Life Cycle Assessment - LCA

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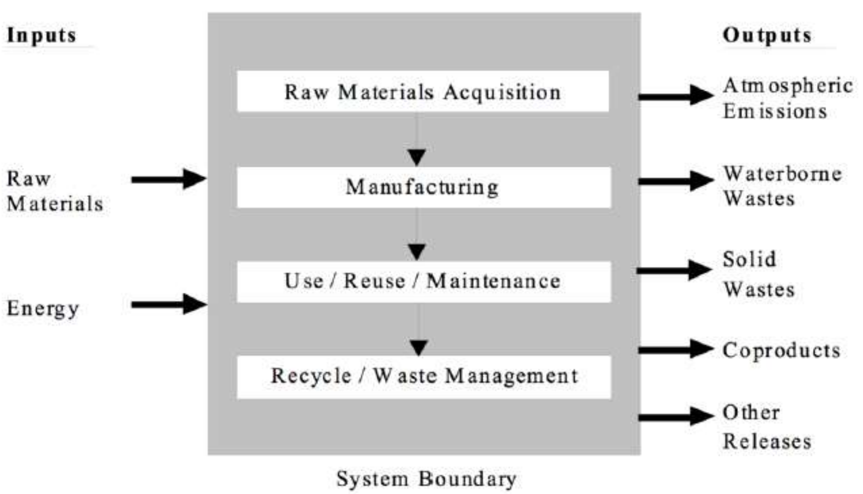
Agenda

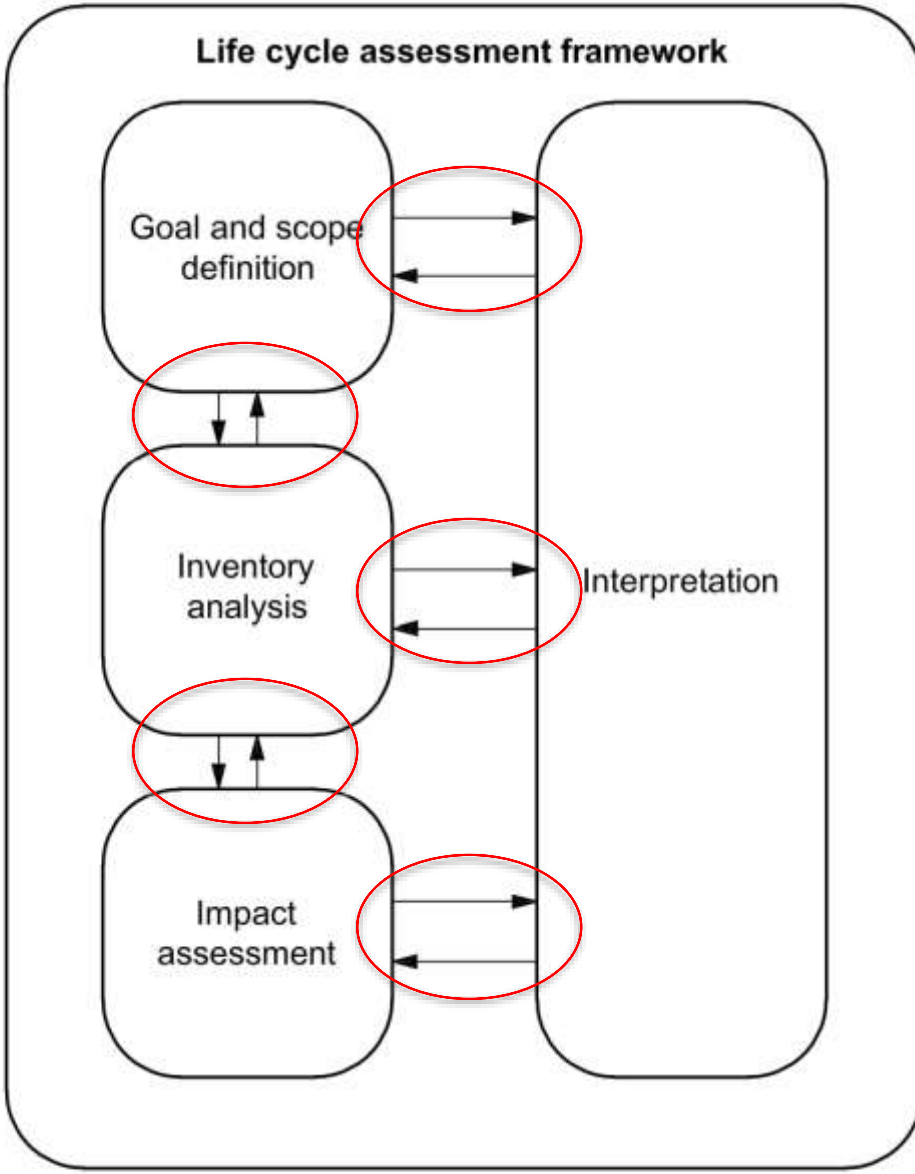
- Life cycle thinking
- Quantitative methods and life cycle cost analysis
- The ISO LCA standard
- Life cycle inventory
  - Data needs and data quality
  - Data sources
  - Handling multifunction systems (disaggregation and allocation)
  - Uncertainty
  - Input-output LCA
- Impact assessment
- Conclusions

Phases of an LCA - Iterative

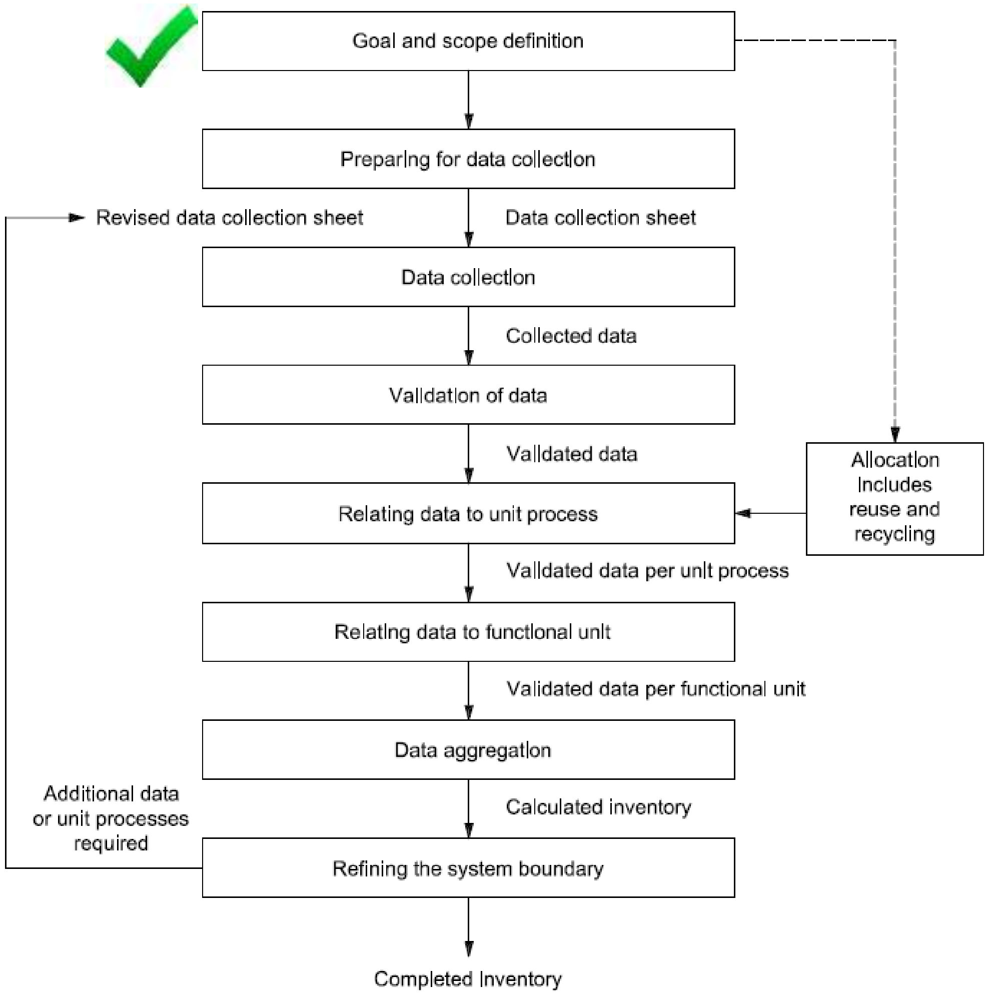
- Not a once through process - all phases are iterative!
- Adjust as you go along
- Changes after iteration happen in ~100% of studies



Overview of LCA – US EPA

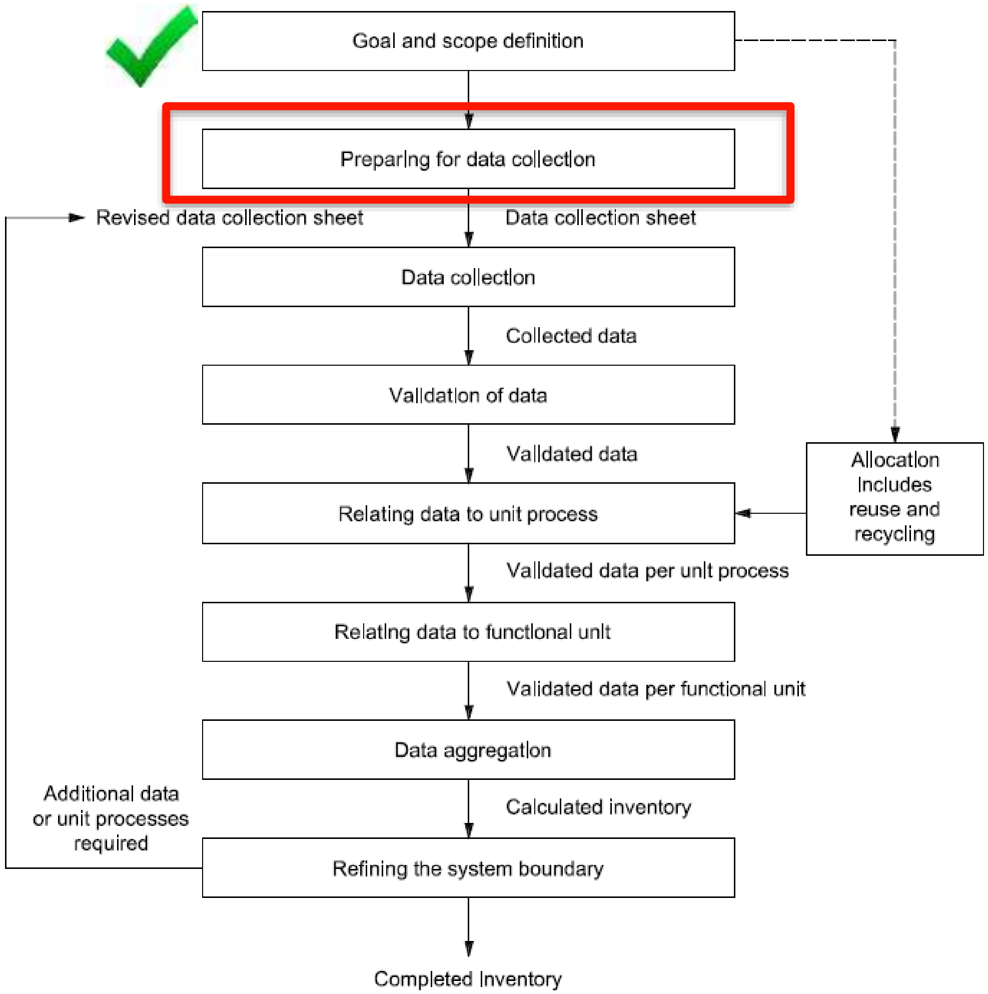


ISO Life Cycle Inventory Analysis Overview



Source: ISO 14044, Fig. 1

Step 1: preparing for data collection



Source: ISO 14044, Fig. 1

Data needs overview

- Must know what you are tracking for your inventory
- Need data for all inputs and outputs
- Level of detail/aggregation may depend on:
  - Purpose of study
  - Data availability
  - Amount of uncertainty/variability
- Follow data quality requirements
- Remember: data needs and goal/scope are set iteratively

Inventory scope

- We don’t just choose “air emissions” or “water emissions”
  - We choose specific emissions of gases or substances
    - e.g., CO_2, SO_2, ..
- Can be guided by desired impact categories
  - Planned focus on fuel use, climate change, etc.

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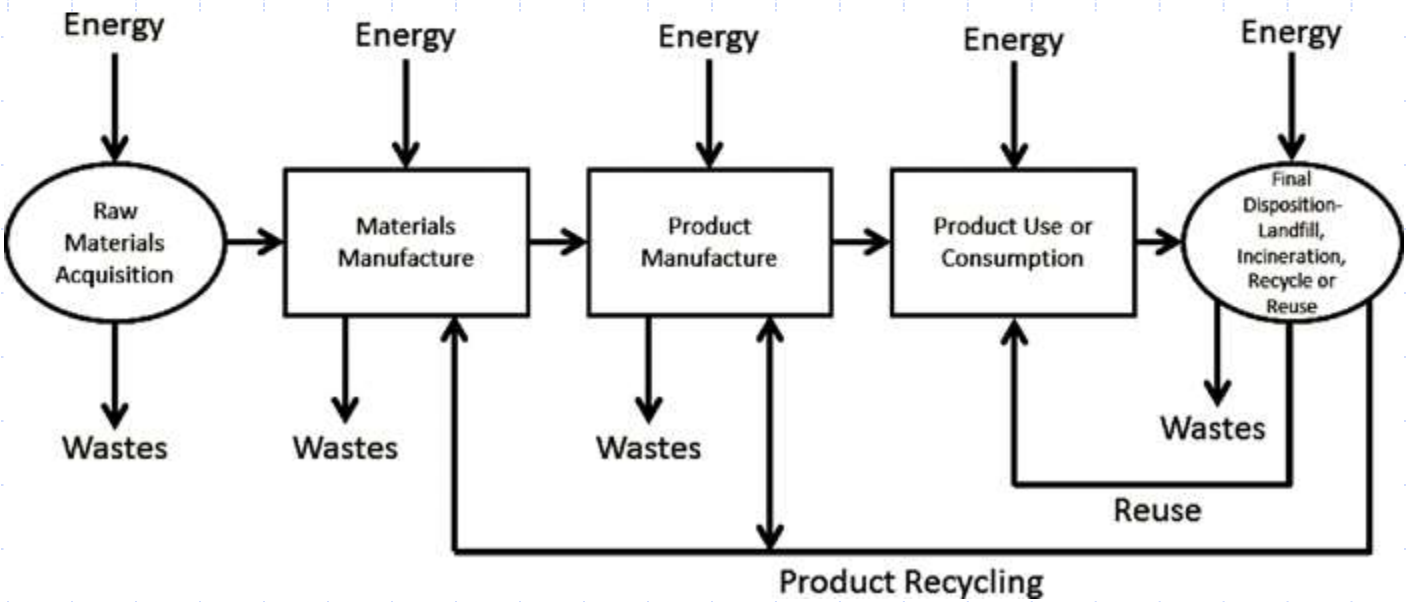
Elementary and product flows



- From ISO 14044:
  - Energy inputs, raw material inputs, ancillary inputs, other physical inputs
  - Products, co-products and waste
  - Releases to air, water and soil
  - Other environmental aspects (noise, odor, land, resource depletion …)

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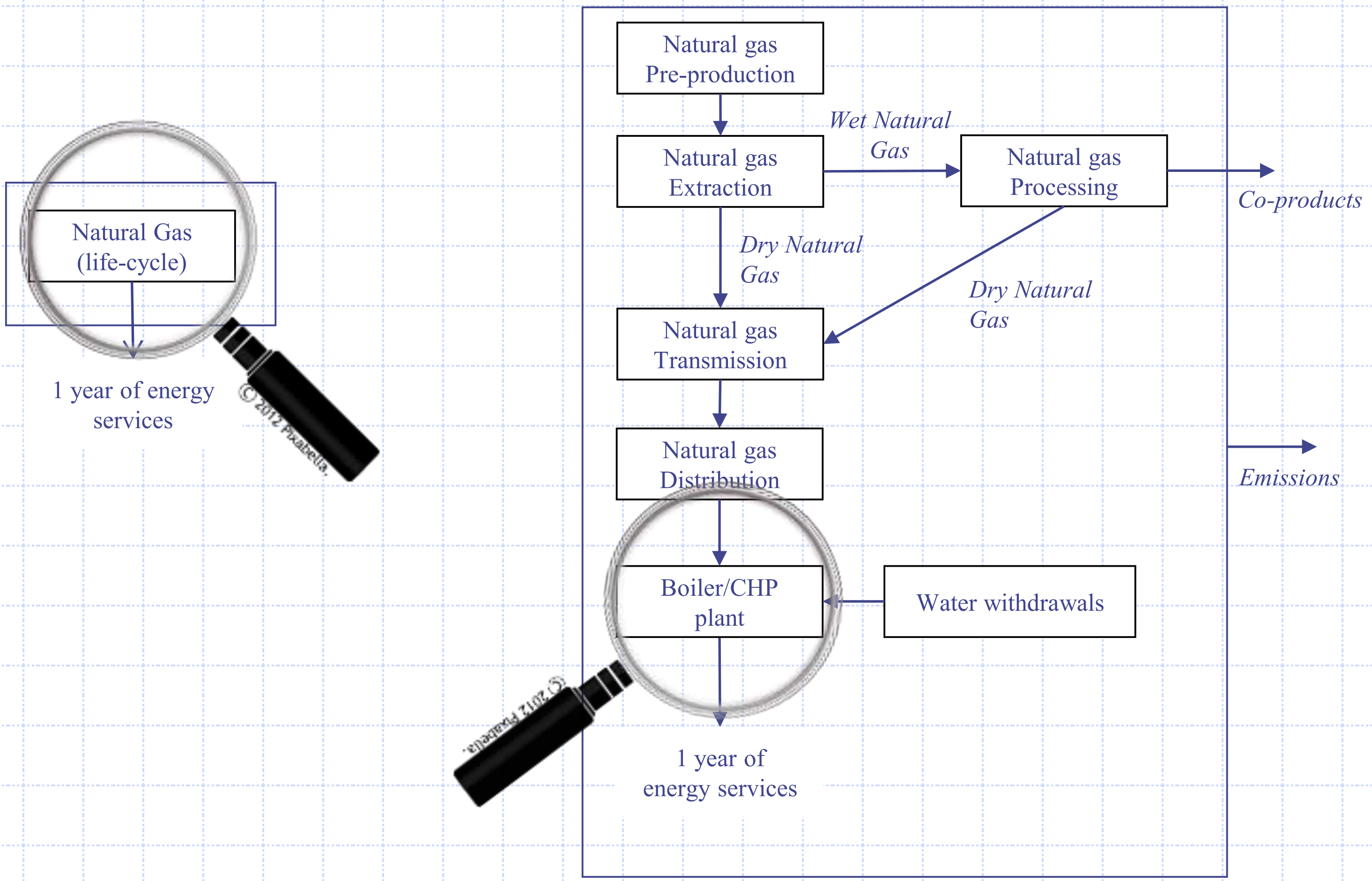
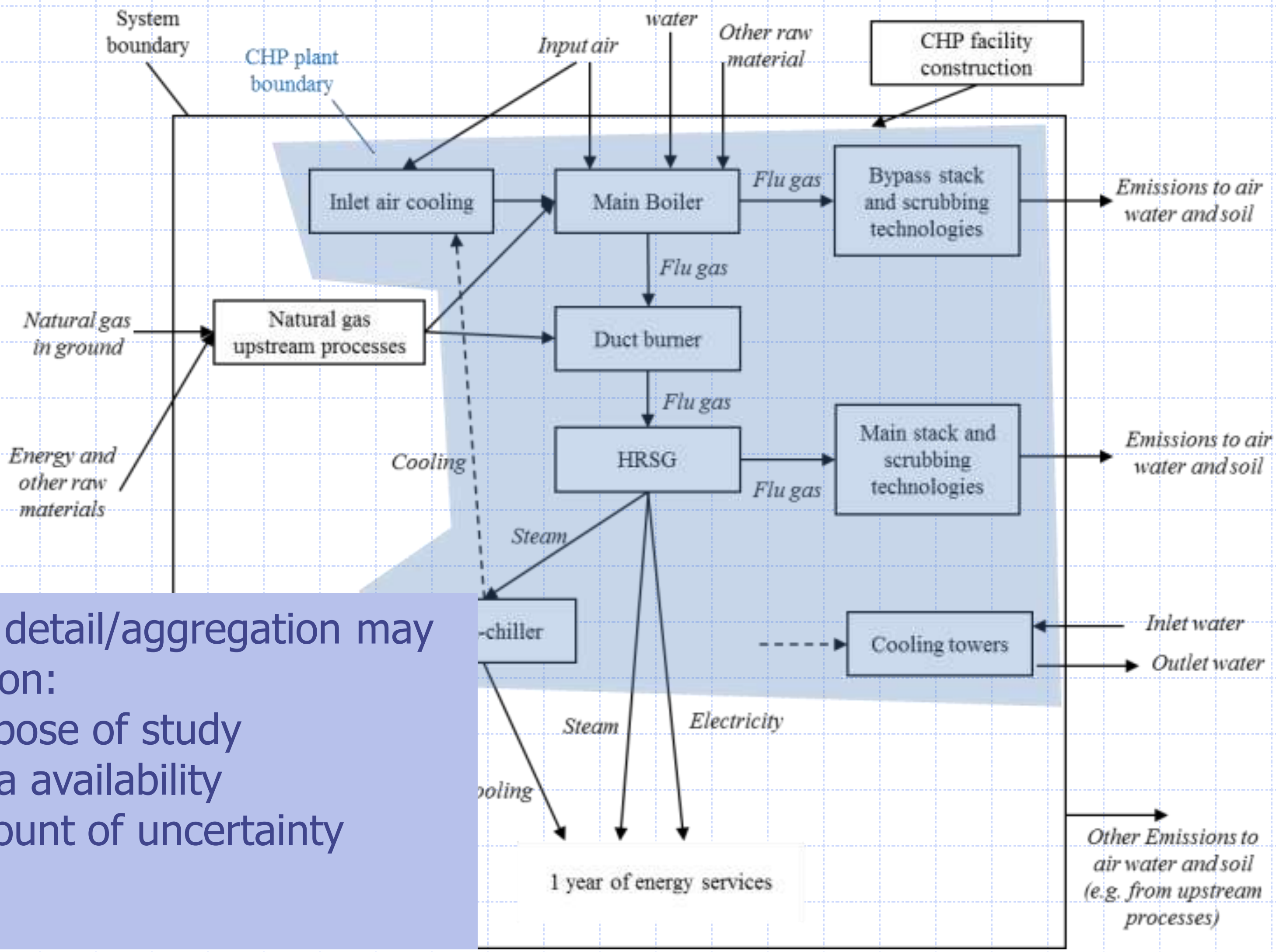
Aggregation: simplest models



Aggregation or more detail

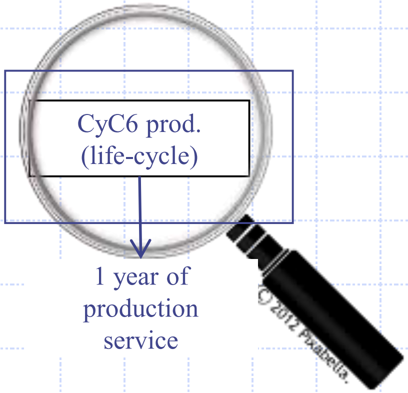


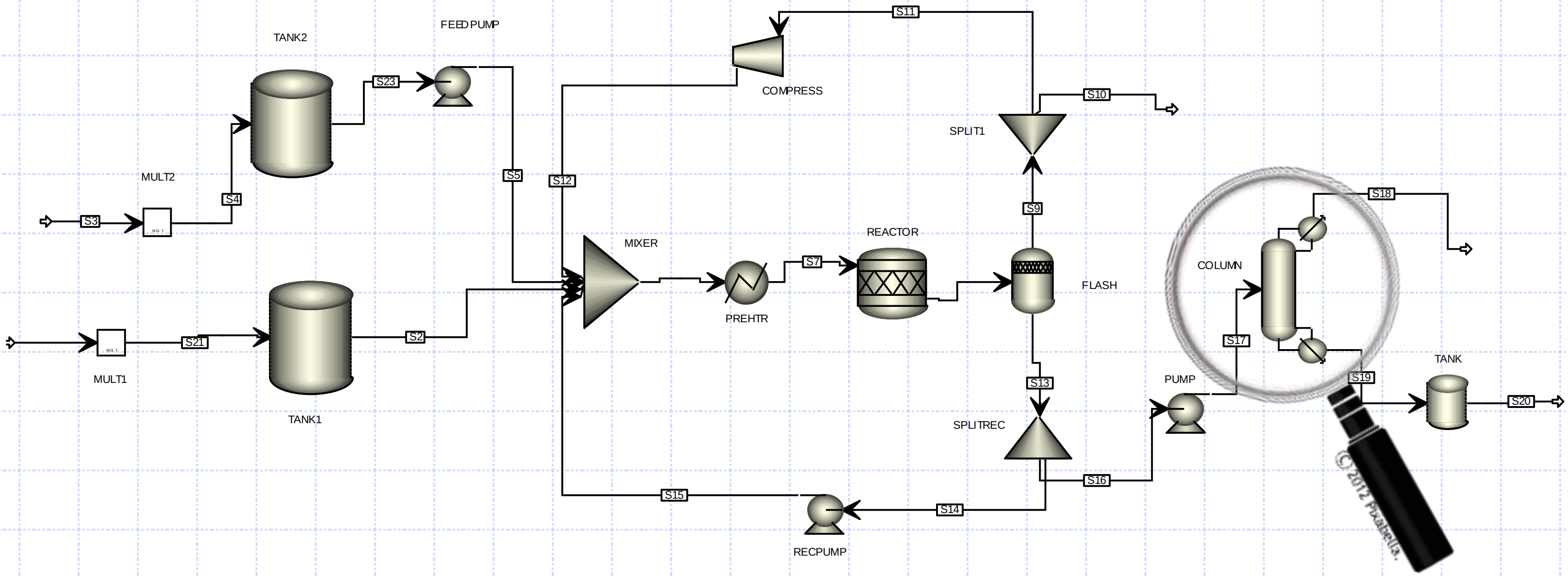
Level of detail/aggregation may depend on:

