	1%	54%	0%	0%	11%	0%	3%	1%	0%	1%
Smog	3%	1%	1%	1%	8%	0%	0%	20%	0%	52%	0%	2%	12%

Relative Environmental Impact For Single-Use Wipes



Functional unit
1,000 wipes

Thank You!

Questions?

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go.ncsu.edu/venditti