- Purpose of study
- Data availability
- Amount of uncertainty

Process engineering example:

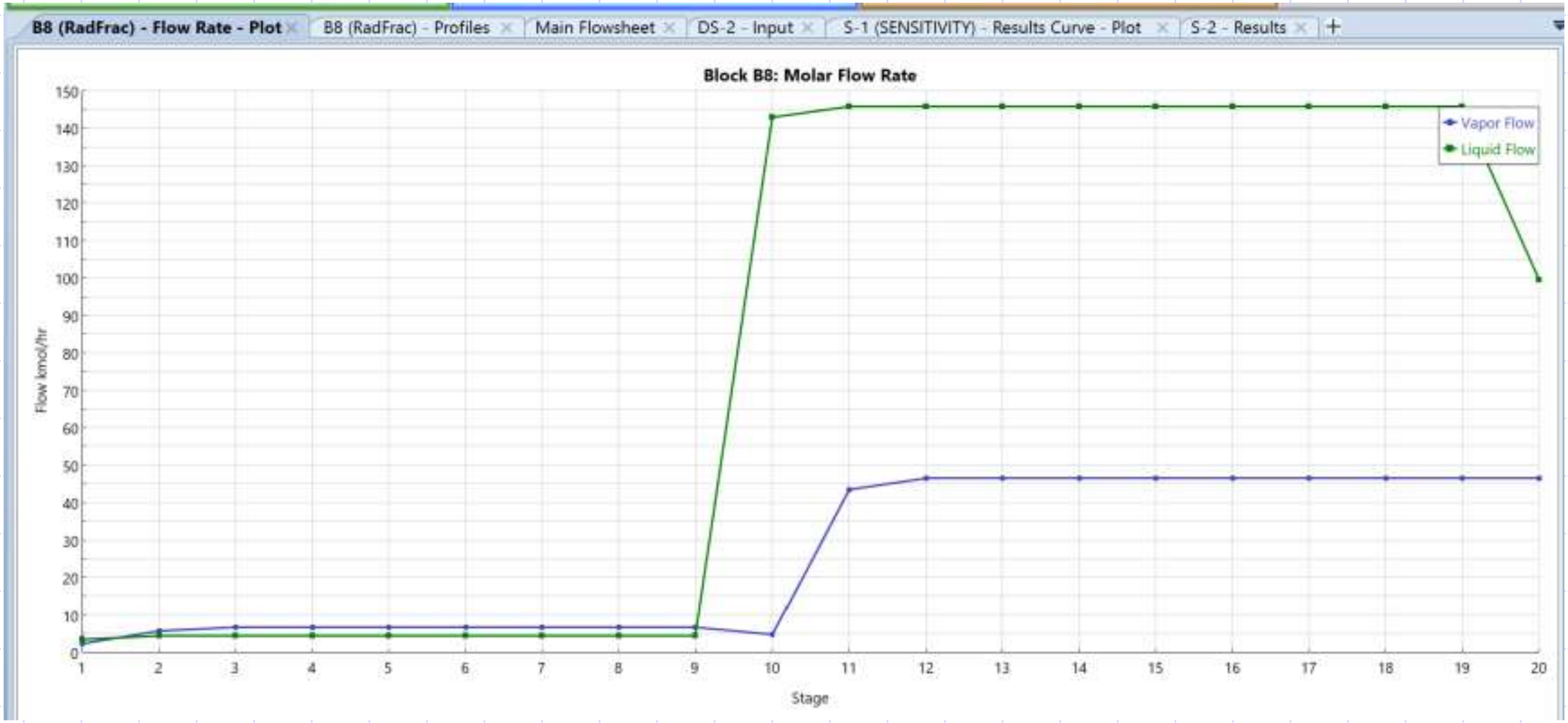
- Cyclohexane production process
  - Process simulation made in Aspen+
  - Crucial unit for the production is the distillation column





Process engineering example:

- Cyclohexane production process
  - Flow rates of liquid and vapor in the column
  - RADFRAC profiles in Aspen+



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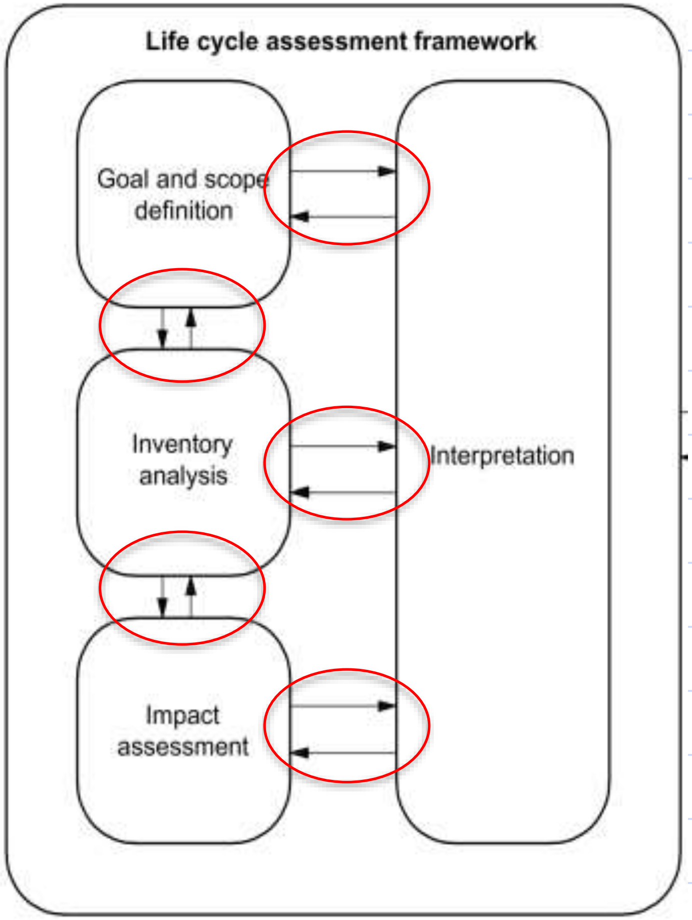
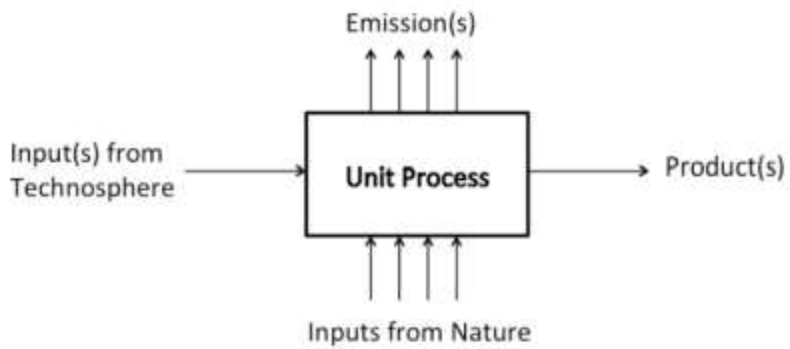
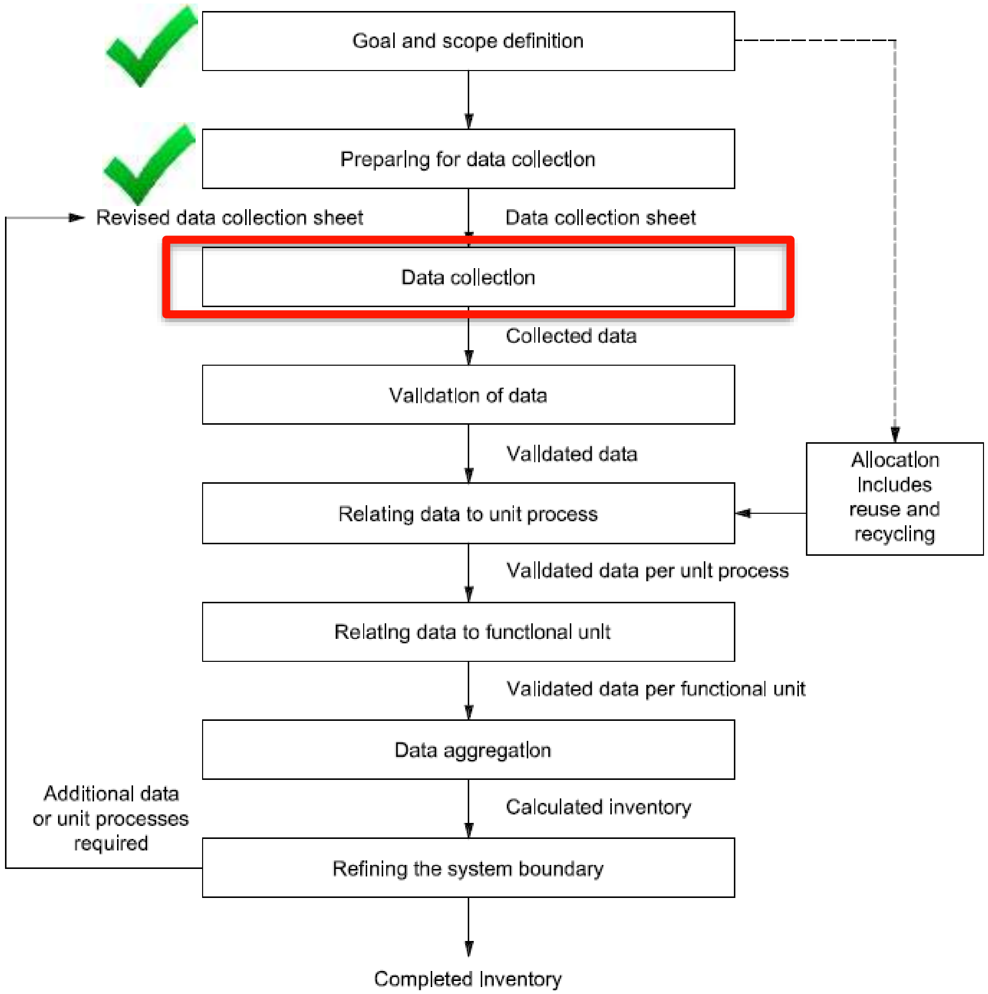




Step 2: Data Collection

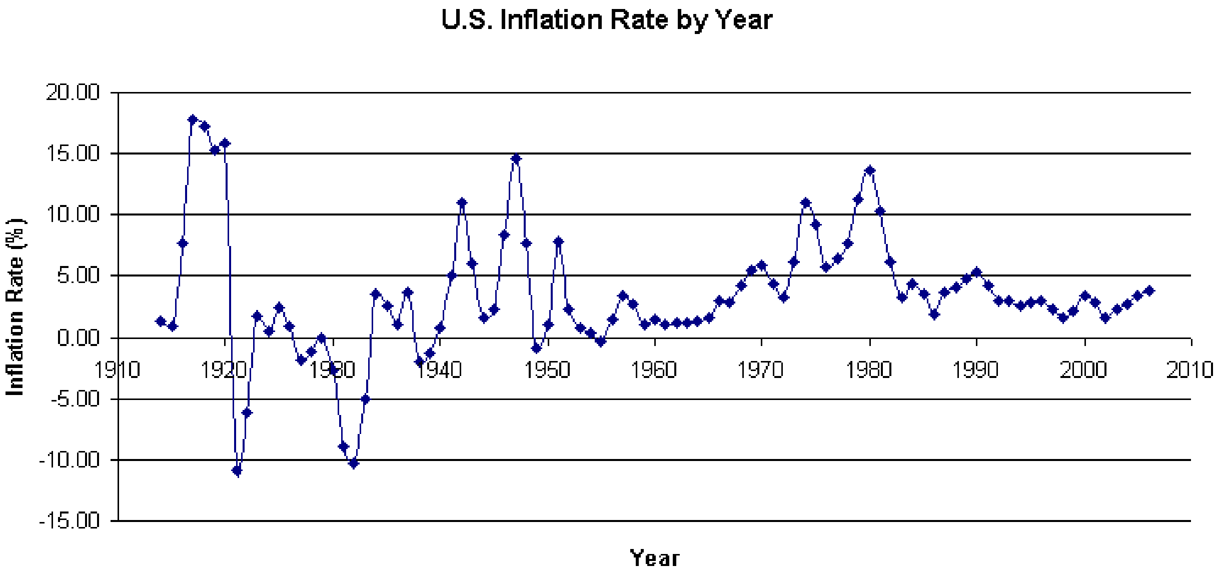


SDP: Data Quality Requirements

- Fundamental expectations of needed data
  - Temporal
  - Geographical
  - Technology
  - Sources
  - Precision
  - Uncertainty
  - Completeness
  - See ISO 14044 for more

Data Quality Requirements: Temporal

- What is my year of analysis?
- Has the process changed recently?
- Is it likely to change in the near future?
- Have upstream/downstream processes changed?
- Has new information arisen recently?
- From what year is the data?
  - NOT the same as the year of publication!!!
- …

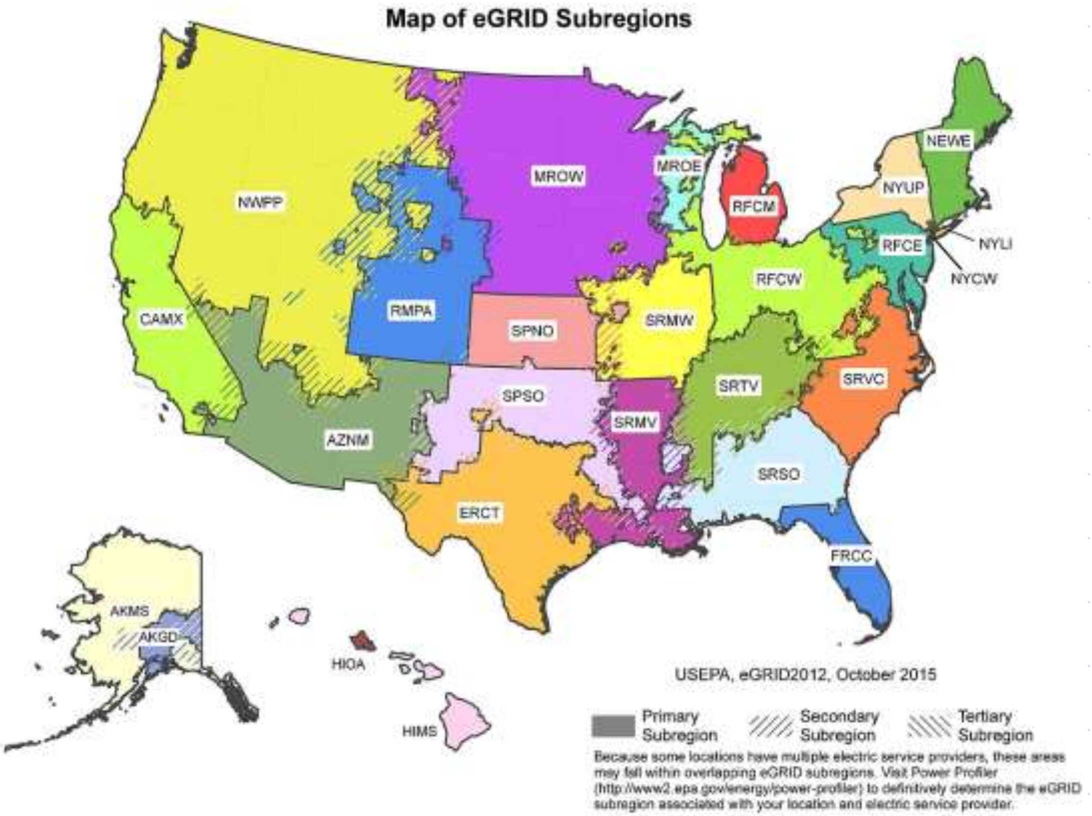


Data Quality Requirements: Geographical

- Are you looking for a specific location? A general region? ...
- Why does geography matter?

Data Quality Requirements: Geographical

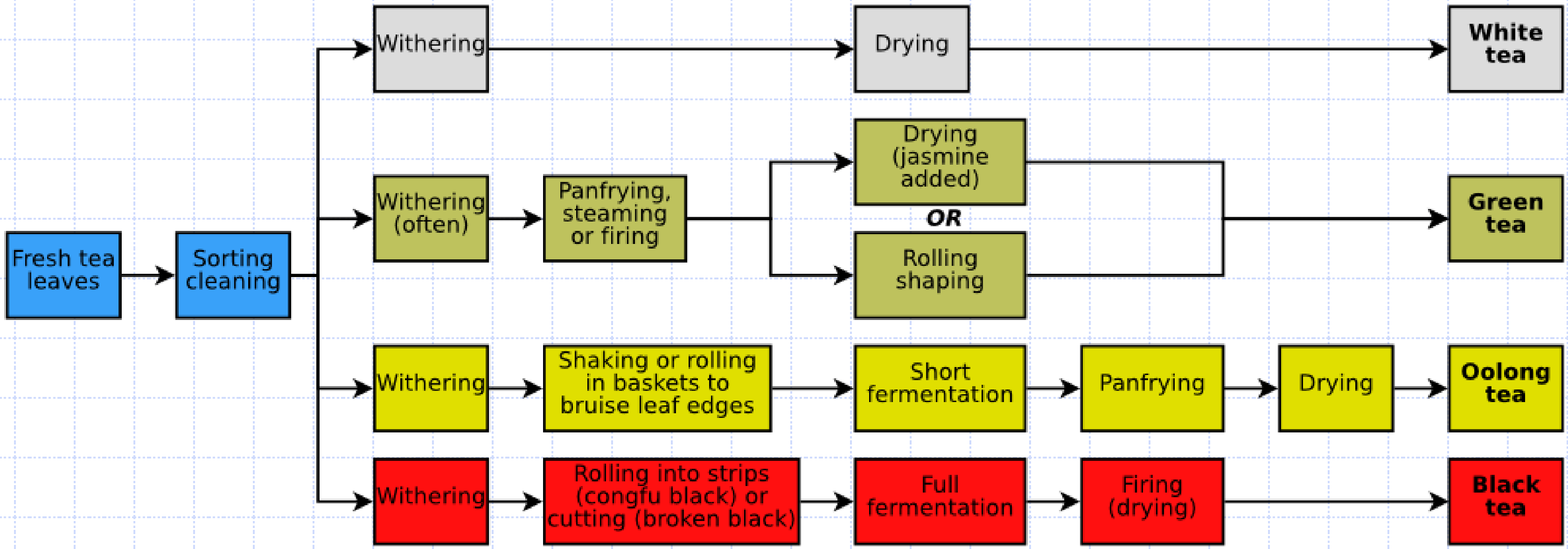
- Geography could affect:
  - Regional emissions factors
  - Technology choice
  - Operational requirements
  - Transportation
  - Potential emissions / impact of emissions
  - Transparency
  - …



Data Quality: Technology

- Different pathways to same product
  - Main technology and supporting technologies
- Possible criteria:
  - Specific company
  - Specific technology/technologies
  - Average technology mix
  - Representative technology

Tea (Cameillia Sinensis) Processing Chart



Data Quality: Data Sources

- Trustworthy source?
- Peer reviewed?
- Underlying assumptions?
- Type of data?
  - Measured?
  - Estimated?
  - Calculated?
  - Aggregated?
- Selecting multiple sources (why?)
  - Careful! What is the original data source? (may not provide independent data points!)
- Common data-driven Mistakes
  - Using data that is inconsistent with targeted process
  - Developing internally inconsistent models
  - Treating missing data as zero
  - Treating highly uncertain data as zero
  - Treating analytical detection limits as detections

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Data sources

- Primary Data
- LCI Databases
- Government Sources
- Industry Reports
- Academic Literature
- Estimated

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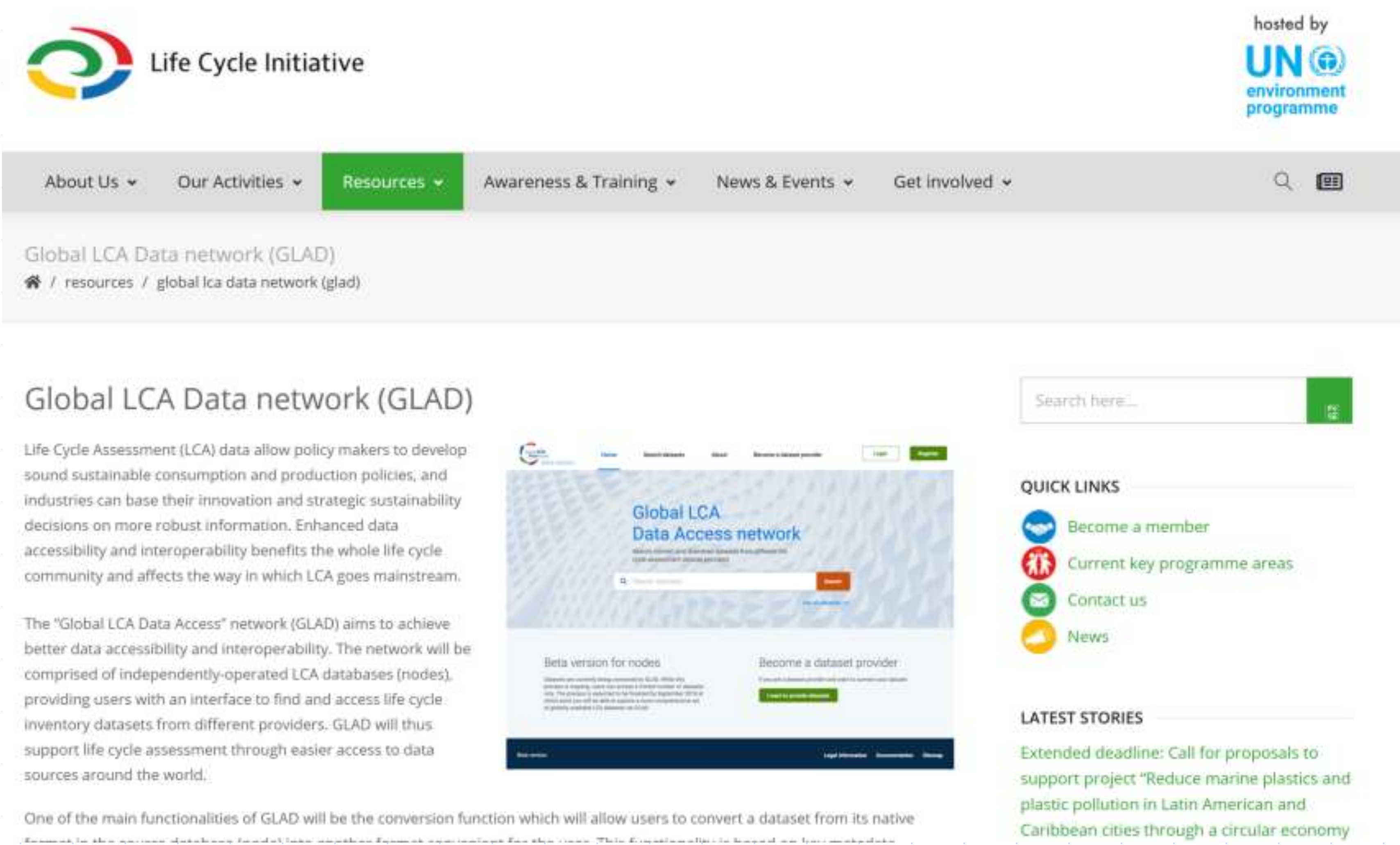
LCA Databases

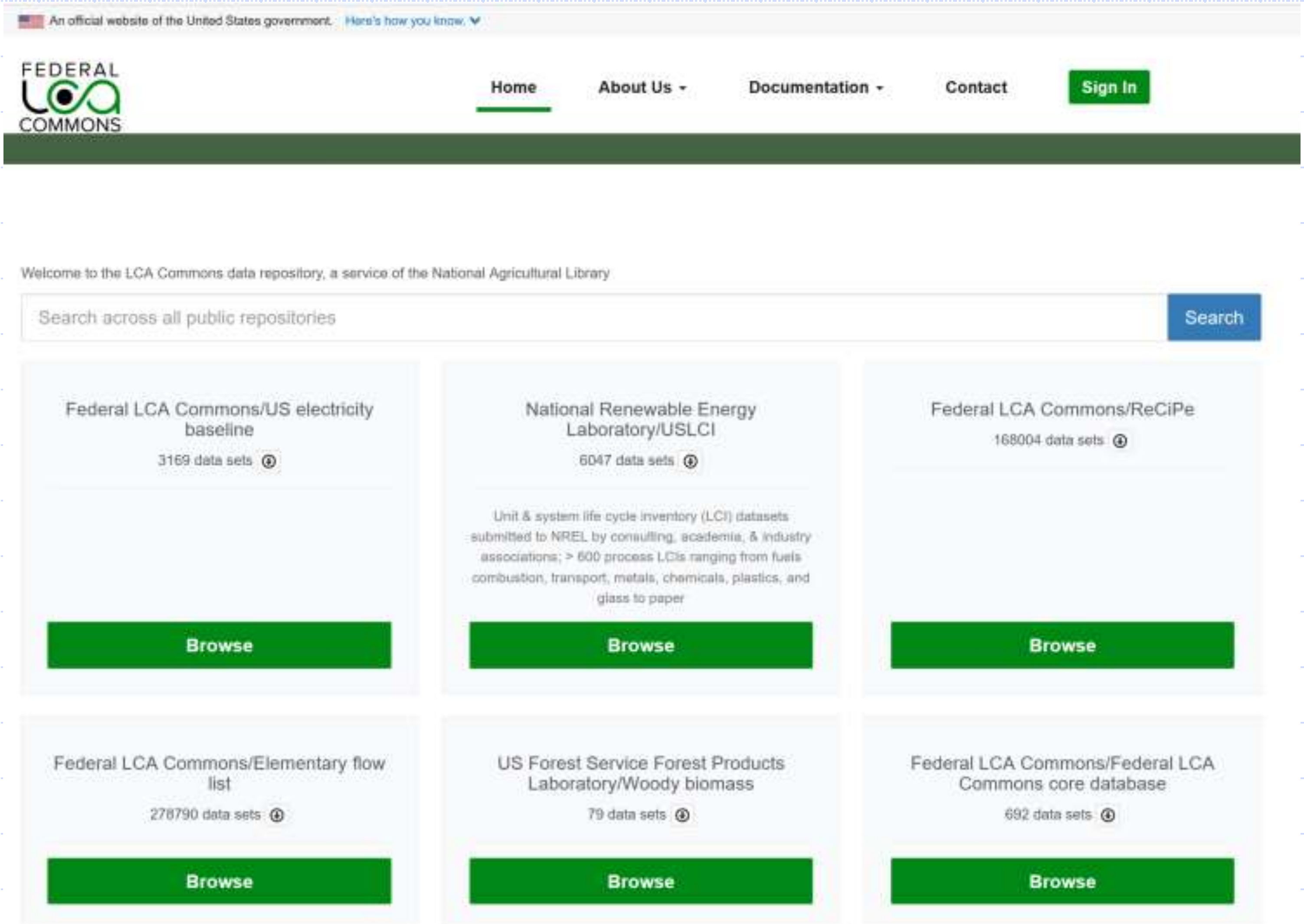
- Don't despair, you do not need to collect all of your own data for LCAs:
  - US NREL LCI Database (broad focus, using extensively, free)
  - Simapro databases (broad focus, using extensively under CMU license, $$, includes ecoinvent)
  - BEES (construction materials, free)
  - Athena (building materials, etc. $$)
  - GaBi ($$)
  - Eco Invent (free)
  - JRC EU commission (free)
  - UN Environmental programme: Global LCA Data network (free)

UN Environmental programme: Global LCA Data network



Federal LCA **Commons…**

- A central point of access to a collection of data repositories for use in Life Cycle Assessment



US NREL LCI Database

U.S. Life Cycle Inventory Database

NREL
Transforming ENERGY

» U.S. Life Cycle Inventory Database

- About the Project
- Federal Commons
- Life Cycle Assessments
- Related Links

NREL and its partners created the U.S. Life Cycle Inventory (USLCI) Database to help life cycle assessment practitioners answer questions about environmental impact.

The USLCI database provides individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the U.S.

U.S. Life Cycle Inventory Database

ACCESS DATABASE

For video tutorials on how to use the database, view the NREL U.S. Life Cycle Inventory Database Quick Help Series.

The USLCI database provides supporting information on GitHub with links to many resources related to submission of data to and end-use of the USLCI Database, including:

- USLCI Data Submission Handbook (including metadata guidance)
- USLCI Database Archives (past release versions in various file formats)
- USLCI Release Change Log
- USLCI Update Press Release.

openLCA available databases: ecoinvent

openLCA Nexus

Your source for LCA and sustainability data.

Databases

- ecoinvent
- UVEK LCI Data
- The Evah Pigments Database
- LCA Commons (complete)
- Environmental Footprints
- IMPACT World+
- OzLCI2019
- idea
- Agri-footprint
- exiobase
- ARVI
- Agribalyse
- soca
- EuGeos' 15804-IA
- NEEDS
- PSILCA
- ESU World Food
- ELCD
- LC-Inventories.ch
- Social Hotspots
- ProBas
- bioenergiedat
- Ökobaudat
- openLCA LCIA methods

Info | Details | Documents

!!!Update!!!

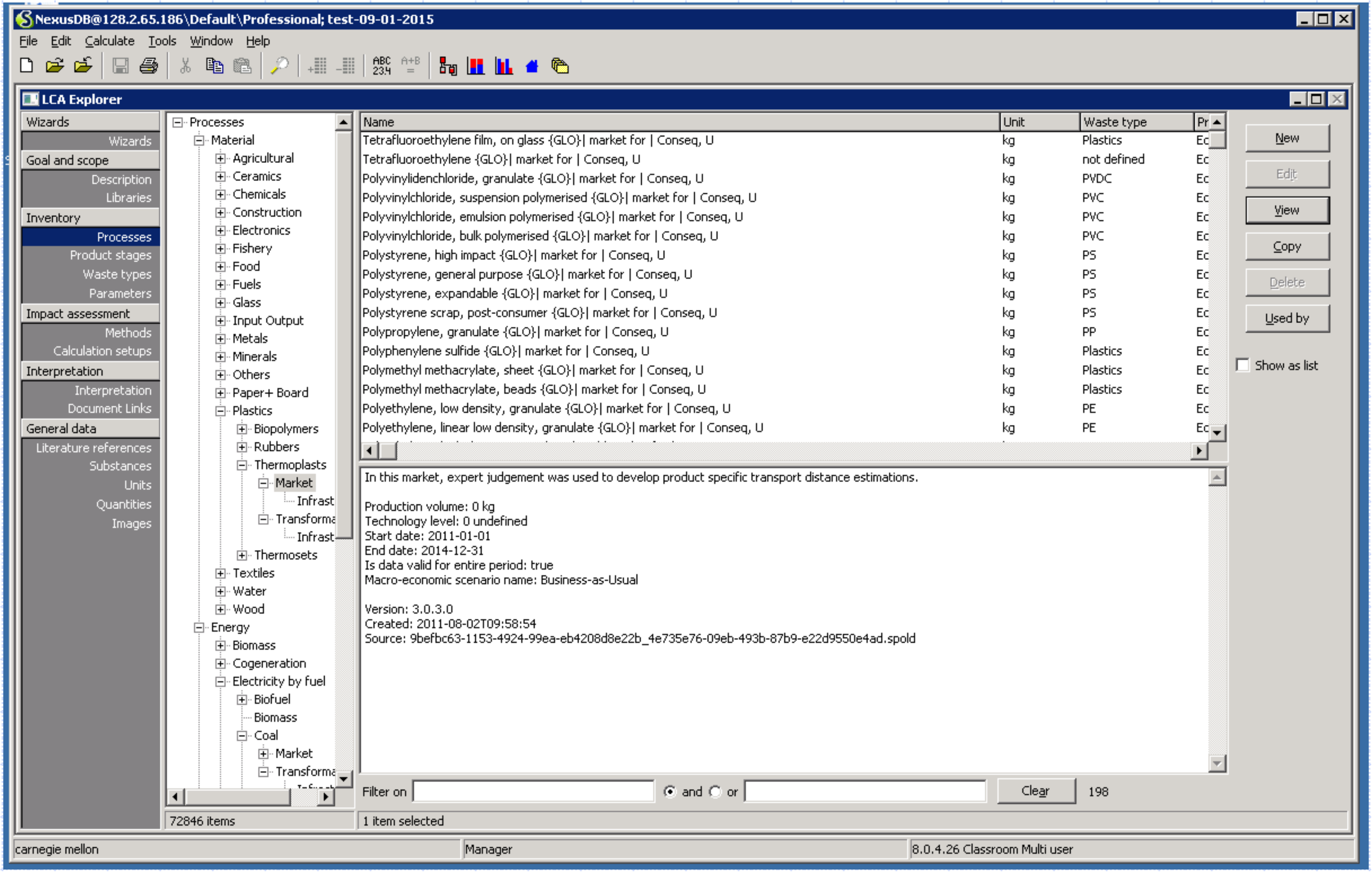
Releasing ecoinvent 3.7.1, an updated version of ecoinvent 3.7. The update rectifies two issues with version 3.7, for more details, please check ecoinvent website or you can also read the document on changes from 3.7 to 3.7.1 by clicking here.

A leading LCA database by the ecoinvent association, ecoinvent 3.7.1, the seventh update of ecoinvent version 3, includes more than 900 new datasets, among them 100 new products, and 1000 updated datasets. The new data covers: agriculture, building and construction materials, chemicals, electricity, fishing, metals, refineries, textiles, tourism, transport, waste treatment and recycling, and water supply.

We offer a fully valid ecoinvent licence with full access to the ecoinvent website and with databases specifically adapted to openLCA.

Ordering databases is also possible outside of Nexus. Additional fees may apply. Please see here for more details. If you are interested, send us a message.

SimaPro


NexusDB@128.2.65.186\Default\Professional; test-09-01-2015
File Edit Calculate Tools Window Help
LCA Explorer
Wizards
Goal and scope
Description
Libraries
Inventory
Processes
Product stages
Waste types
Parameters
Impact assessment
Methods
Calculation setups
Interpretation
Document Links
General data
Literature references
Substances
Units
Quantities
Images
Processes
Material
Agricultural
Ceramics
Chemicals
Construction
Electronics
Fishery
Food
Fuels
Glass
Input Output
Metals
Minerals
Others
Paper+ Board
Plastics
Biopolymers
Rubbers
Thermoplasts
Market
Thermosets
Textiles
Water
Wood
Energy
Biomass
Cogeneration
Electricity by fuel
Biofuel
Biomass
Coal
Market
Name
Unit
Waste type
Tetrafluoroethylene film, on glass {GLO}| market for | Conseq, U
Tetrafluoroethylene {GLO}| market for | Conseq, U
Polyvinylidenchloride, granulate {GLO}| market for | Conseq, U
Polyvinylchloride, suspension polymerised {GLO}| market for | Conseq, U
Polyvinylchloride, emulsion polymerised {GLO}| market for | Conseq, U
Polyvinylchloride, bulk polymerised {GLO}| market for | Conseq, U
Polystyrene, high impact {GLO}| market for | Conseq, U
Polystyrene, general purpose {GLO}| market for | Conseq, U
Polystyrene, expandable {GLO}| market for | Conseq, U
Polystyrene scrap, post-consumer {GLO}| market for | Conseq, U
Polypropylene, granulate {GLO}| market for | Conseq, U
Polyphenylene sulfide {GLO}| market for | Conseq, U
Polymethyl methacrylate, sheet {GLO}| market for | Conseq, U
Polymethyl methacrylate, beads {GLO}| market for | Conseq, U
Polyethylene, low density, granulate {GLO}| market for | Conseq, U
Polyethylene, linear low density, granulate {GLO}| market for | Conseq, U
New
Edit
View
Copy
Delete
Used by
Show as list
In this market, expert judgement was used to develop product specific transport distance estimations.
Production volume: 0 kg
Technology level: 0 undefined
Start date: 2011-01-01
End date: 2014-12-31
Is data valid for entire period: true
Macro-economic scenario name: Business-as-Usual
Version: 3.0.3.0
Created: 2011-08-02T09:58:54
Source: 9befbc63-1153-4924-99ea-eb4208d8e22b_4e735e76-09eb-493b-87b9-e22d9550e4ad.spold
Filter on
and
or
Clear
198
72846 items
1 item selected
carnegie mellon
Manager
8.0.4.26 Classroom Multi user

Data Sources - Heart of Tools

- All 'tools' such as SimaPro are 'front ends' to databases
  - Aggregate and calculate inventories
  - Do impact assessment
- The data is the important part
- The interface is just there to help
- Examine data documentation and metadata to get what you need

Metadata in NREL USLCI

Details for Polylactide Biopolymer Resin, at plant

Return to Results List

Activity | Modeling | Administrative | Exchanges

Name	Polylactide Biopolymer Resin, at plant
Category	Chemical Manufacturing - Plastics Material and Resin Manufacturing
Description	Data has been peer reviewed by Dr. I. Boustead from Boustead Consulting, UK. Data only represents Ingeo polylactide (PLA) resin production by NatureWorks LLC in Blair Nebraska and cannot be used for PLA production in general. Final review report is attached to the Data Module Report.
Location	RNA (RNA)
Geography Comment	North America
Infrastructure Process	False
Quantitative Reference	Polylactide Biopolymer Resin, at plant
Start Date	2009-01-01
End Date	2009-01-01
Time description	
Technology Description	Ingeo Polylactide polymer production technology developed by NatureWorks LLC

Metadata in NREL USLCI (continued)

Activity | Modeling | Administrative | Exchanges

LCI Method

Modelling constants

Data completeness

Data selection

Data treatment

Sampling procedure

Data collection period

Reviewer

Other evaluation

Sources

E.T.H. Vink 2004 The life cycle of NatureWorks® Polylactide, Corn production inventory data and corn production eco-profile

H. Shapouri 2002 The Energy Balance of Corn Ethanol: An Update, U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, Agricultural Economic Report No. 814,

E.T.H. Vink 2006 The life cycle of NatureWorks® Polylactide, The production of dextrose via corn wet milling

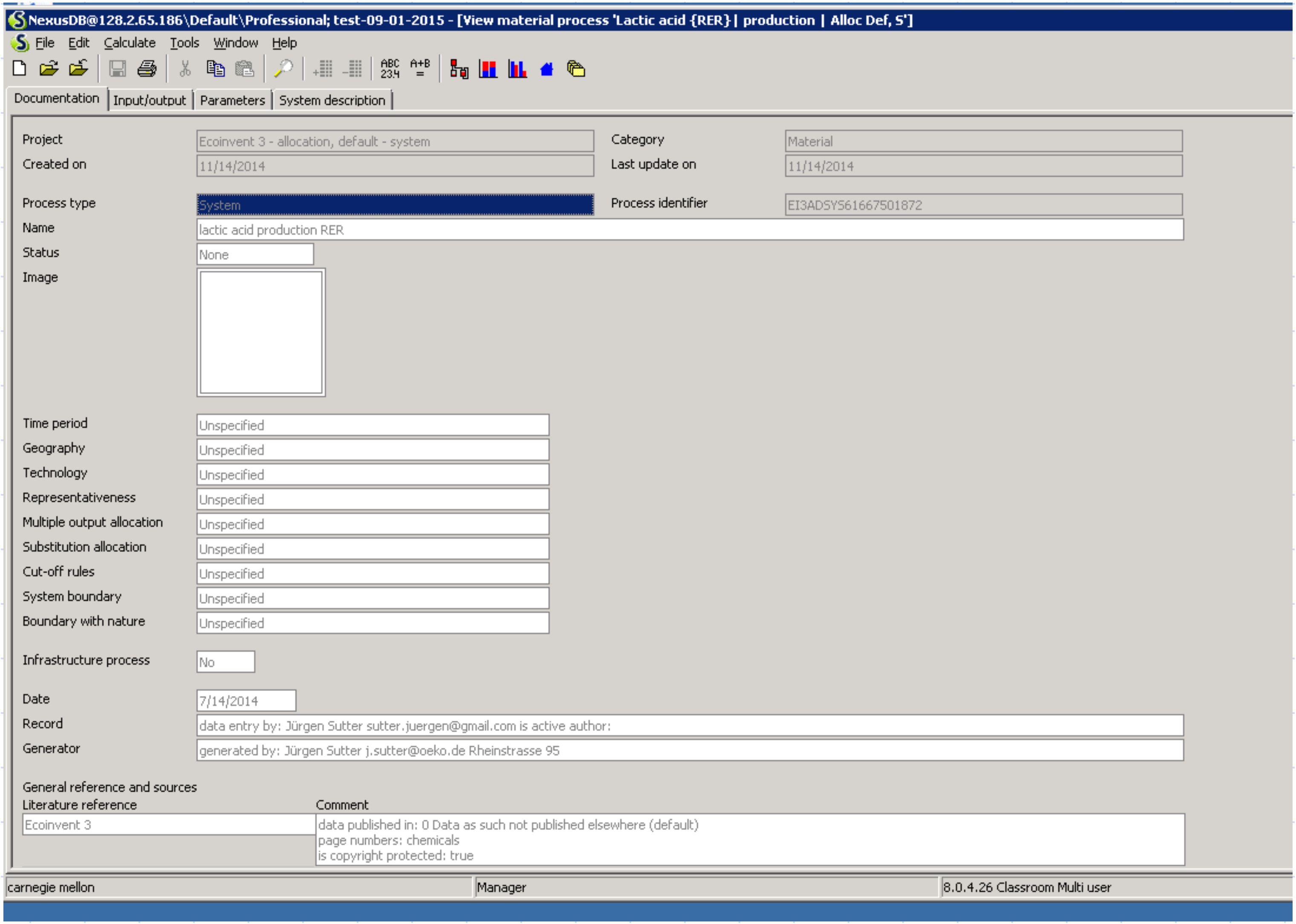
E.T.H. Vink 2005 Applications of life cycle assessment to NatureWorksTM polylactide (PLA) production.

P. Gruber 2002 Polylactides "NatureWorksTM PLA. In: Biopolymers in 10 volumes, Volume 4, Polyesters III, Applications and Commercial Products

E.T.H. Vink 2007 The eco-profiles for current and near future NatureWorks® polylactide (PLA) production

I. Boustead 2007 Peer review report

Metadata in SimaPro



Metadata in SimaPro (continued)

Documentation | Input/output | Parameters | System description

Collection method	sampling procedure: Literature data
Data treatment	extrapolations: This dataset has been extrapolated from year 2010 to the year of the calculation (2014). The uncertainty has been adjusted accordingly.
Allocation rules	
Verification	

Comment

Lactic acid and some of its derivatives (salts and esters) are used in three main applications: foods, polymers, and industrial.

Food Uses
The food industry is the traditional large consumer of lactic acid and lactate salts. It is mainly used as an acidulant and preservative. Lactic acid has a mild acid taste and does not overpower weaker aromatic flavors. Since it occurs naturally, it does not introduce a foreign element into the food, and its salts are very soluble, thus giving the possibility of partially replacing the acid in buffering systems. Lactic acid and its salts are used in a variety of beverages, candies, meat, and sauces.
Calcium lactate can be used in a variety of foods to make a calcium-enhanced product. Steroyl lactate and its sodium and calcium salts are used in bread.

Polymers
The fastest growing use for lactic acid is its use as a monomer for the production of polylactic acid or polylactide (PLA). NatureWorks LLC produces PLA via ring-opening polymerization of lactide [53]. Lactide is made by condensation of two lactic acid entities. Applications for PLA include containers for the food and beverage industries, films and rigid containers for packaging, and serviceware (cups, plates, utensils). The PLA polymer can also be spun into fibers and used in apparel, fiberfill (pillows, comforters), carpet, and nonwoven applications such as wipes.

Industrial Uses
There are a variety of industrial uses for lactic acid and its derivatives. It is used in metal plating, cosmetics, and the textile and leather industry. Lactate esters are used in the manufacture of paints and inks, electronics, and metal cleaning. Agricultural uses include animal feed.

Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007) Overview and Methodology. Final report ecoinvent v2.0 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Gendorf (2000) Umwelterklärung 2000, Werk Gendorf. Werk Gendorf, Burgkirchen as pdf-File under: http://www.gendorf.de/pdf/umwelterklaerung2000.pdf

Surinder P. Chahal/John N. Starr: Lactic Acid. Published online: 2006. In: Ullmann's Encyclopedia of Industrial Chemistry, Seventh Edition, 2004 Electronic Release (ed. Fiedler E., Grossmann G., Kersebohm D., Weiss G. and Witte C.). 7 th Electronic Release Edition. Wiley InterScience, New York, Online-Version under: DOI: 10.1002/14356007.a15_097.pub2

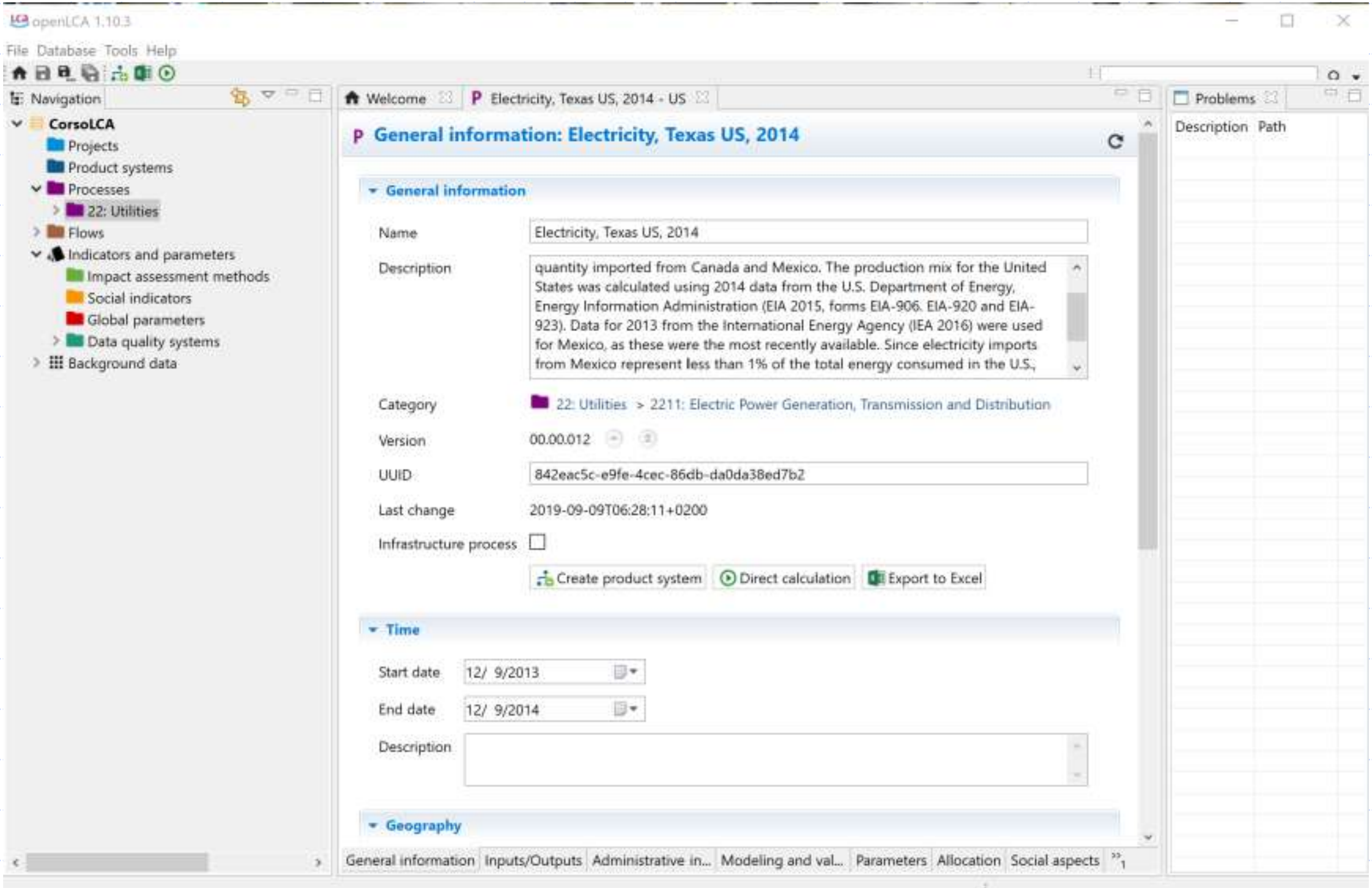
The process "lactic acid , at plant, RER" is modelled for the production of lactic acid from acetaldehyde in Europe. Raw materials are modelled with a stoechiometric calculation. Emissions are estimated. Energy consumptions, infrastructure and transports are calculated with standard values.

Lactic acid (CH3CH(OH)COOH; CAS 50-21-5, 2-hydroxypropionic acid) is the simplest hydroxycarboxylic acid with an asymmetrical carbon atom. It occurs as a racemate (dl) and in two optically active forms, l-(+)-lactic acid and d-(–)-lactic acid. Lactic acid is produced on an industrial scale by fermentation or a synthetic method. Since ca. 1995, all new lactic acid production capacity has employed the fermentation approach because it produces lactic acid with high chiral purity that is needed for the food and polymer markets.

Synthesis of Lactic Acid
Since the 1960s, racemic lactic acid has also been produced via synthetic routes. The present industrial synthesis of lactic acid is based on the reaction of acetaldehyde with hydrogen cyanide followed by the hydrolysis of the resultant lactonitrile:

Production volume: 5000000 kg
Included activities end: production of lactic acid including materials, energy uses, infrastructure, and emissions
Energy values: Undefined (default)
Geography: The inventory is modelled for Europe.
Technology level: 3 Current (default)
Technology: hydrolysis of lactonitrile

Metadata in openLCA



What you can get from these tools

- Key inputs / outputs
- Unit process emissions and other inventory data
- Life-cycle emissions and other inventory data
- Data sources
- Impact Assessment

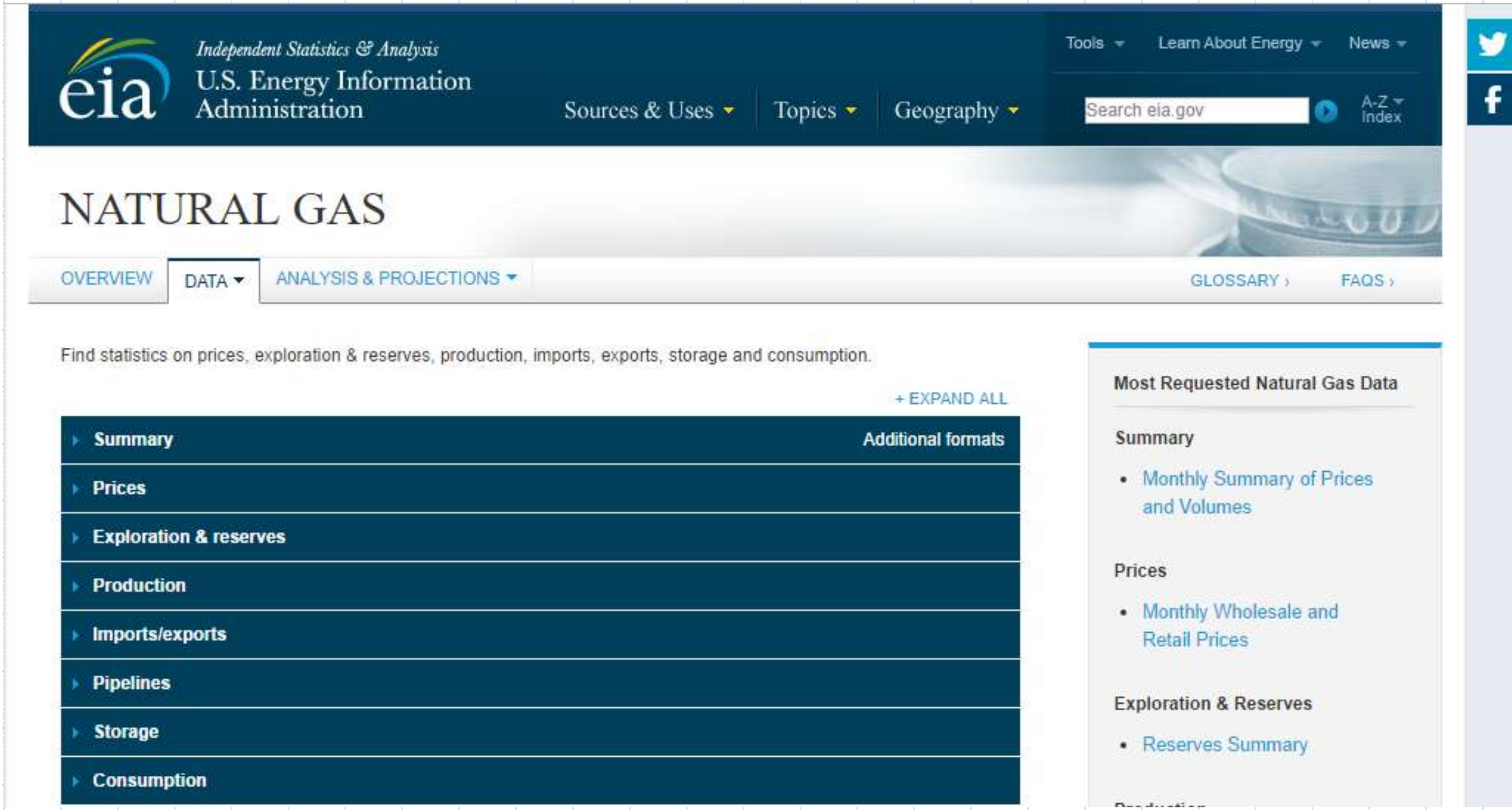
Data sources

- Primary Data
- LCI Databases
- Government Sources
- Industry Reports
- Academic Literature
- Estimated

Government Sources

- Government databases are an excellent source of up-to-date information
- There is no central/comprehensive list of where to look.
  - Let's look at some examples

U.S. EIA: Fossil Fuel Data



http://www.eia.gov/naturalgas/data.cfm

U.S. EIA: Fossil Fuel Data (continued)

NATURAL GAS

OVERVIEW | DATA ▾ | ANALYSIS & PROJECTIONS ▾

Natural Gas Gross Withdrawals and Production

(Volumes in Million Cubic Feet)

Area: U.S. ▾ **Period-Unit:** Annual-Million Cubic Feet ▾

Download Series History Definitions, Sources & Notes

Show Data By: ◉ Data Series ○ Area	Graph Clear	2010	2011	2012	2013	2014	2015	View History
Gross Withdrawals		26,816,085	28,479,026	29,542,313	29,522,551	31,405,381	32,894,727	1936-2015
From Gas Wells		13,247,498	12,291,070	12,504,227	10,759,545	10,123,418	9,784,840	1967-2015
From Oil Wells		5,834,703	5,907,919	4,965,833	5,404,699	5,999,955	6,452,680	1967-2015
From Shale Gas Wells		5,817,122	8,500,983	10,532,858	11,932,524	13,974,936	15,475,887	2007-2015
From Coalbed Wells		1,916,762	1,779,055	1,539,395	1,425,783	1,307,072	1,181,320	2002-2015
Repressuring		3,431,587	3,365,313	3,277,588	3,331,456	3,291,091	3,410,693	1936-2015
Vented and Flared		165,928	209,439	212,848	260,394	293,916	278,623	1936-2015
Nonhydrocarbon Gases Removed		836,698	867,922	768,598	368,469	322,620	452,477	1973-2015
Marketed Production		22,381,873	24,036,352	25,283,278	25,562,232	27,497,754	28,752,935	1900-2015
Dry Production		21,315,507	22,901,879	24,033,266	24,205,523	25,889,605	27,059,503	1930-2015

Click on the source key icon to learn how to download series into Excel, or to embed a chart or map on your website.

\- = No Data Reported; -- = Not Applicable; **NA** = Not Available; **W** = Withheld to avoid disclosure of individual company data.

Notes: Beginning with monthly data for January 2006, "Other States" volumes include all of the natural gas producing states except: Alaska, Arkansas, California, Colorado, Kansas, Louisiana, Montana, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, Utah, West Virginia, Wyoming, and the Gulf of Mexico. Data for 2014 are estimated. Monthly preliminary (from January 2014 to present) state-level data for the production series, except marketed production, are not available until after the final annual reports for these series are collected and processed. Final annual data are generally available in the third quarter of the following year. For years prior to 2007, coalbed production data are included in Gas Well totals. For 2007-forward, gross production from coalbed methane and shale data are from PointLogic Energy. Prior to 1997, state production for Texas, Louisiana, and Alabama includes a portion of the Federal Offshore Gulf of Mexico production. Production for these states prior to 1997 excluding the Federal Offshore Gulf of Mexico can be found at the state energy data system (seds). See Definitions, Sources, and Notes link above for more information on this table.

Release Date: 01/31/2017
Next Release Date: 02/28/2017

EIA has an enormous amount of data on a large range energy-related topics

http://www.eia.gov/dnav/ng/ng_prod_sum_dcu_NUS_a.htm

U.S. EPA: eGRID

EPA United States Environmental Protection Agency

Environmental Topics | Laws & Regulations | About EPA | Search EPA.gov

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- Greenhouse Gas Equivalencies Calculator
- **eGRID**

Emissions & Generation Resource Integrated Database (eGRID)

The Emissions & Generation Resource Integrated Database (eGRID) is a comprehensive source of data on the environmental characteristics of almost all electric power generated in the United States. These environmental characteristics include:

- air emissions for nitrogen oxides, sulfur dioxide, carbon dioxide, methane, and nitrous oxide;
- emissions rates;
- net generation;
- resource mix; and
- many other attributes.

eGRID data can be used for the following activities:

- greenhouse gas registries and inventories,
- carbon footprints,
- consumer information disclosure,
- emission inventories and standards,
- power market changes, and
- avoided emission estimates.

Contact Us

- eGRID Release Notification
- Feedback or Questions
- Satisfaction Survey EXIT

Related Information

- FAQs
- Power Profiler
- Power Profiler Emissions Tool (XLS) (1 pg, 4 MB)
- Carbon Footprinting with eGRID

eGRID2014

Released: 1/13/2017

- eGRID2014 Data File (XLS) (1 pg, 14 MB)
- Technical Support Document (PDF)
- Summary Tables (PDF)
- Summary Tables (XLS) (1 pg, 2 MB)
- Subregion GHG output emission rates (PDF)
- eGRID2014 subregion map (JPG) (851K)
- NERC region map (JPG) (1137KB)
- eGRID2014 Release Notes (TXT) (1 pg, 4 K)

https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

U.S. EPA: Toxics Release Inventory

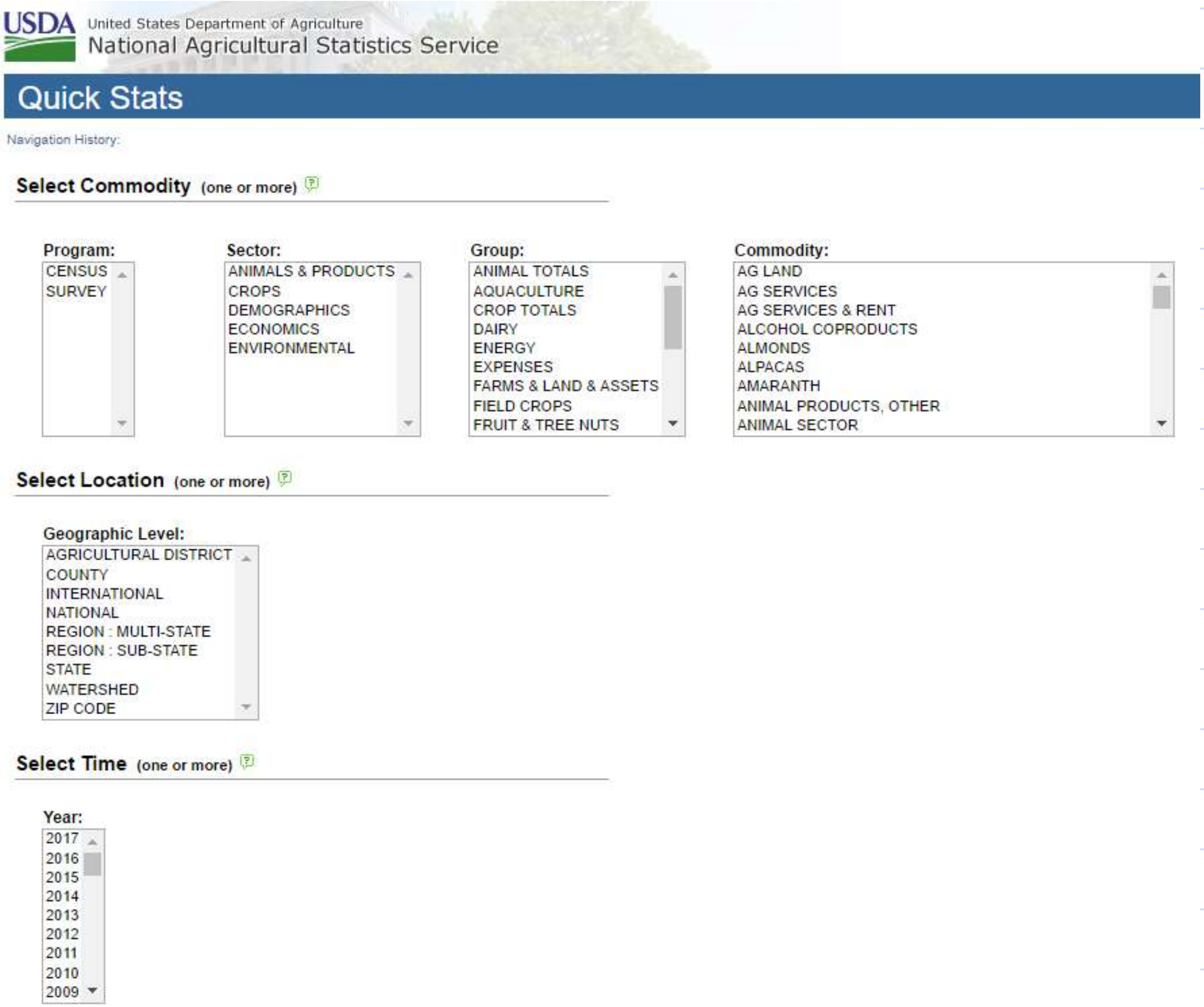
http://www2.epa.gov/toxics-release-inventory-tri-program

U.S. EPA: Greenhouse Gas Reporting Program

Note: EPA has an enormous amount of data spread across different programs

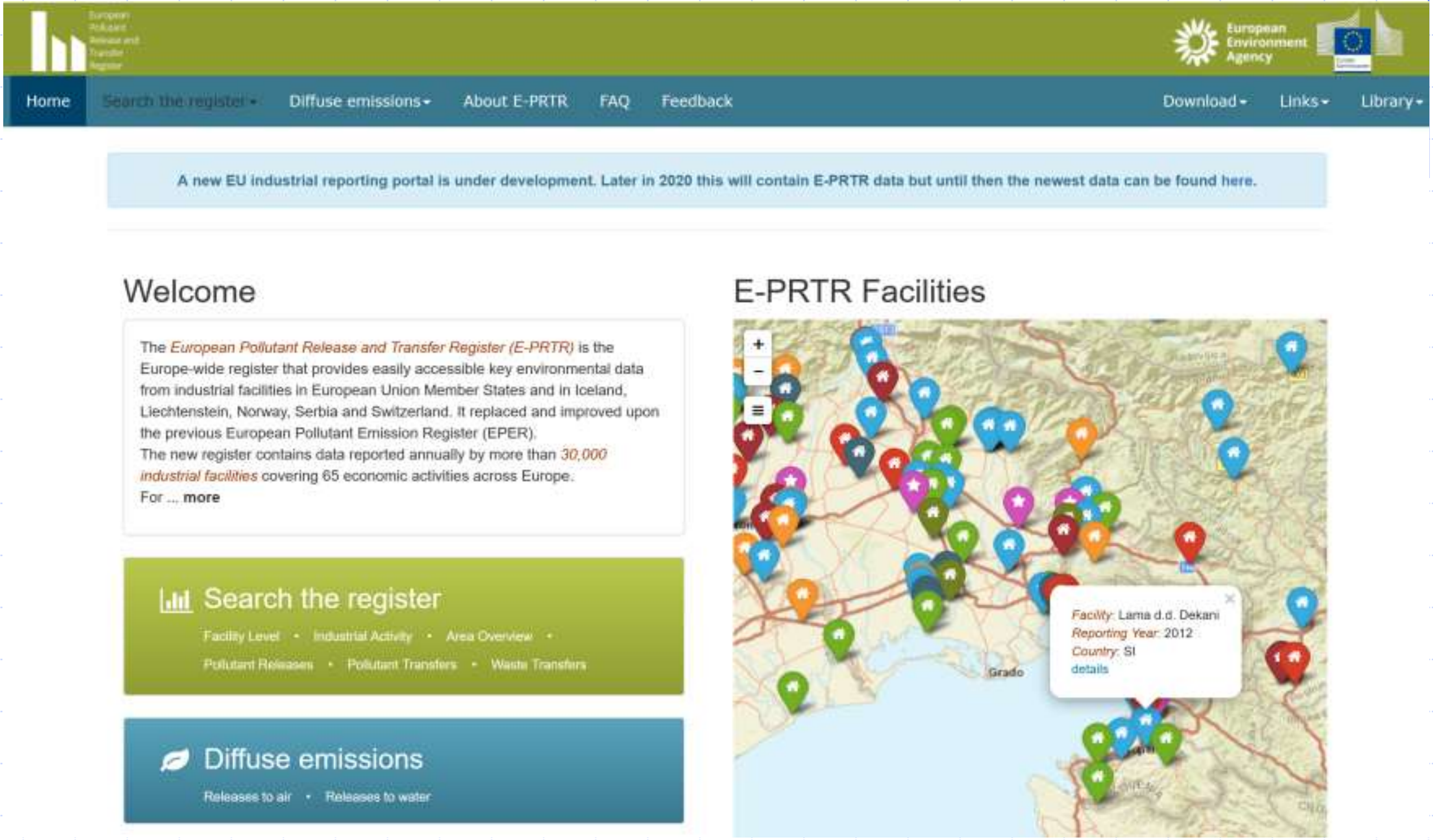
http://www.epa.gov/ghgreporting/

USDA: Quick Stats



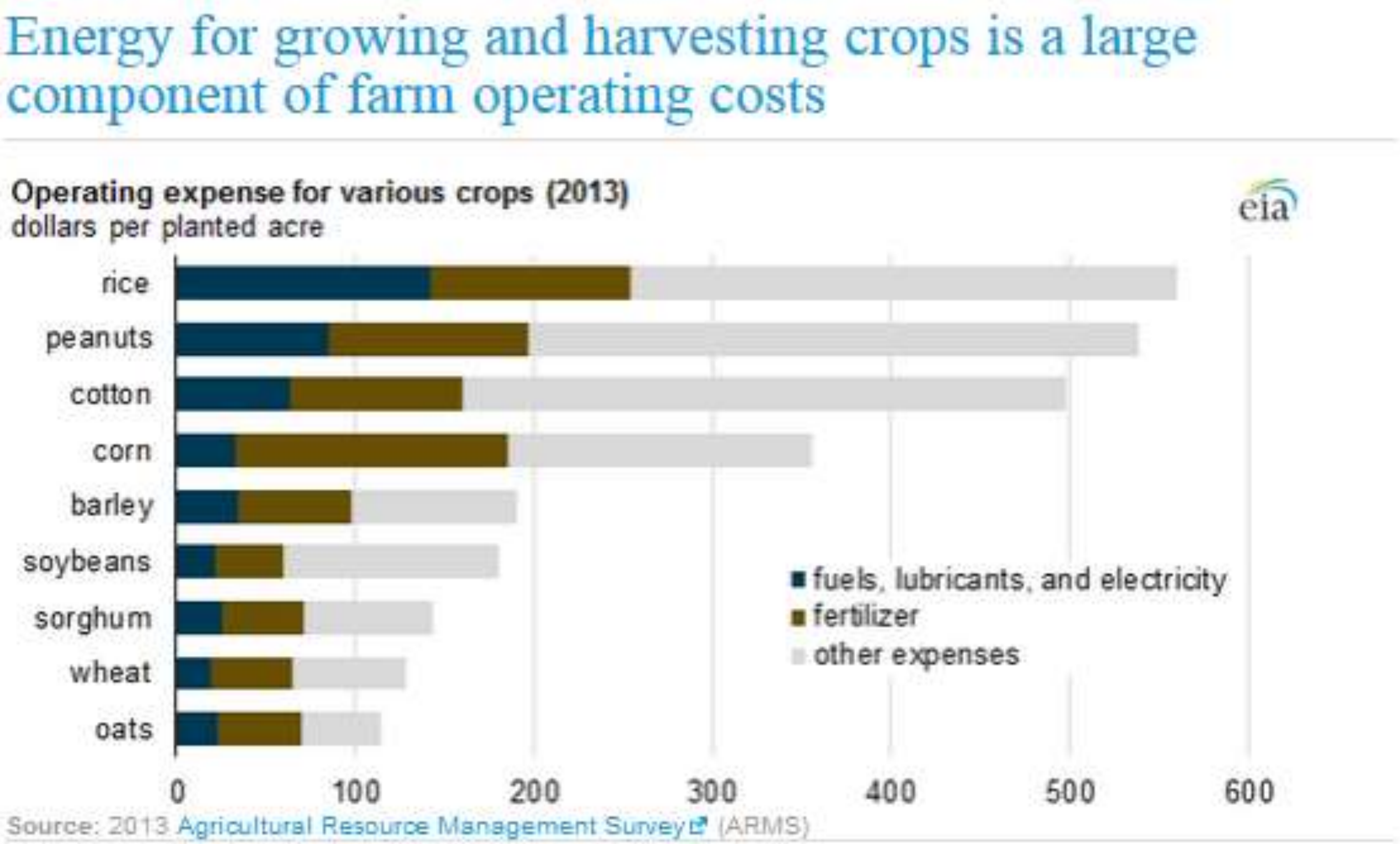
http://quickstats.nass.usda.gov/

European Pollutant Release and Transfer Register



Government Sources

- Lots of other sources
- Be creative!



Data sources

- Primary Data
- LCI Databases
- Government Sources
- Industry Reports
- Academic Literature
- Estimated

Data sources

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- Industry Reports
- Academic Literature
- Estimated

Academic Literature

- Academic literature is an important source of LCA information
  - Complete inventories from existing LCA studies
  - Inventories from unit processes
    - Can be useful even if study relates to a different system
  - Reporting of primary data not available elsewhere
  - Estimation of difficult parameters
    - May not necessarily be an LCA study
  - See how similar studies were scoped out
- Find using databases, Google Scholar, Web of Science, etc.
- CMU Library – Xiaoju (Julie) Chen is our resource!

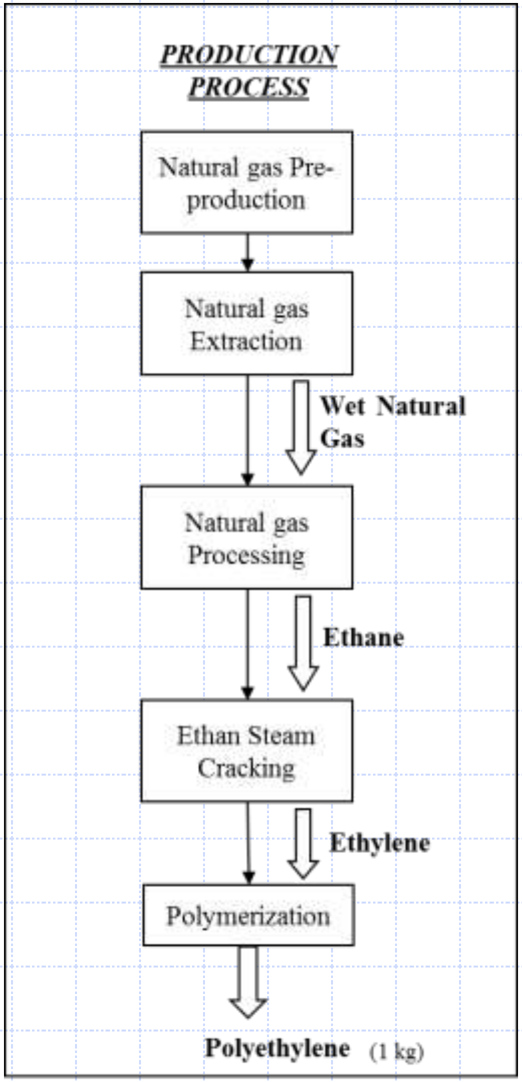
Data sources

- Primary Data
- LCI Databases
- Government Sources
- Industry Reports
- Academic Literature
- Estimated

Data "Collection"

- LCA rarely is primary data only
  - Usually have to use at least some secondary sources!
  - Many studies are 100% based on secondary sources
- This is usually the longest, most labor intensive part of an LCA study.

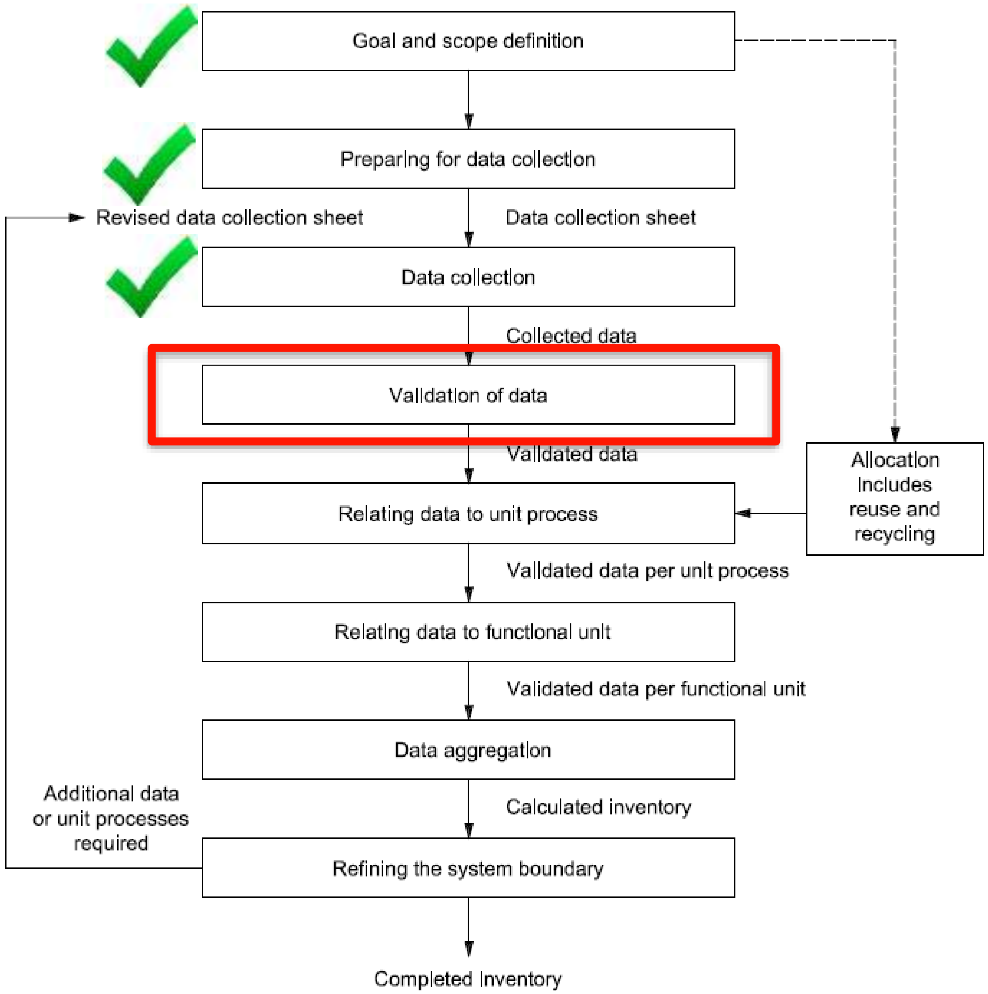
Example: Greenhouse Gas Emissions From Polyethylene Plastic Production



- Natural gas pre-production
  - literature value
- Natural gas extraction
  - direct from government data
- Natural gas processing
  - analysis of government data
- Steam cracking
  - estimated
- Polymerization
  - from LCA databases and industry reports
- End of life?

Posen *et al.* (2015). *Environ. Sci. Technol.* **49**(1): 93-102

Step 3: Data Validation

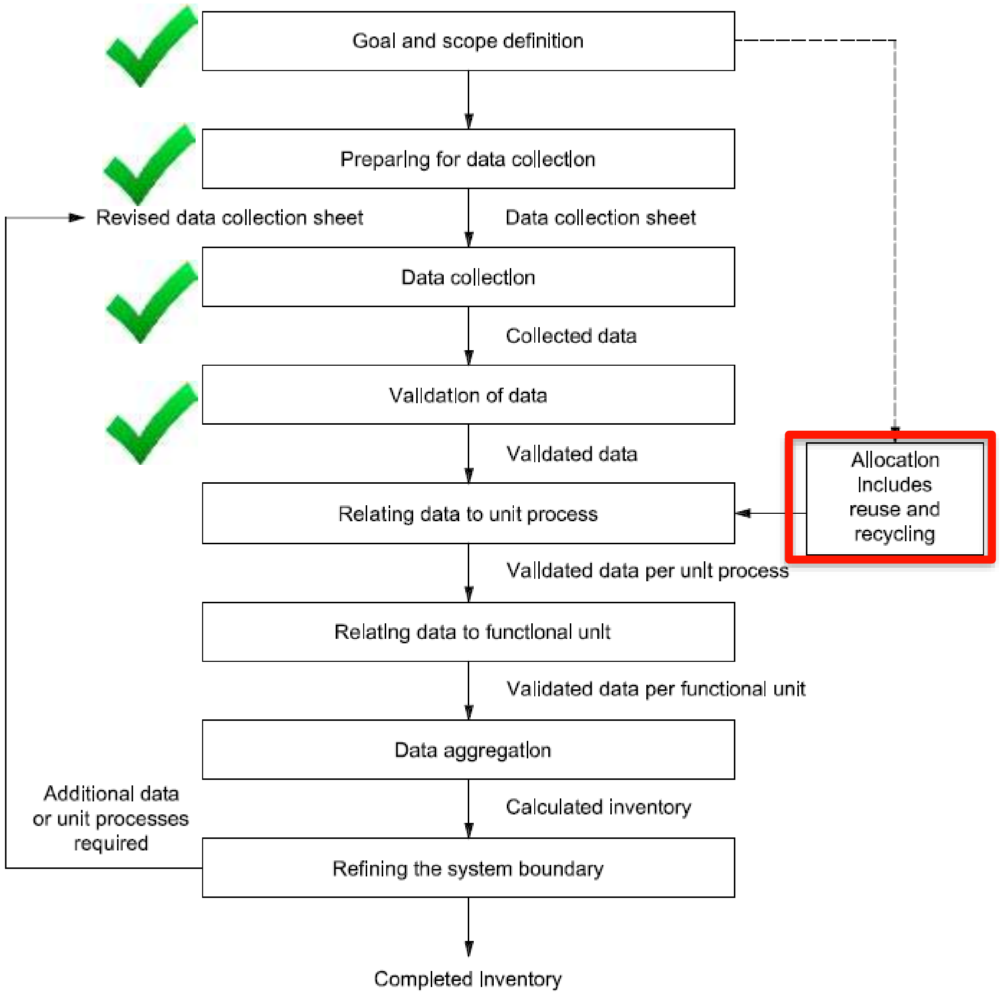


Data Validation

- After collecting data, pause, assess
  - Meeting data quality requirements?
  - Within range expected?
  - **Mass balance maintained?**
  - Comparable to other processes?
  - Modification of scope needed?
- Results go in your report

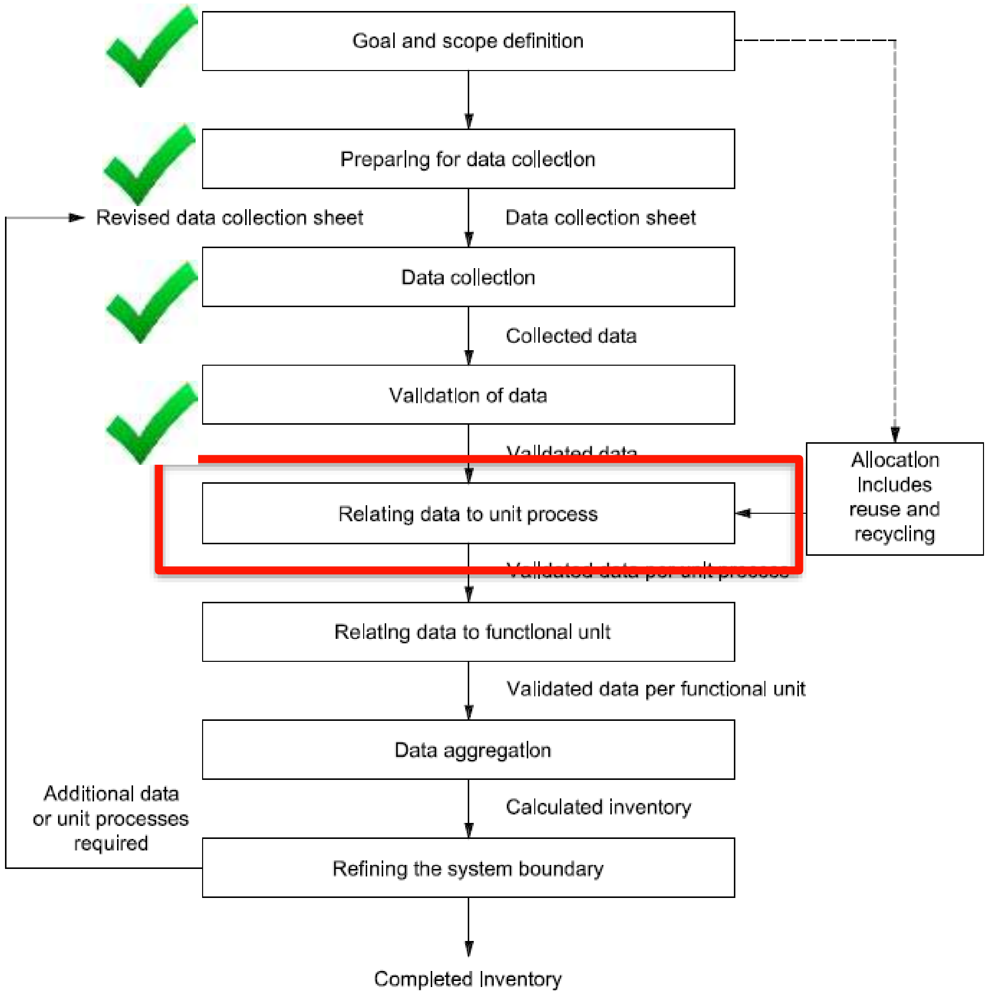
Step 4: data allocation (if needed)

ISO 14040: 5.3
ISO 14044: 4.3
(focus on 4.3.1-4.3.3 for now)



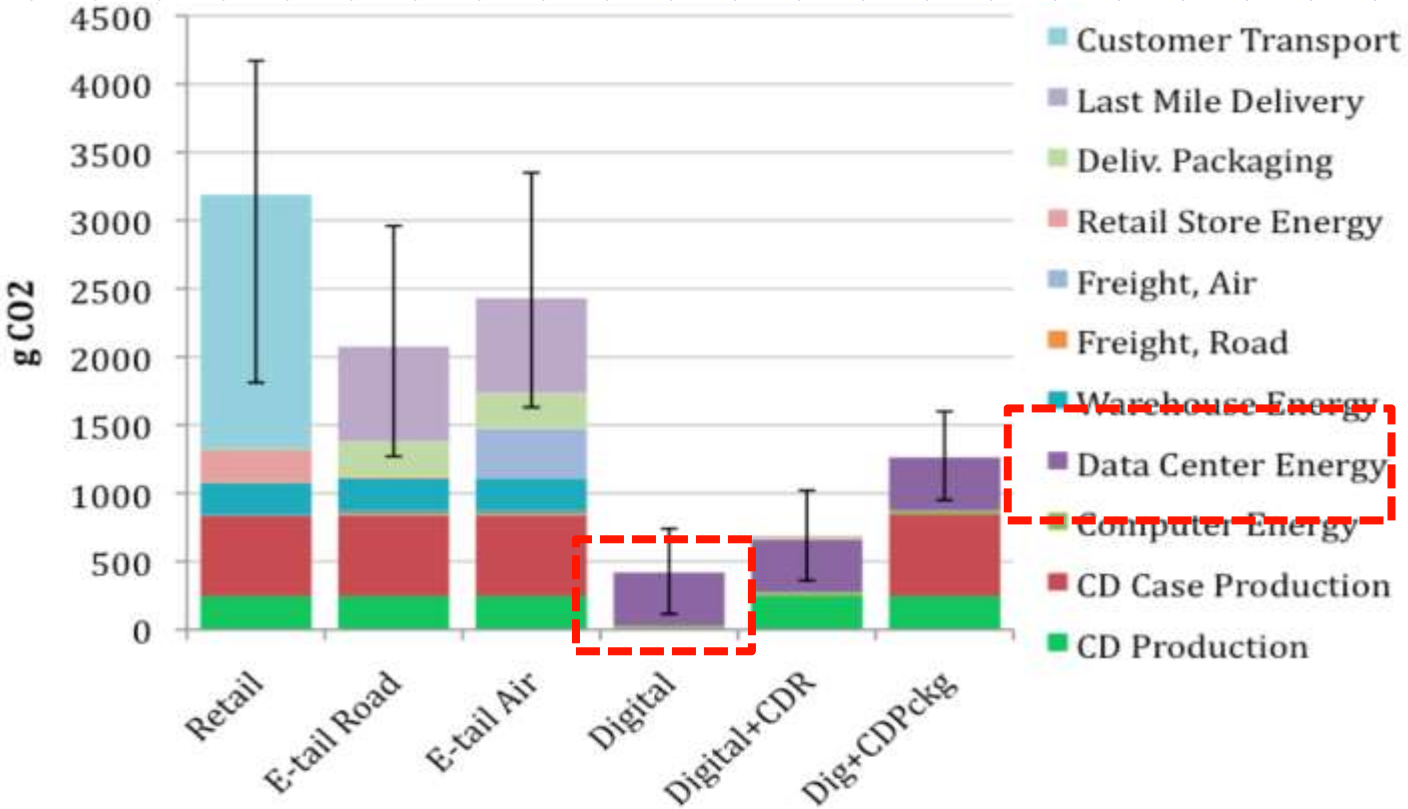
Step 4: relating data to unit process

ISO 14040: 5.3
ISO 14044: 4.3
(focus on 4.3.1-4.3.3 for now)



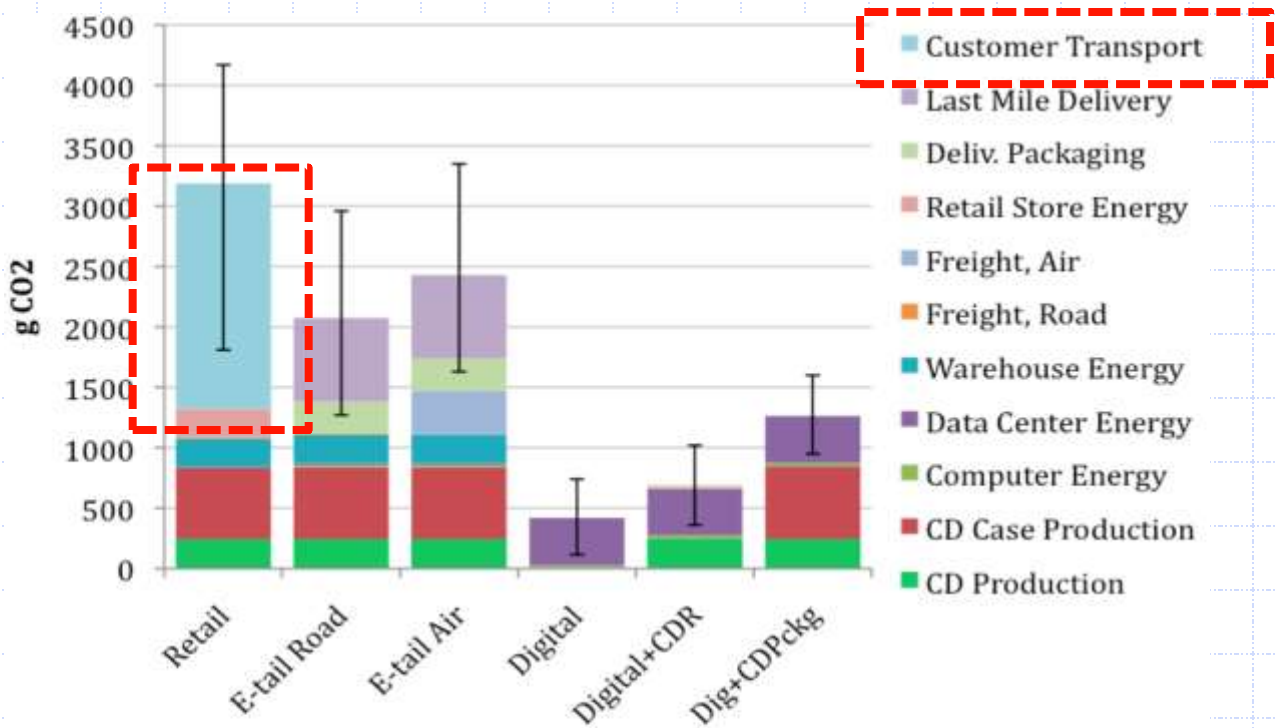
Example: Music Delivery Case Study

- a SW company decided to study energy and CO_2 impacts of downloading music
- Goal: Compare methods of delivering music to consumers
  - CDs vs. downloads
  - Additional distinction for CDs: buy at retail store or online
- CO_2 impact
  - Dematerialization increases environmental performance, partially offset by internet energy use



Discussion

- Sensitivity — what parameters could flip result
  - Retail with zero customer transport emissions (bicycle/walk)
  - 5 hours of web browsing for online shopping
  - 260 MB data transfer (lossless files)



Agenda

- Life cycle thinking
- Quantitative methods and life cycle cost analysis
- The ISO LCA standard
- Life cycle inventory
  - Data needs and data quality
  - Data sources
  - Handling multifunction systems (disaggregation and allocation)
  - Uncertainty
  - Input-output LCA
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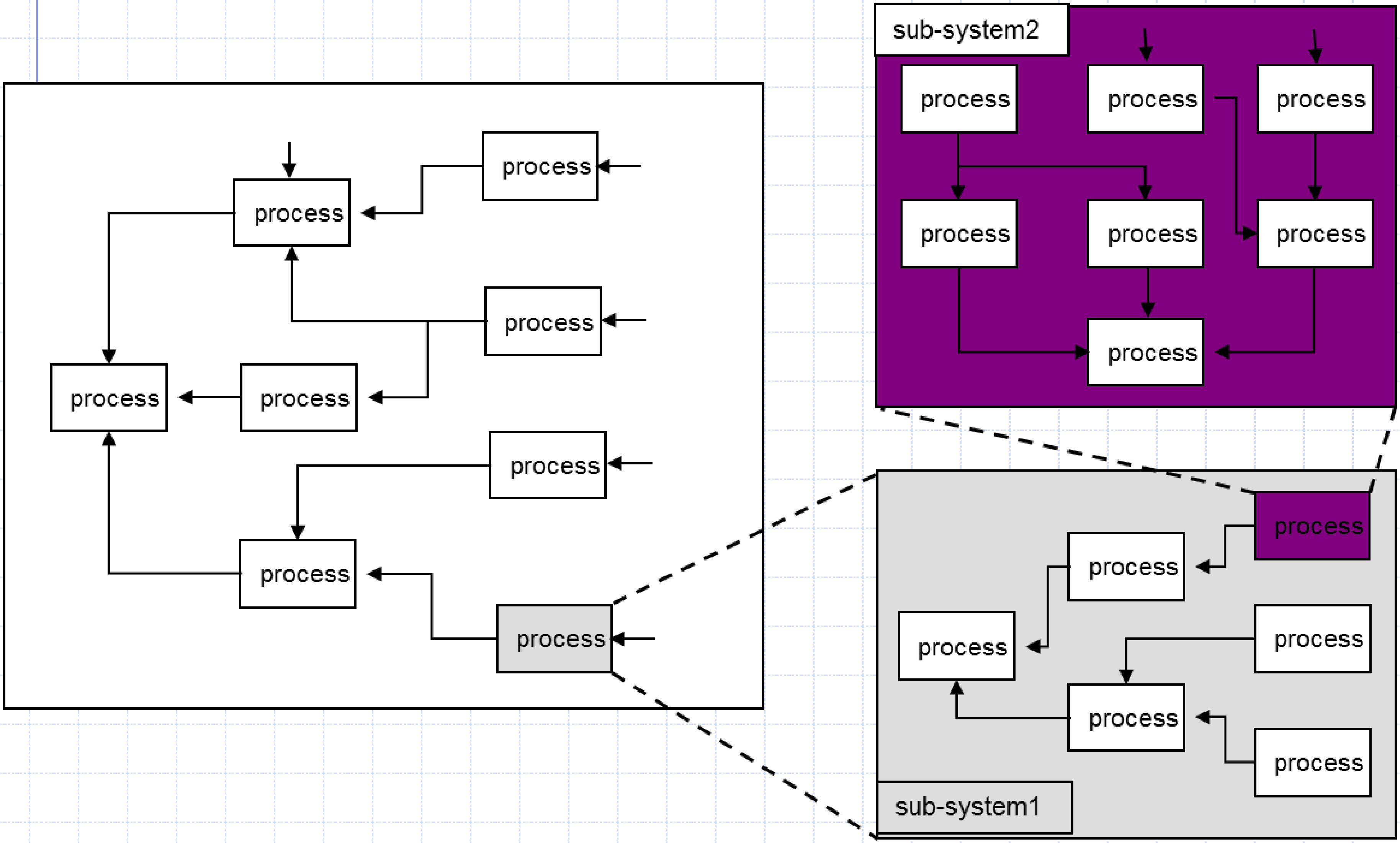
Life Cycle Inventory

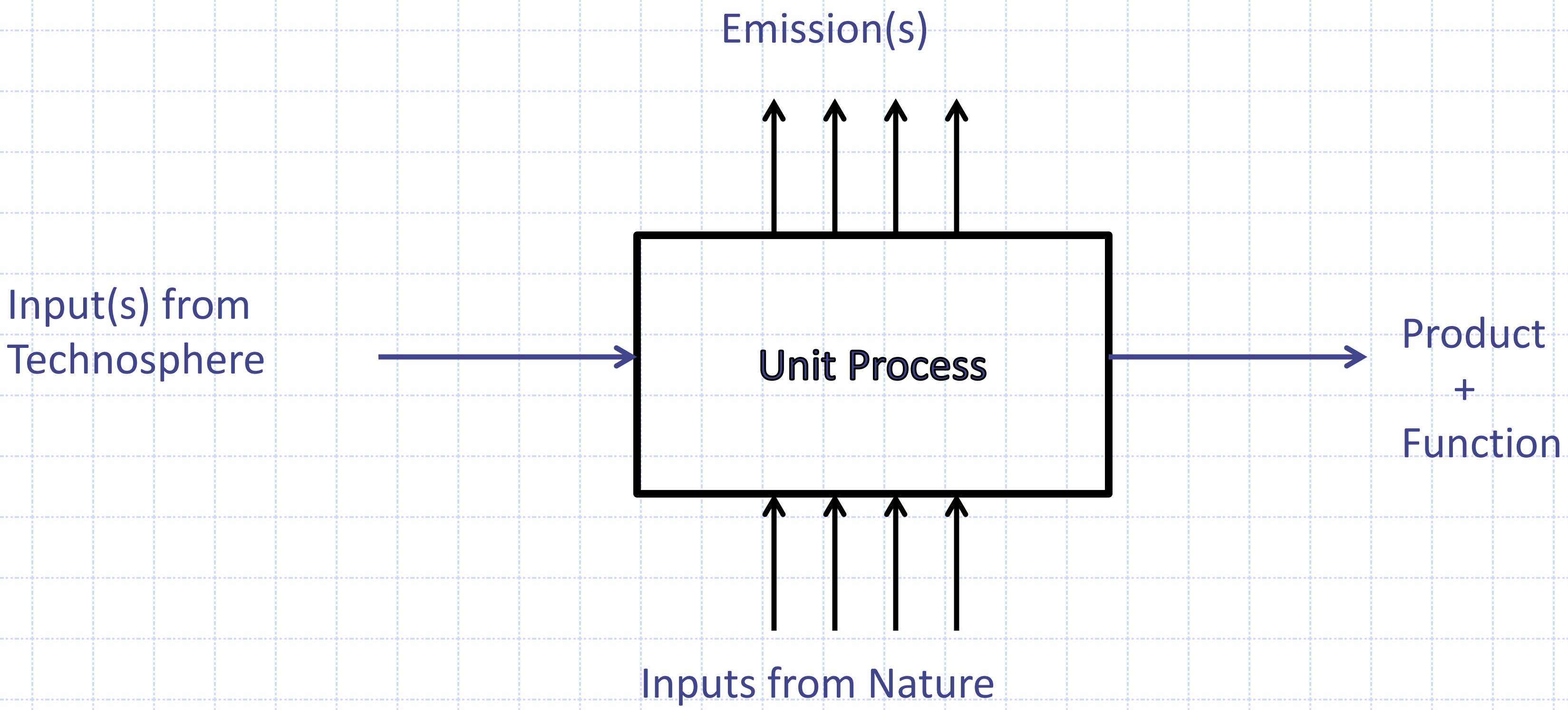
ISO 14040: 5.3
ISO 14044: 4.3
(focus on 4.3.1-4.3.3 for now)

Structure of a Process-based LCA Model



Typical Unit Processes

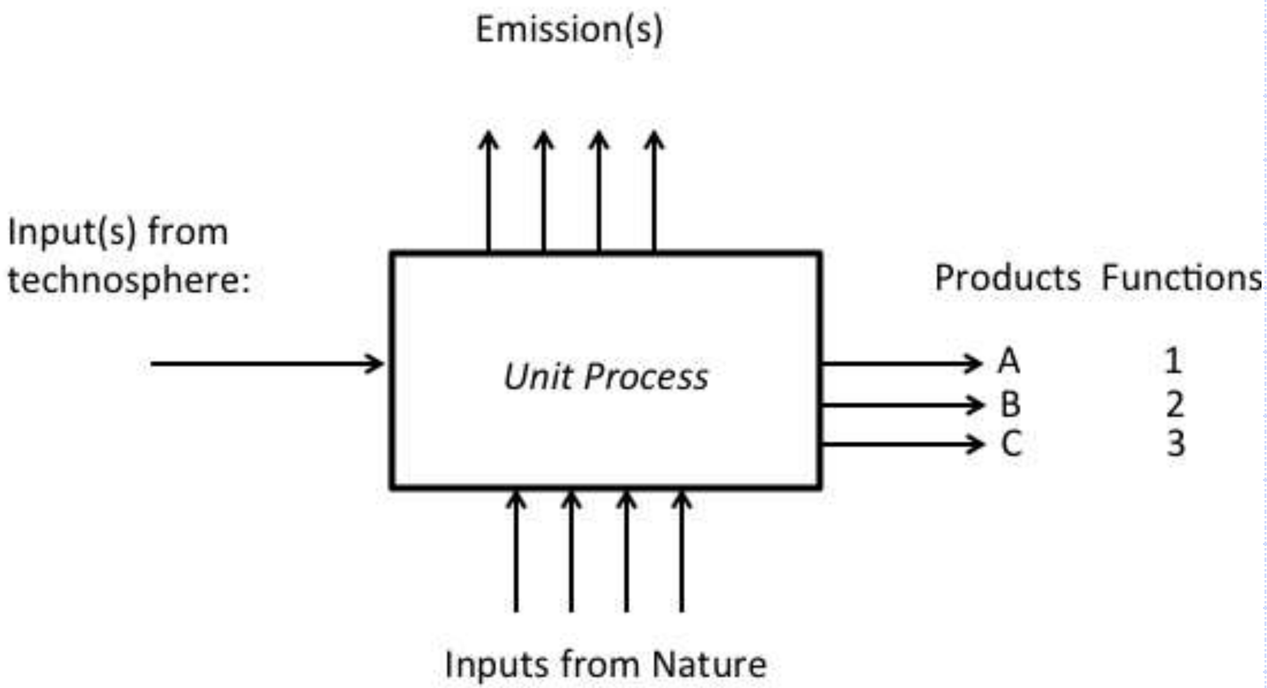
- For 1 product...



- With only one product, obvious and direct connection between that product and its input and output flows

Multifunction systems

- May be multiple products / co-products
- More importantly, may have multiple functions



- Then what?
  - The data will still be "overall at the total process level"
  - But we inevitably want it by function and/or product

ISO 14044:2006, 4.3.4.2

ISO Ranks Three Options

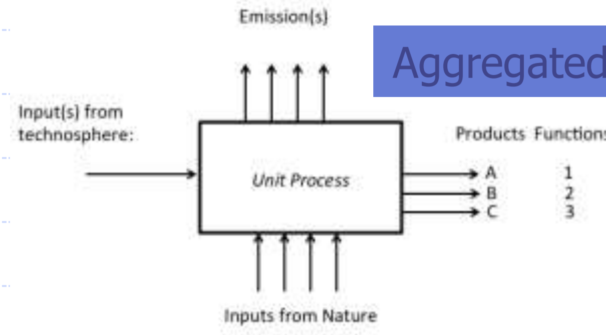
- Disaggregation
  - ISO prefers
- System expansion
  - "Changing the rules" by redefining the system boundary to avoid allocation
  - ISO encourages when disaggregation can't be done
- Allocation
  - Attributing the input and output flows via some mathematical relationship to the various products
  - ISO does not prefer

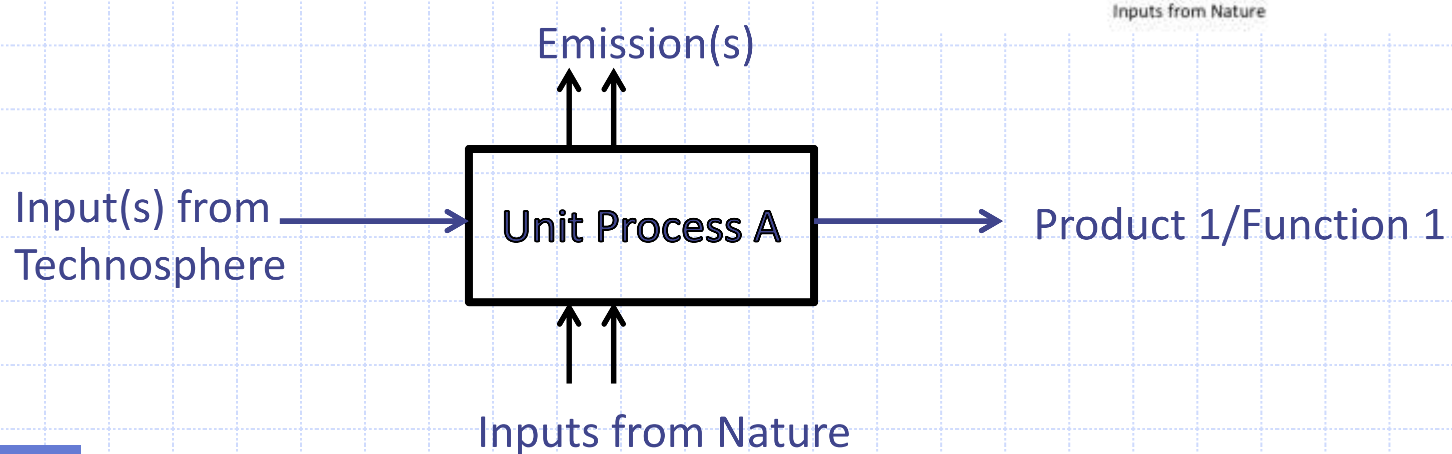
Disaggregation

- Zoom in as far as the data will let you
- Does more granularity let you isolate functions?

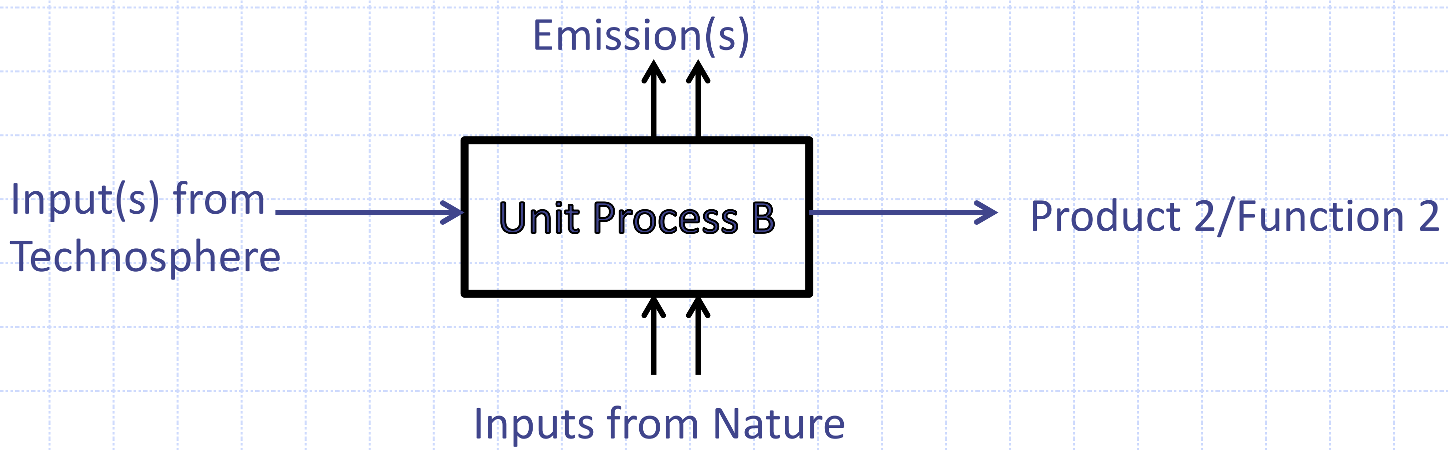
Do the data let you do this?

Aggregated





Disaggregated



Disaggregation challenge?

- Data at this fine level of detail may not exist
- Processes may be too intertwined to pull apart

- ISO suggests "system expansion" as the fallback approach
- If system expansion isn't possible, ISO grudgingly identifies "allocation" as an option
  - Different allocation methods give different results
  - Caveats, documentation, sensitivity analyses

Allocation Basics

- Need to assign inputs and/or outputs to the various products of the system
  - If only one product, don't need to allocate!
  - Must be documented/justified
  - Generally method (math) is simple – deriving allocation factors
  - ***Original in/out must equal sum of allocated values
- Use sensitivity analysis to assess effect of alternative allocations

Allocation Steps (from ISO)

- 1) Try to avoid allocation!
  - Disaggregation?
  - System expansion?
  - If not feasible, then…
- 2) Allocate by partitioning inputs/outputs to products based on "underlying physical relationships"
  - Mass, volume, heat content, etc.
  - Allocate proportionately.
- 3) If allocation cannot be based on physical characteristics, other methods can be used
  - e.g., by economic value (this is NOT a default choice of method)
  - How much is A worth vs. B?

- Generally use consistent allocation across system (not 'picking and choosing' for each)
- Special rules for recycling, etc. we will see later
- Use sensitivity analysis to compare allocation methods (mass or energy based allocation)

Allocation examples

- Consider a truck transporting different fruits and vegetables.
- The truck consumes 5 liters of diesel fuel and emits pollutants

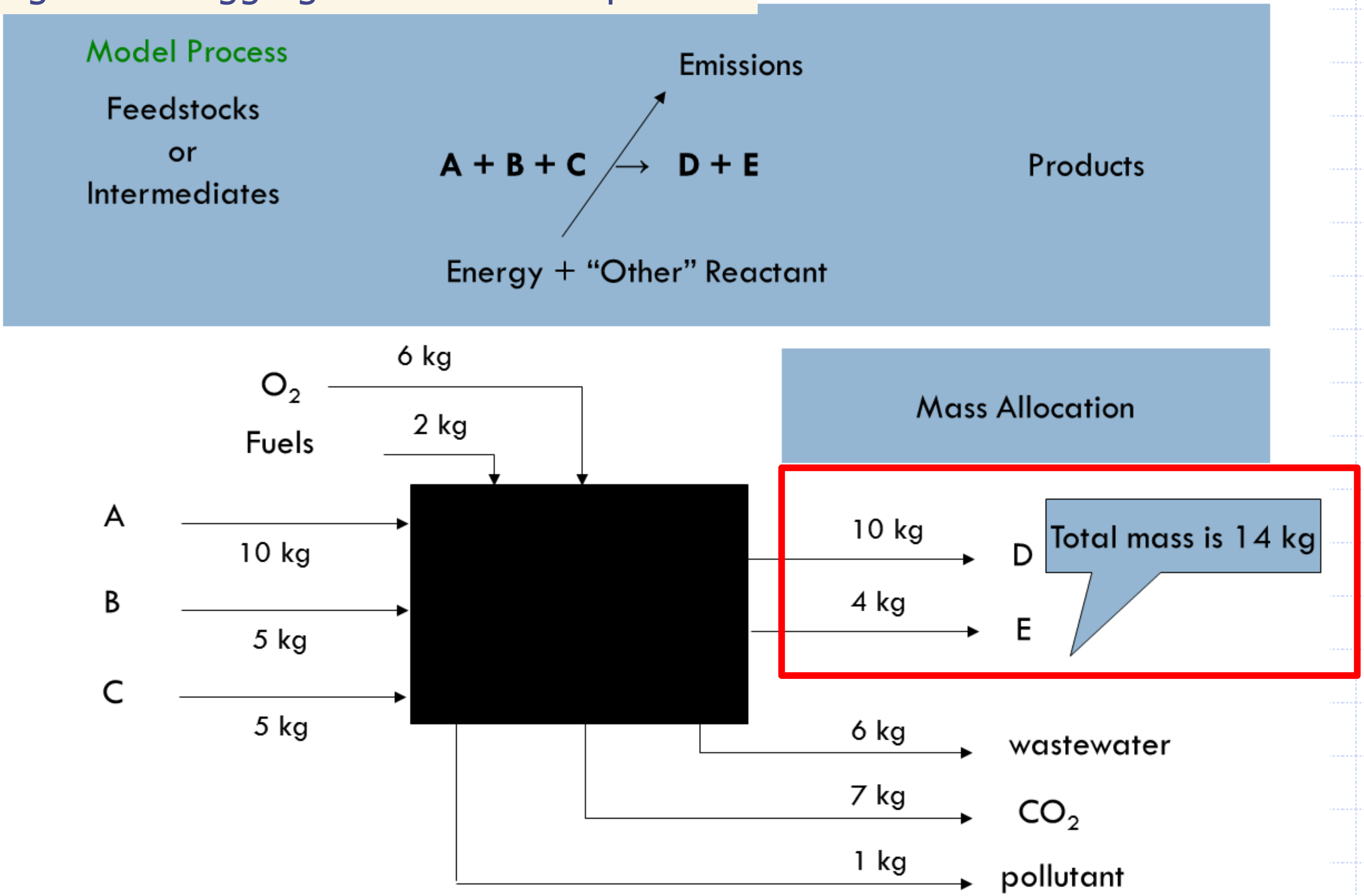
Summary info

	Items	Mass		Market Value	
	Pieces	Per Piece	Per Type	Per Piece	Per Type
Apples	100	0.2 kg	20 kg	$0.40	$40
Watermelon	25	2 kg	50 kg	$4	$100
Lettuce	50	0.4 kg	20 kg	$1	$50
Total	**175 pieces**	-	**90 kg**	-	**$190**

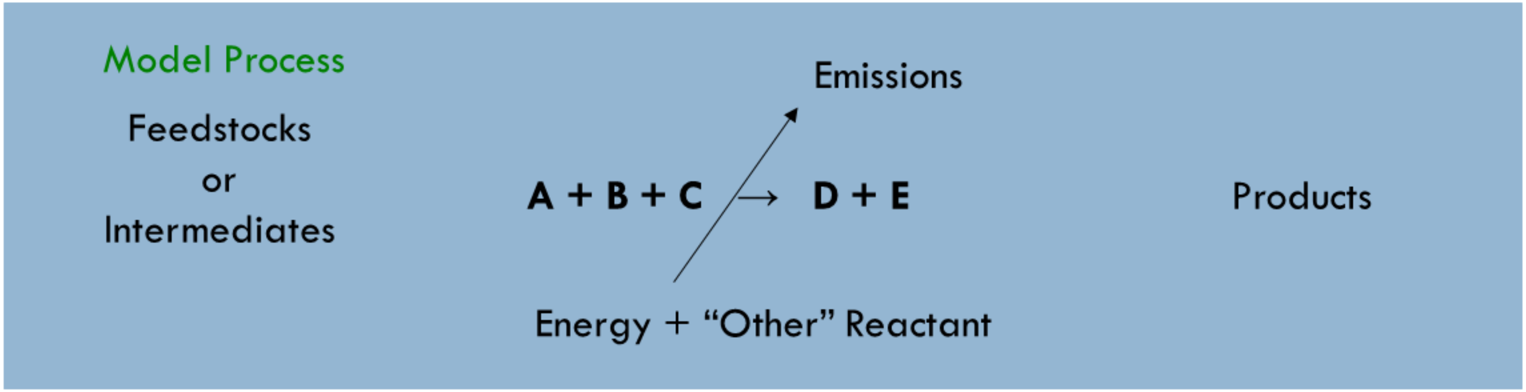
Allocation factors and allocation flows of diesel fuel (5 liters) per type of product

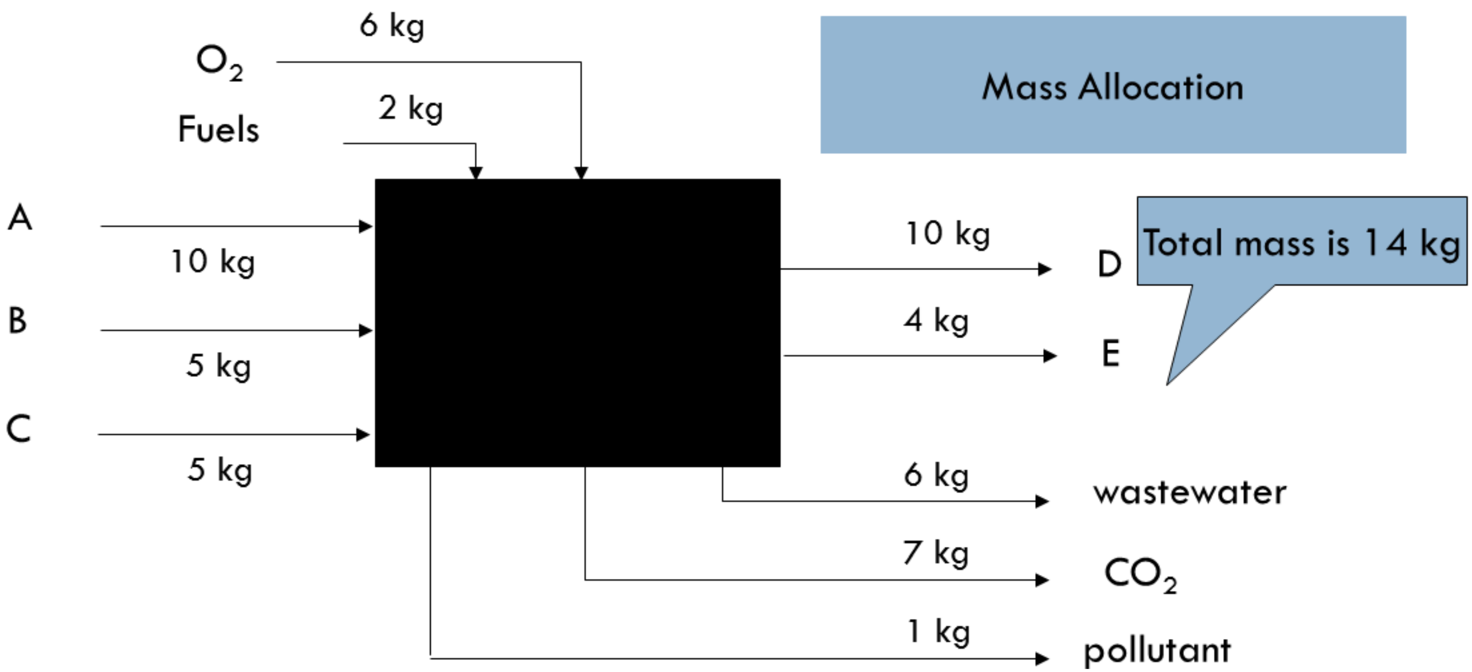
	Item		Mass		Economic	
	Allocation factor	Allocated flow (liters)	Allocation factor	Allocated flow (liters)	Allocation factor	Allocated flow (liters)
Apples	1 item * 1/175 item	0.029	0.2 kg * 1/90 kg	0.011	$0.40 *1/$190	0.011
Watermelon			2 kg * 1/90 kg	0.11	$4 *1/$190	0.11
Lettuce			0.4 kg * 1/90 kg	0.022	$1 *1/$190	0.026

Now, assume processes for D and E cannot be disentangled… disaggregation is not an option



How could we allocate the wastewater, CO_2 and pollutant to the 2 different products on a mass basis?





Mass Allocation Factors:

Product D – 10 kg/14 kg = 0.71

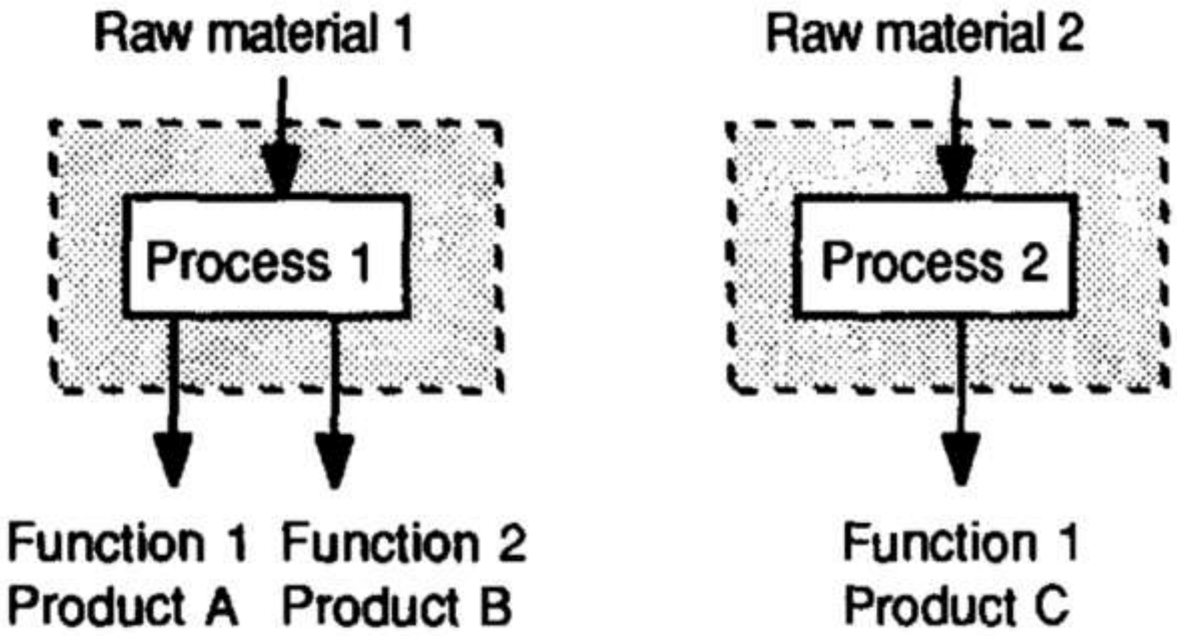
Product E – 4 kg/14 kg = 0.29

Avoiding Allocation

- Allocation is easy, but not preferred because we are making assumptions about physical relationships rather than digging into the process
- What we'll discuss next is **system expansion**, which is a way to avoid allocation by considering the multiple products and functions more broadly.
- When disaggregation isn't feasible…
  - Common finding that data don't exist in enough detail to support disaggregation
    - But worth a look!
  - ISO says... try "System Expansion" next
    - You may be able to shift your system boundary to isolate your targeted function
- System expansion is "*expanding the product system to include the additional functions related to coproducts*"
  - Little details in the standard ISO
  - System expansion adds production of outputs to product systems so that theu can be compared on the basis of having equivalent functions.

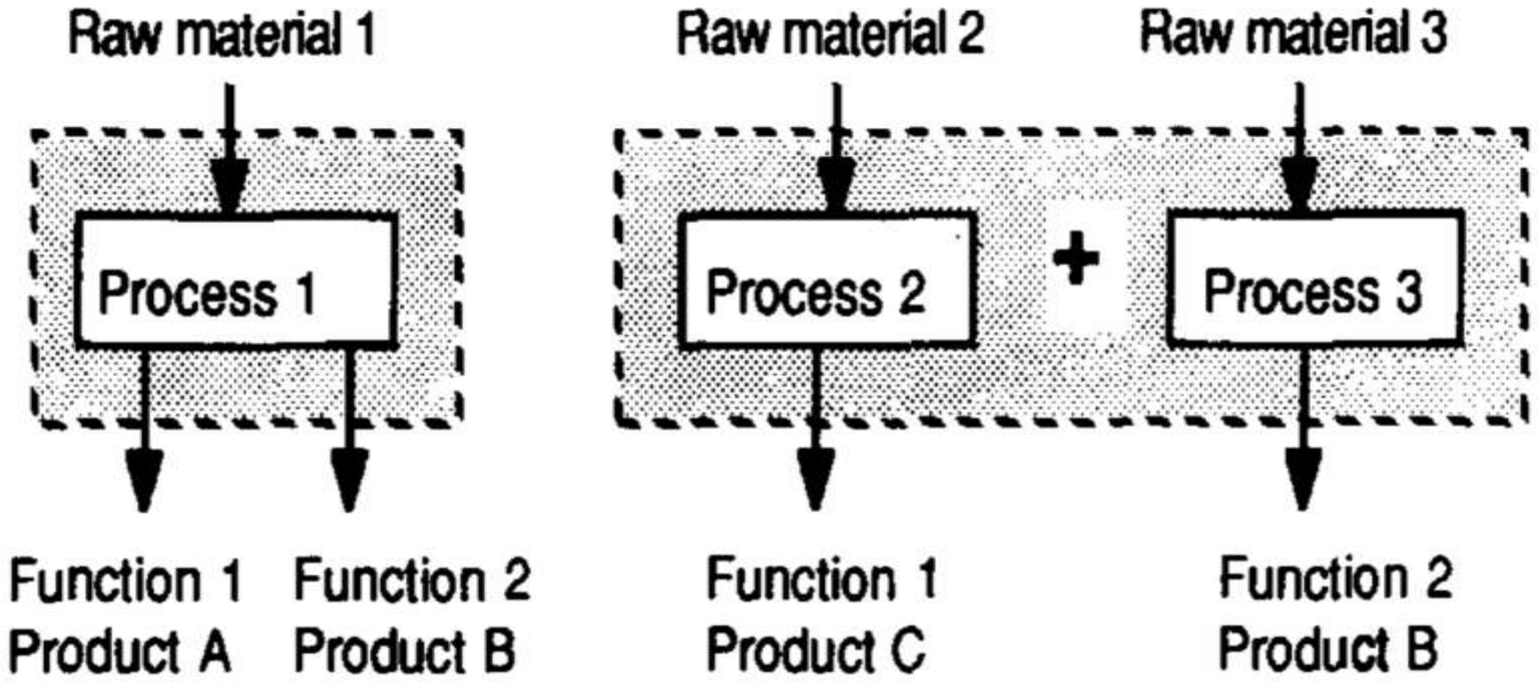
What is System Expansion?

- Typically easiest to motivate and explain in context of a comparison of systems
- Example:
  - system producing heat and electric power, each of these products provides a different function
    - the ability to provide warmth and the ability to provide power.
  - In a hypothetical analysis based only on a functional unit of electricity, comparing a CHP system with a process producing only electricity would be unequal



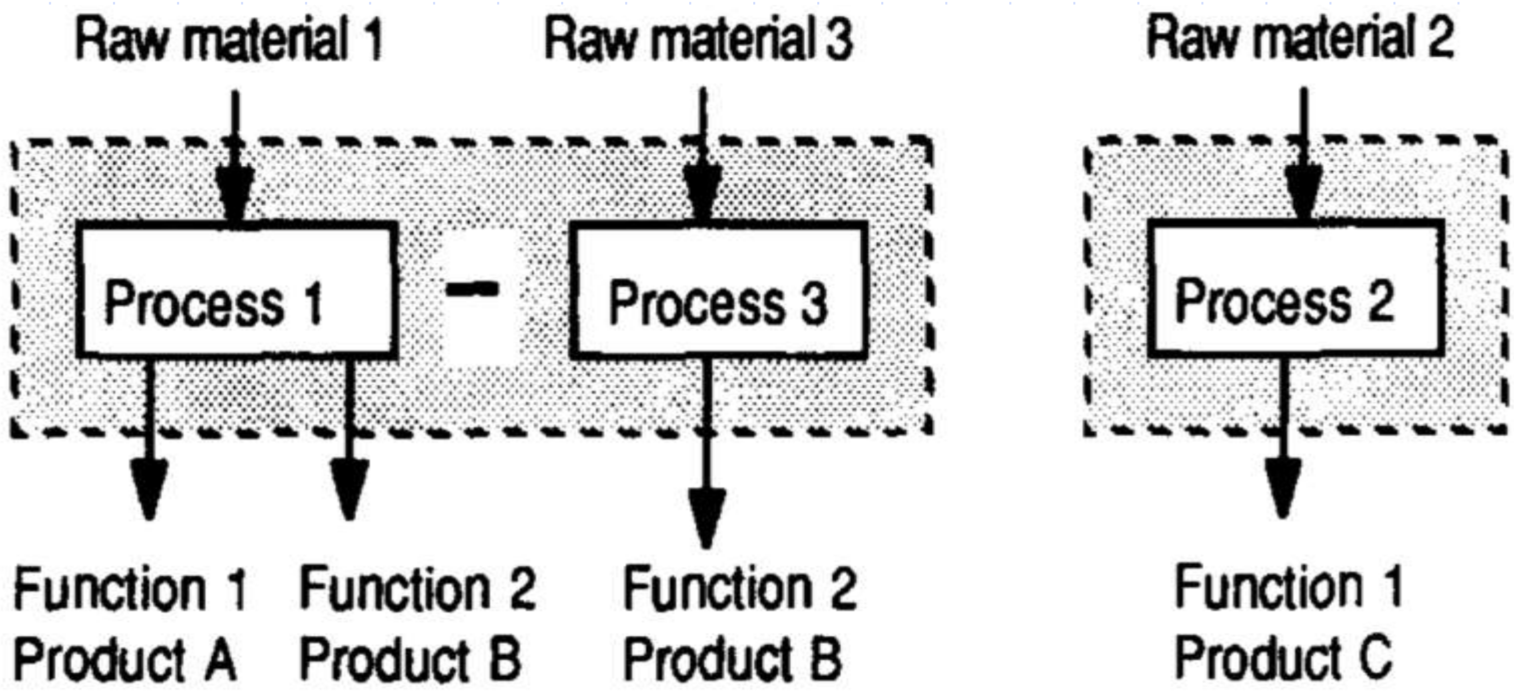
System expansion

- Add an appropriate process to have comparable functions
- Function 1 provides power and Function 2 provides heat
  - system expansion allows the product systems to be compared by adding processes representing the production of heat to the system (making Product B).
  - Note: scope is now different (iterate through SDP)



Substitution approach "Avoided burden"

- OR, subtract a process to give comparable functions



- Note: this is still "system expansion" even though we are subtracting a process

System expansions

- Modeled systems provide same functions
- Additional functions may represent identical or alternate products, technologies or production processes
- Consider alternative technology assumptions for system expansion in sensitivity analysis
- The determining product controls production volumes; dependent product cannot control it
  - Determining product may or not be target of the LCA
  - Only the dependent product can be expanded for.

Impact allocation Methods: impacts are divided

- **Physical allocation** (this is what ISO says)
  - By energy content of products
  - By economic value (to be evaluated carefully)
  - By Mass (preferable)
- **System Expansion**
  - Which is the primary product?
  - What is the secondary displacing?
- Examples
  - Process pricing gold and rocks: allocating between gold and rocks on mass basis won’t work (economical basis should be used)
  - A cow produces milk, meat and skin: allocating on mass basis won’t work
  - Industrial plastic extruder: physical allocation by mass.

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Uncertainty vs. Variability

- Uncertainty: exists because of ignorance or lack of data
  - Likely reducible with further study
- Variability: exists because of heterogeneity or diversity
  - Unlikely to be reducible with more study
- We assume they are the same, and call them both uncertainty
- And do "uncertainty analysis"

ISO 14040 says…

- LCA addresses **potential** environmental impacts; LCA does not predict absolute or precise environmental impacts due to:
  - **relative expression** of potential environmental impacts to a reference unit
  - **integration** of environmental data **over space and time**
  - **inherent uncertainty** in modelling environmental impacts
  - some possible environmental impacts are clearly **future** impacts
- Data quality requirements should address uncertainty of information
  - data, models, and assumptions
- "Uncertainty analysis and sensitivity analysis shall be done for comparative studies intended for public release."

Paper vs. plastic

- Lave et al compared energy use (electricity only) of plastic and paper cups (1995)
- Plastic cup consumed ~50% less electricity
  - plastic cup: 4,400 kWh = 0.015 TJ
  - paper cup: 8,600 kWh = 0.086 TJ
- Updated to consider uncertainty (and total energy) (Chen, 2017):
  - plastic cup: 0.3 – 0.7 TJ
  - paper cup: 0.3 – 0.4 TJ
  - Original conclusions change
  - Overlapping range suggest high potential for ~ same energy use, or for lower energy use for paper cup

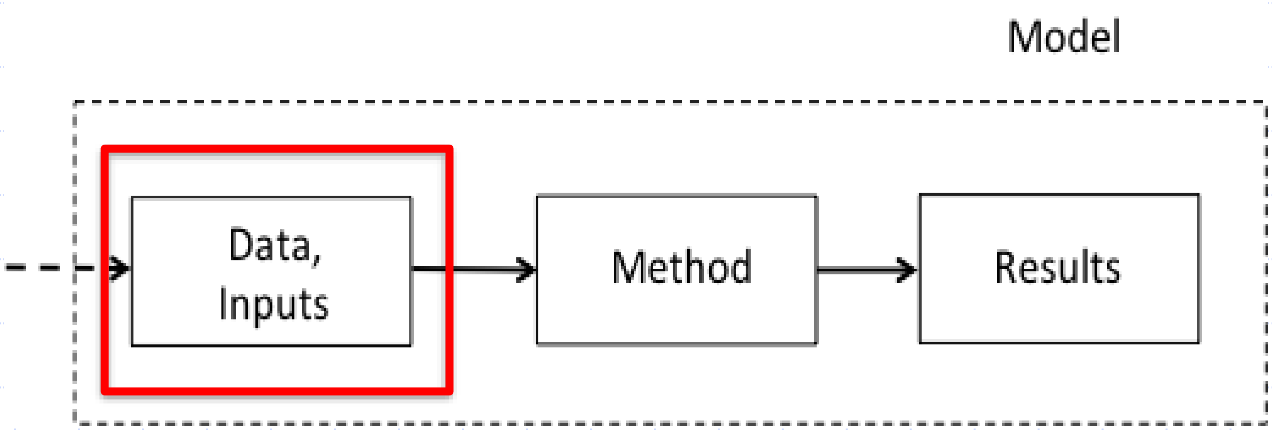
Back to the decision context

- Use care in using simplistic methods to support decisions
- "A decision made without taking uncertainty into account is barely worth calling a decision." (Wilson, 1985)
- Would you really want to redesign a process around the result of a deterministic LCA?

- Measurement vs. Accounting
  - Measurement: observable quantity with an ideal way to measure; limits to precision
    - Uncertainty range might be described as +/- 1%
    - Could be improved with better measurement tools
  - LCI accounting: may lack primary data, raw data leveraged to estimate flows
    - Uncertainty ranges likely to be appreciable
    - Results roll up many, many processes

Data or input uncertainty

- Measurement uncertainty
- Parameter uncertainty
  - Survey errors
  - Incomplete and missing data
  - Unit conversions
- Geospatial uncertainty
- Temporal uncertainty
  - Old data
  - Forecasting



Methods to address uncertainty: qualitative

- Discus sources of uncertainty
- Textual summary without quantification

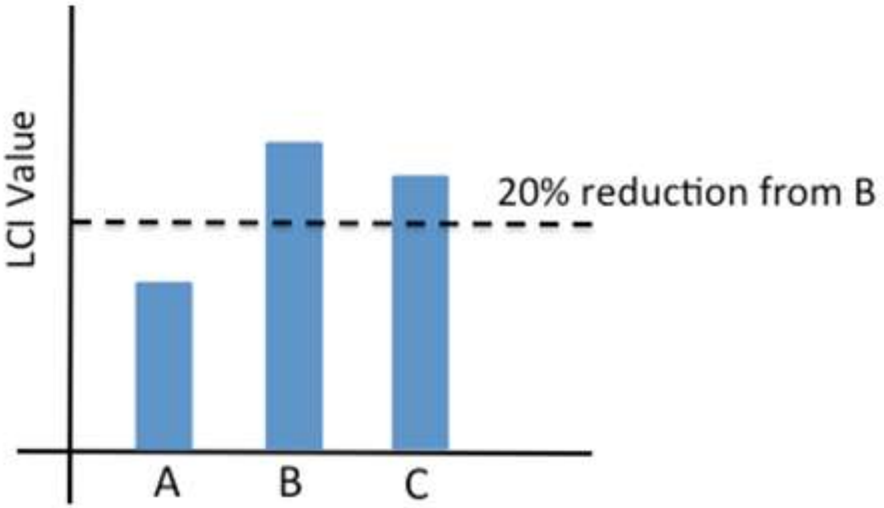
- Reliability: “All data for key processes are based on measurements (primary data), so uncertainty is deemed to be relatively low for this category.”
- Completeness: “Various processes include only effects of direct production, leading to some cutoff uncertainty.”

Methods to address uncertainty: semi-quantitative, Heuristics

- Rule of thumb, preset "rule" for comparisons
  - Example: uncertainties of energy and carbon emissions ~20%; other LCI categories more uncertain
  - Differences <20% … inconclusive
  - No solid science behind "20%", but a useful screening tool
- True quantitative better!

Maintain enough significant digits for comparison:

0.6 and 1.4, not 1 and 1

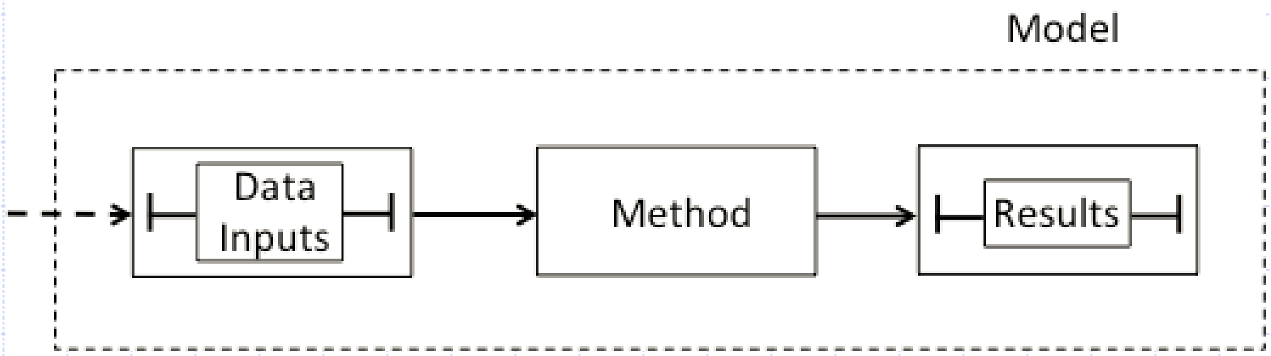


Methods to address uncertainty: quantitative methods

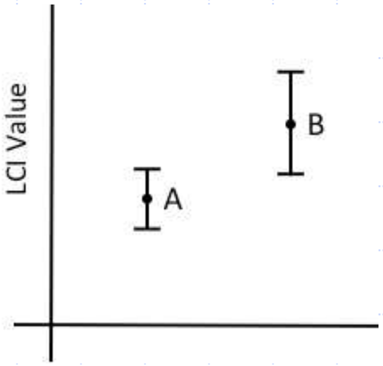
- Ranges
- Sensitivity analysis
- Probabilistic methods and simulation

Using ranges to understand uncertainty

- Use ranges for inputs or outputs
- Recommended: use multiple data sources, not single values



- Ranges quantitatively represents effects of different assumptions/boundaries in underlying data
  - helping to show when they matter
- Appropriate graphical range representation: “uncertainty bars”
  - Linear representation of ranges of results with upper and lower bounds - AKA “error bars” in Excel



Sensitivity analysis

- Quantitative method
- Assess effect on results from changing a single input
  - Change one variable at a time; hold all others constant

- Other methods, such as multi-way sensitivity analysis and simulation, can show effects of changing more than one variable at a time

ISO and Sensitivity Analysis

- **14040:3.31 sensitivity analysis** – systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study
- **14044:4.3.3.4 Refining the system boundary** – "Reflecting the iterative nature of LCA, decisions regarding the data to be included shall be based on a sensitivity analysis to determine their significance…"
- "The sensitivity analysis may result in
  - exclusion of life cycle stages or unit processes when lack of significance can be shown by the sensitivity analysis,
  - exclusion of inputs and outputs that lack significance to the results of the study, or
  - inclusion of new unit processes, inputs and outputs that are shown to be significant in the sensitivity analysis."

ISO and Sensitivity Analysis

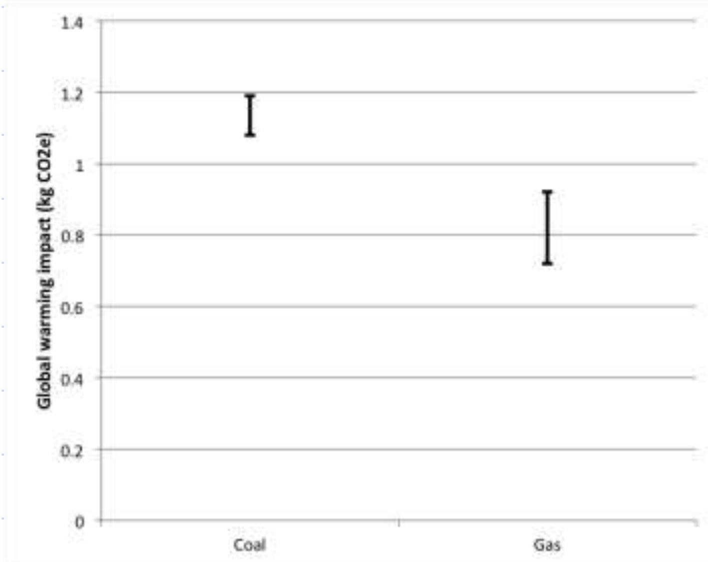
- **14044:4.3.4.1: Allocation** "…Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach."
- And in LCIA to show impact of different modeling choices (normalization, weighting)
- Required for "comparative assertions intended to be disclosed to the public"

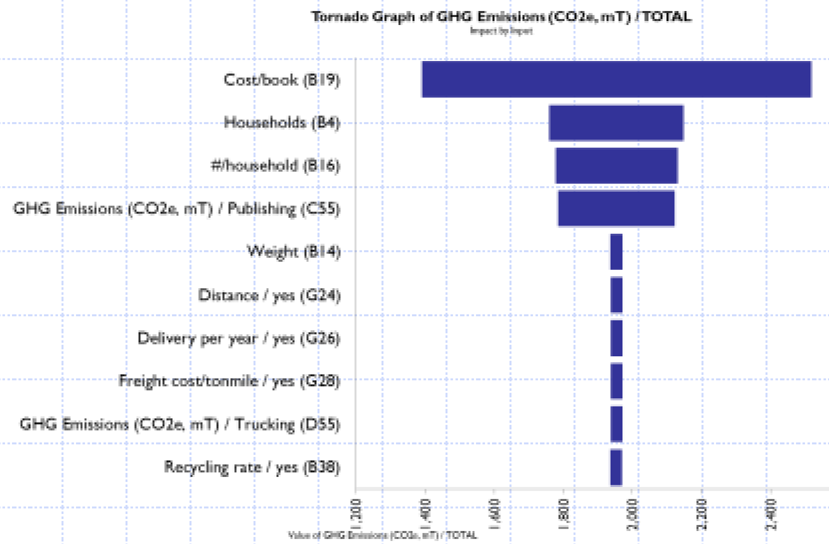
Sensitivity analysis

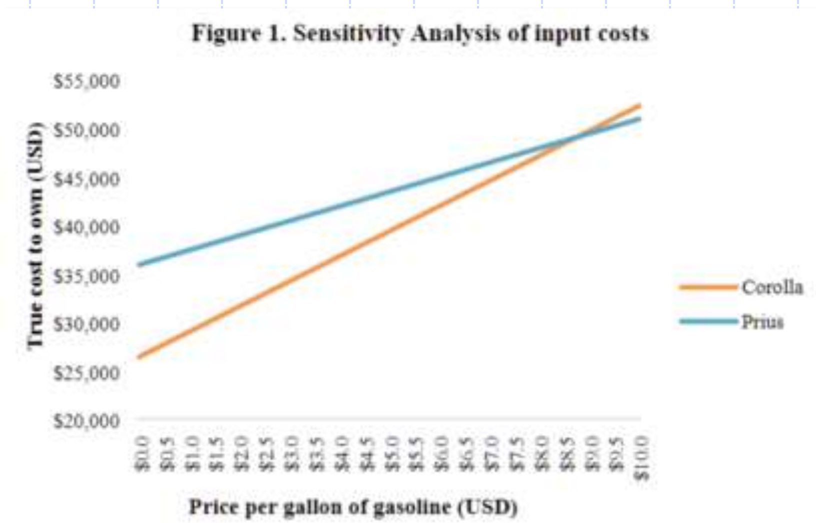
- "By hand" or using sensitivity analysis tools in Matlab, @Risk, Excel (What-If analysis), SimaPro (if you have a higher level license than the course license), etc.
- Applies to inputs and assumptions (parameter choices, allocation methods, etc.)
- Choose appropriate sensitivity ranges
  - What makes sense?
  - Not just automatic acceptance of +/-50% defaults

Depicting sensitivity analysis

- Simple hi/lo chart (Excel or Matlab)
- @Risk, TopRank or other software to generate tornado or spider type graphs







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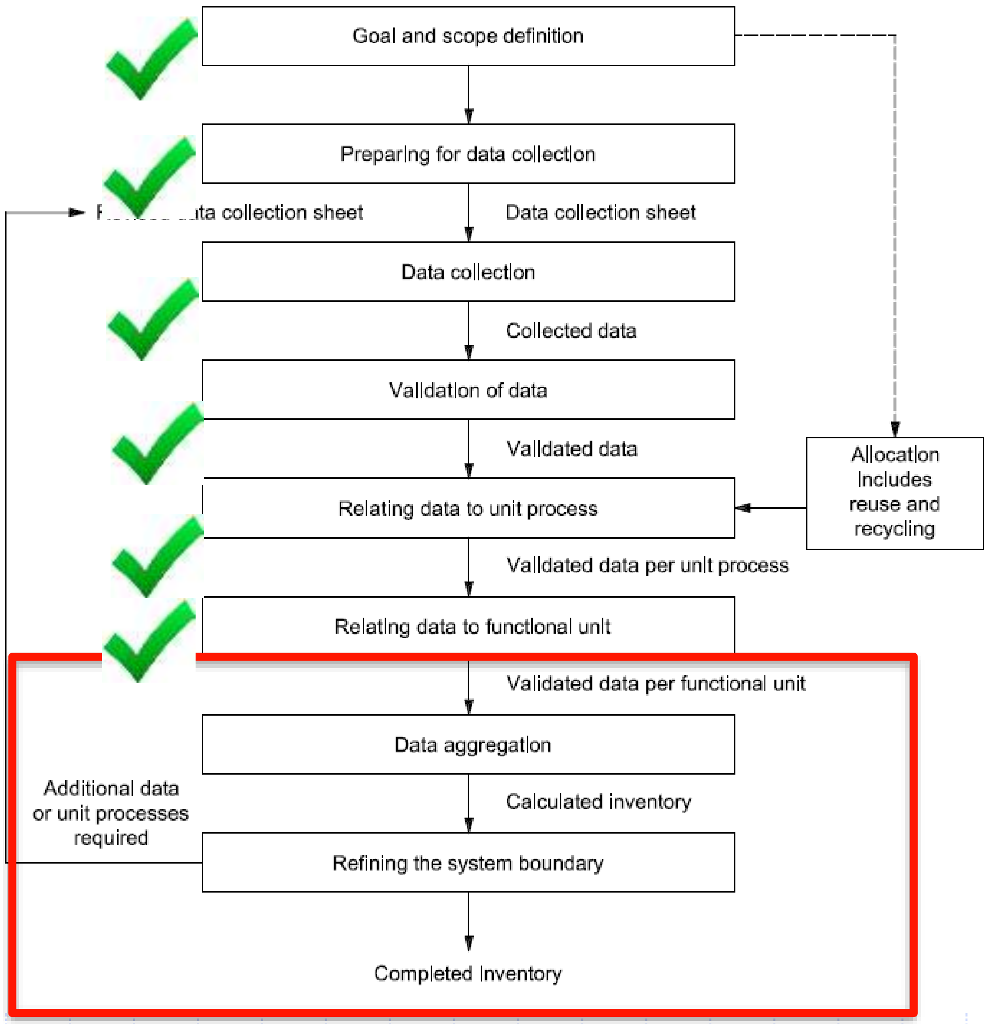
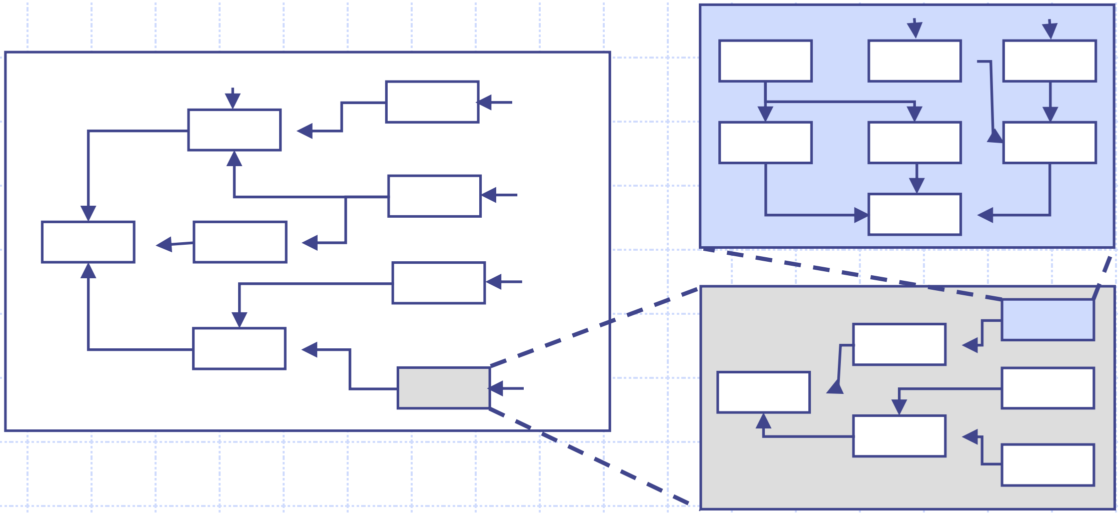
Life Cycle Inventory



Conceptual View

- So far, we have
  - *process flow diagrams*
  - *input-output* based methods

- Process flow diagrams are specific, but limited by need to add processes "by hand"
- IO models are general, but give top-down, comprehensive views of system (entire production economy!)



Process Matrix Analysis for Life Cycle Inventory (LCI)

- Develops network by selecting most important processes, and combining data about their resource use, emissions, etc. to obtain life cycle consumption
- Relies on data about specific industrial or manufacturing processes
  - Available as industrial data or via simulation
- Systematic approach for combining modular process data

Adding processes

- Can add as many processes as you have time/resources to consider
- Could expand process boundary to include refining petroleum, and capture effects of diesel inputs – adding rows and columns to A and B matrices
  - Matrix representation of process flow diagram with interconnected upstream flows
- Can use Excel, MATLAB, etc. to manage data and matrix math

- Know how to make process matrix models using LCI data
  - Would take a long time, and require lots of repeated effort
  - US LCI has ~1,000 processes. Do you really want to build that model?
  - Same challenge as before – when to stop adding?
- SimaPro, OpenLCA, Gabi have already built these models
  - Complete, comprehensive matrix based versions of these process based databases (e.g., US LCI, ecoinvent)

SimaPro thinkstep GaBi openLCA umberto know the flow.

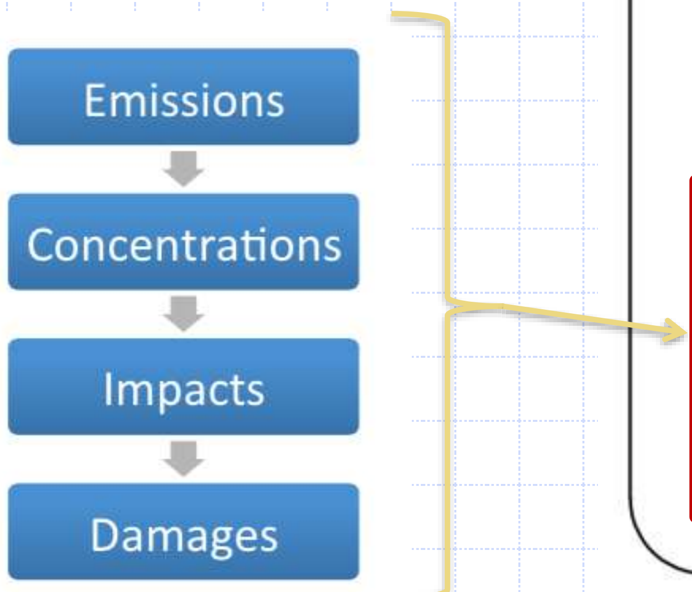
Agenda

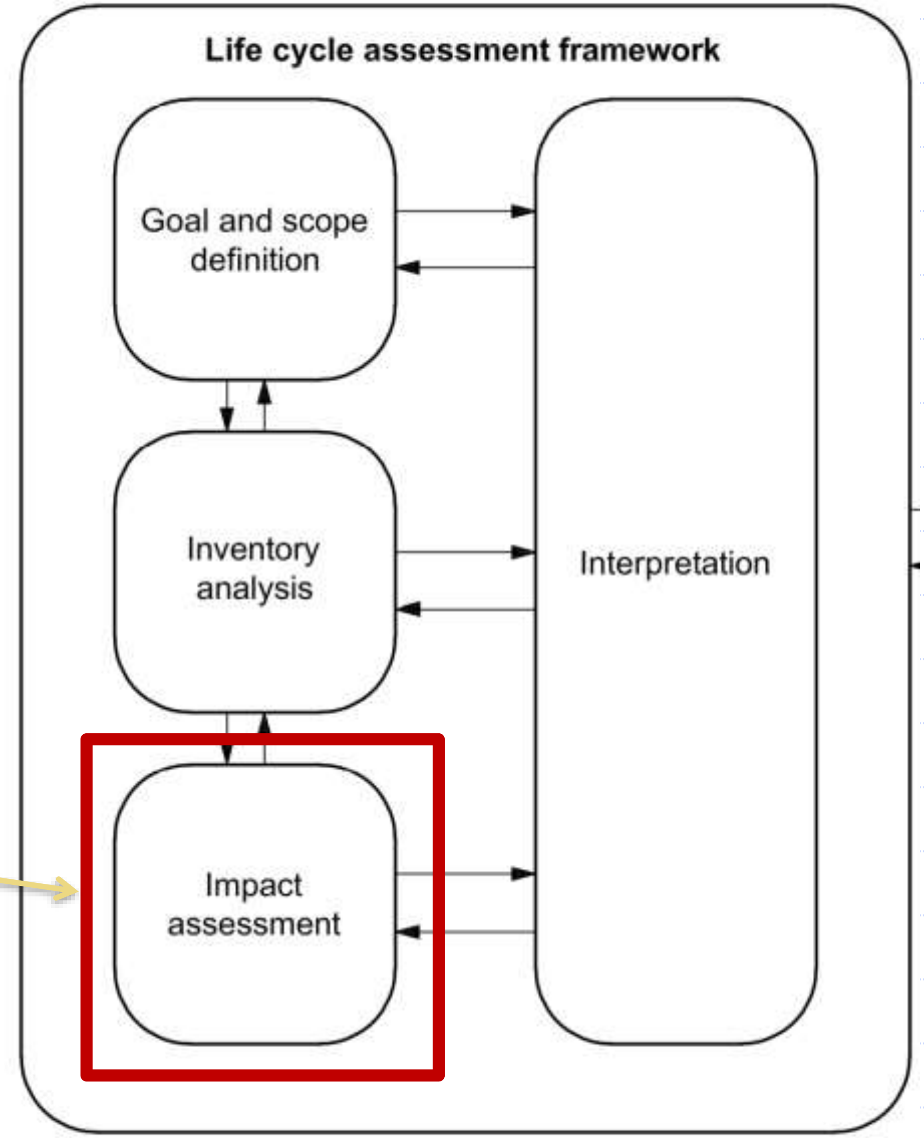
- Life cycle thinking
- Quantitative methods and life cycle cost analysis
- The ISO LCA standard
- Life cycle inventory
  - Data needs and data quality
  - Data sources
  - Handling multifunction systems (disaggregation and allocation)
  - Uncertainty
  - Input-output LCA
- Impact assessment
- Conclusions

ISO 14040: Figure 1

Phases of an LCA

- Goal and scope definition
- Inventory
- Impact assessment
- Interpretation





Life Cycle Impact Assessment - LCIA

- Impact assessment considers actual effects
  - On humans, ecosystems, and resources
  - Not just tracking quantities (tons of emissions, gallons of fuel consumed as a result of production)
- Indicators of impacts:
  - Why do we care about GHG emissions?
    - Potential to change our climate
  - Why care about sulfur dioxide emissions?
    - Potential to acidify rain, waterways
  - Why care about particulate emissions?
    - Potential to harm health
- Impact assessment not new
  - Environmental impact assessment
  - Risk assessment
  - Performance benchmarking, etc.
- Key feature of LCIA:
  - Link to a particular functional unit
  - Entire life cycle as a boundary
  - Focuses attention on impacts as a function of that specific normalized quantity

Environmental impact categories: how to choose

- Table reports a typical result of Inventory analysis

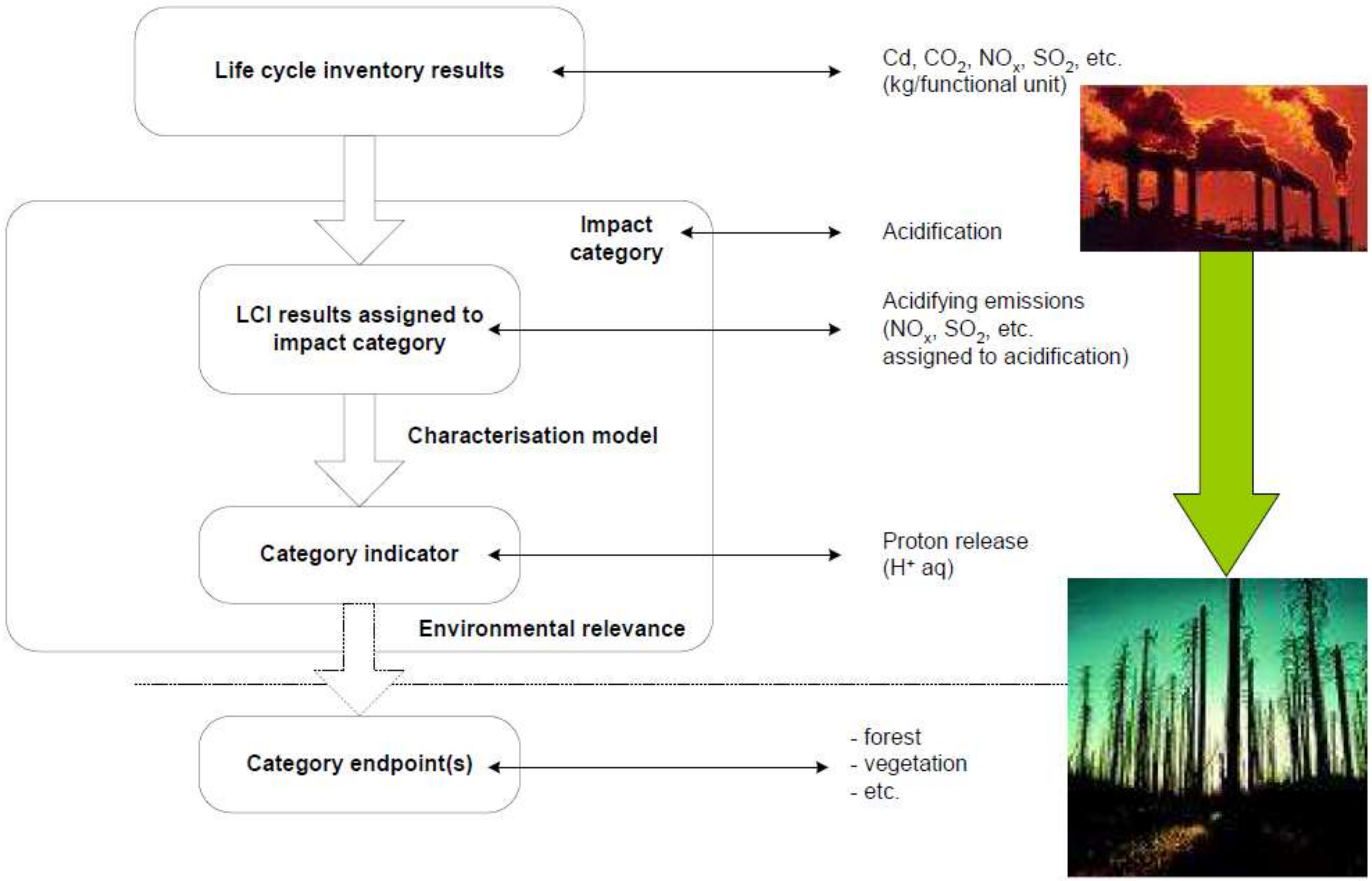
Flux	Compartment	Unit	Option A	Option B
Carbon dioxide, fossil (CO_2)	Air	Kg	5	2
Sulfur dioxide (SO_2)	Air	Kg	2	5
Oil			10	8

- Statement "A is always better then B" is not always obvious
  - Particularly in different scenarios
- In presence of more fluxes (CO_2, SO_2, oil) **which one should be chosen?**

From LCI to LCIA: the impact categories

LCI

LCIA



Impact Categories

- Global warming
  - Global in scale
  - CO_2, CH_4, N_20, as well as chlorofluorocarbons and other halogenated hydrocarbons
- Stratospheric ozone depletion
  - Global in scale
  - Chlorofluorocarbons and other halogenated hydrocarbons
- Acidification
  - Regional or local in scale
  - Sulfur oxides, nitrogen oxides, hydrochloric acid, hydrofluoric acid, ammonia
- And more .... See table

Impact Category	Scale	Examples of LCI Data (i.e. classification)
Global Warming	Global	Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH_3Br)
Acidification	Regional, Local	Sulfur Oxides (SO_x), Nitrogen Oxides (NOx), Hydrochloric Acid (HCl), Hydrofluoric Acid (HF), Ammonia (NH_4)
Eutrophication	Local	Phosphate (PO_4), Nitrogen Oxide (NO), Nitrogen Dioxide (NO_2), Nitrates,Ammonia (NH4)
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global, Regional, Local	Total releases to air, water, and soil.
Resource Depletion	Global, Regional, Local	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications
Water Use	Regional, Local	Water used or consumed

Figure 10-2: Summary of Impact Categories (US EPA 2006)

Impact Assessment Models

- Various impact assessment models
  - Some are single category
    - Cumulative Energy Demand – resource consumption
    - IPCC – climate change
  - Other models cover wide range of categories
    - TRACI – US-focused
    - ReCiPe
    - Eco-indicator 99
- Tools like SimaPro / Gabi / openLCA incorporate many models
- Impact assessment model choice
  - No need to choose – look at multiple results
  - Understand breadth of impacts of your system
    - Surprises?
    - Convergence of conclusions?
    - New avenues of research?
  - Particularly useful for comparative LCAs

Models and Impact categories

Model	Climate change	Ozone depletion	Respiratory inorganics	Human toxicity	Ionising radiation	Ecotoxicity	Ozone formation	Acidification	Terrest. eutrophication	Aquatic eutrophication	Land use	Resource consumption
CED												X
CML2002	X	X		X	X	X	X	X	X	X	X	X
Eco-indicator 99	X	X	X	X	X		X	X	X		X	X
EDIP 2003/EDIP976	X	X	X	X	X	X	X	X	X	X		X
EPS 2000	X	X	X	X	X	X	X	X	X	X	X	X
Impact 2002+	X	X	X	X	X	X	X	X		X	X	X
IPCC	X											
LIME	X	X	X	X		X	X	X	X	X	X	X
LUCAS	X	X		X		X	X	X	X	X	X	X
MEEuP	X	X	X	X		X	X	X	X	X		X
ReCiPe	X	X	X	X	X	X	X	X	X	X	X	X
Swiss Ecoscarcity 07	X	X	X	X	X	X	X	X	X	X	X	X
TRACI	X	X	X	X		X	X	X	X	X		X
USEtox				X		X						

Figure 10-3: Summary of Impact Categories (Characterization Models) Available in Popular LCIA Methods (modified from ILCD 2010)

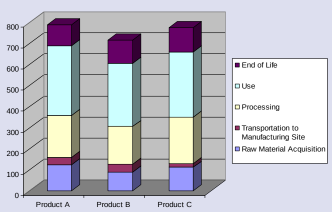
The TRACI LCIA Model

<u>Inventory of Stressors</u>
Chemical Emissions
Fossil Fuel Use
Land Use
Water Use

<u>Impact Categories</u>
Ozone Depletion
Global Warming
Acidification
Eutrophication
Smog Formation
Human Health
  Particulate
  Cancer
  Noncancer
Ecotoxicity
Fossil Fuel Use
Land Use
Water Use

Characterization (e.g., Human Health Noncancer)

....
Ozone Depletion
Global Warming
Human Health Noncancer



TRACI

Tool for the Reduction and Assessment of Chemical and other environmental Impacts

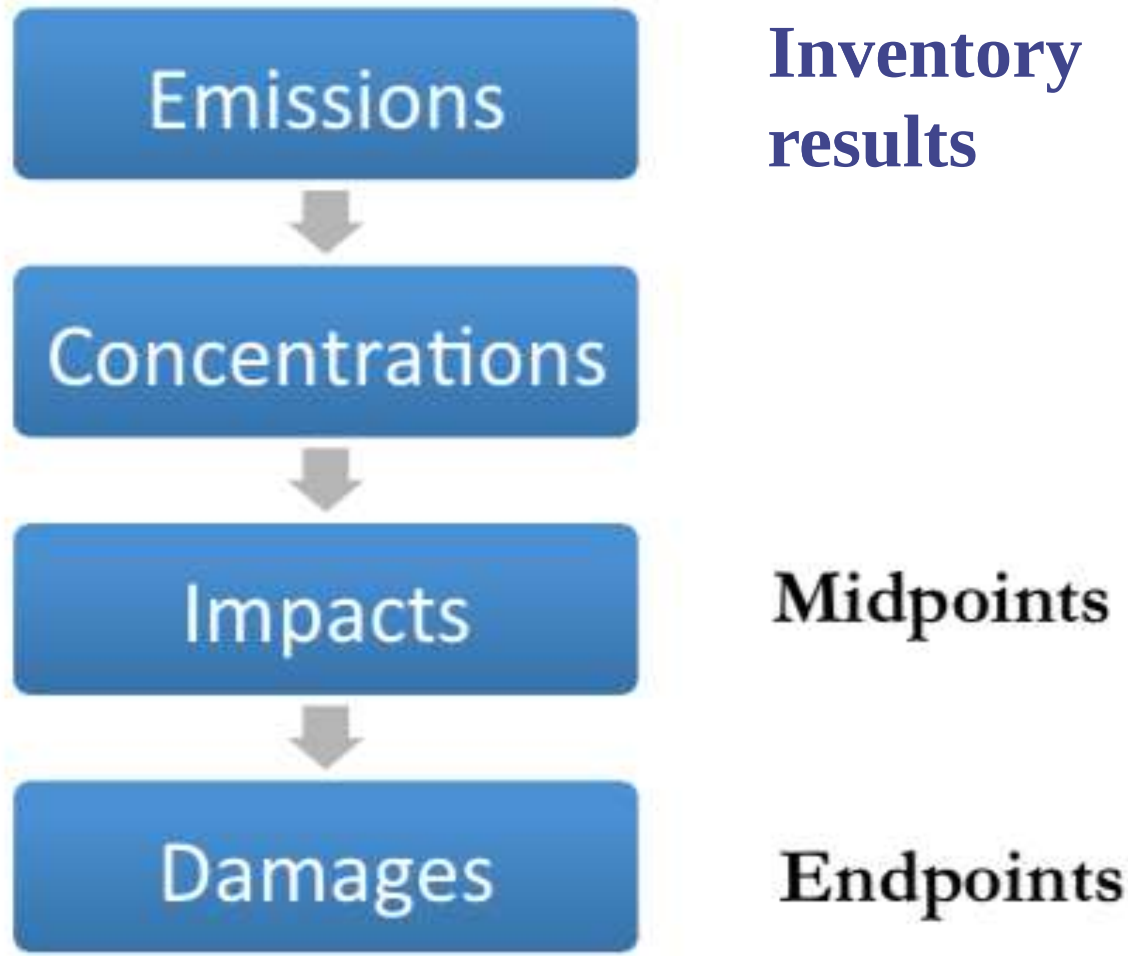
Cause-Effect Chain
Specific to an emissions example

Methane release from well venting

CH_4 mg/m^3

Increased radiative forcing

Rising sea level
Coral reef damage
Increased severe weather



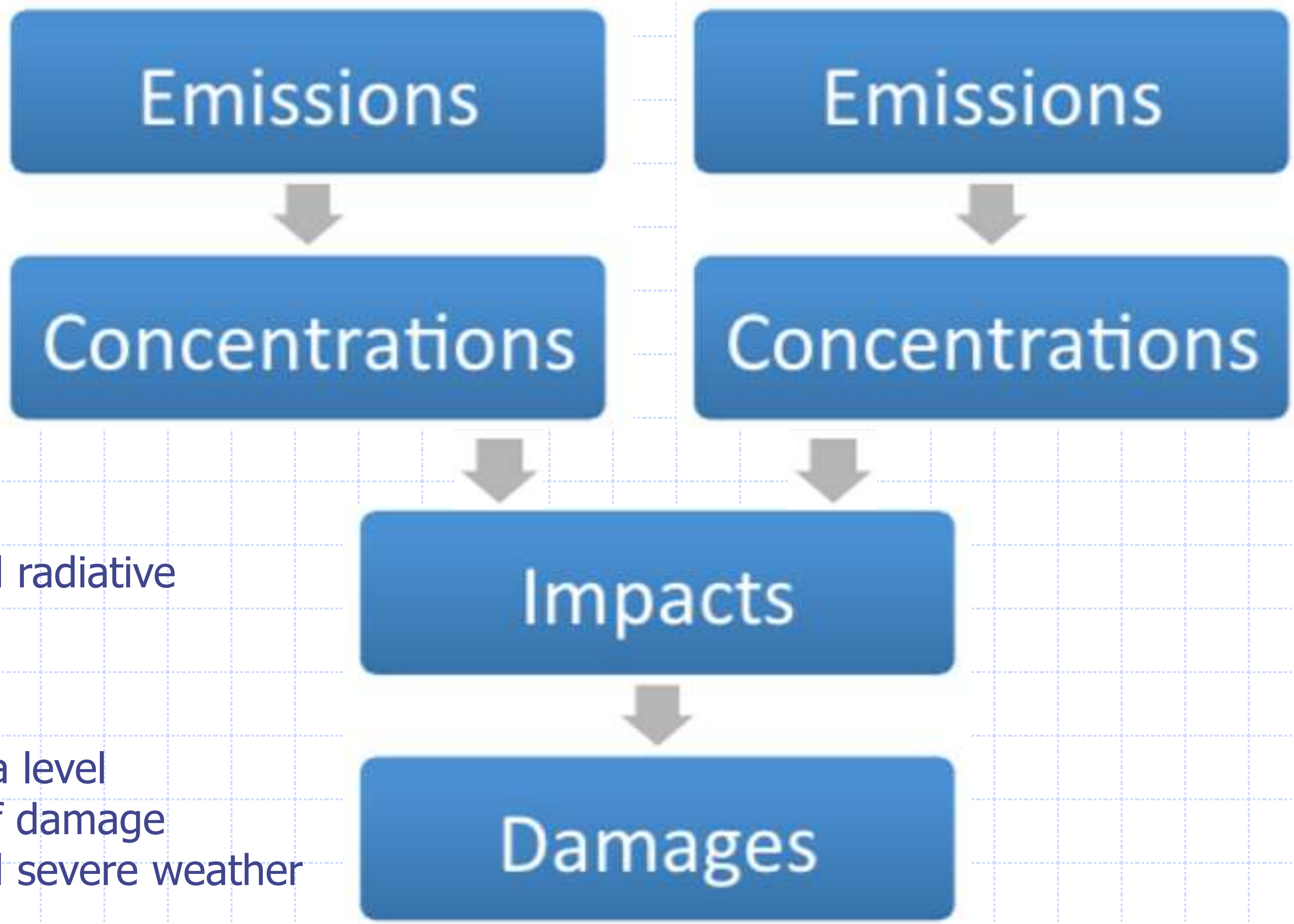
Cause-Effect Chain
Specific to an emissions example

Methane release from well venting

Carbon dioxide release from well venting

CH_4 mg/m^3

CO_2 mg/m^3



Increased radiative forcing

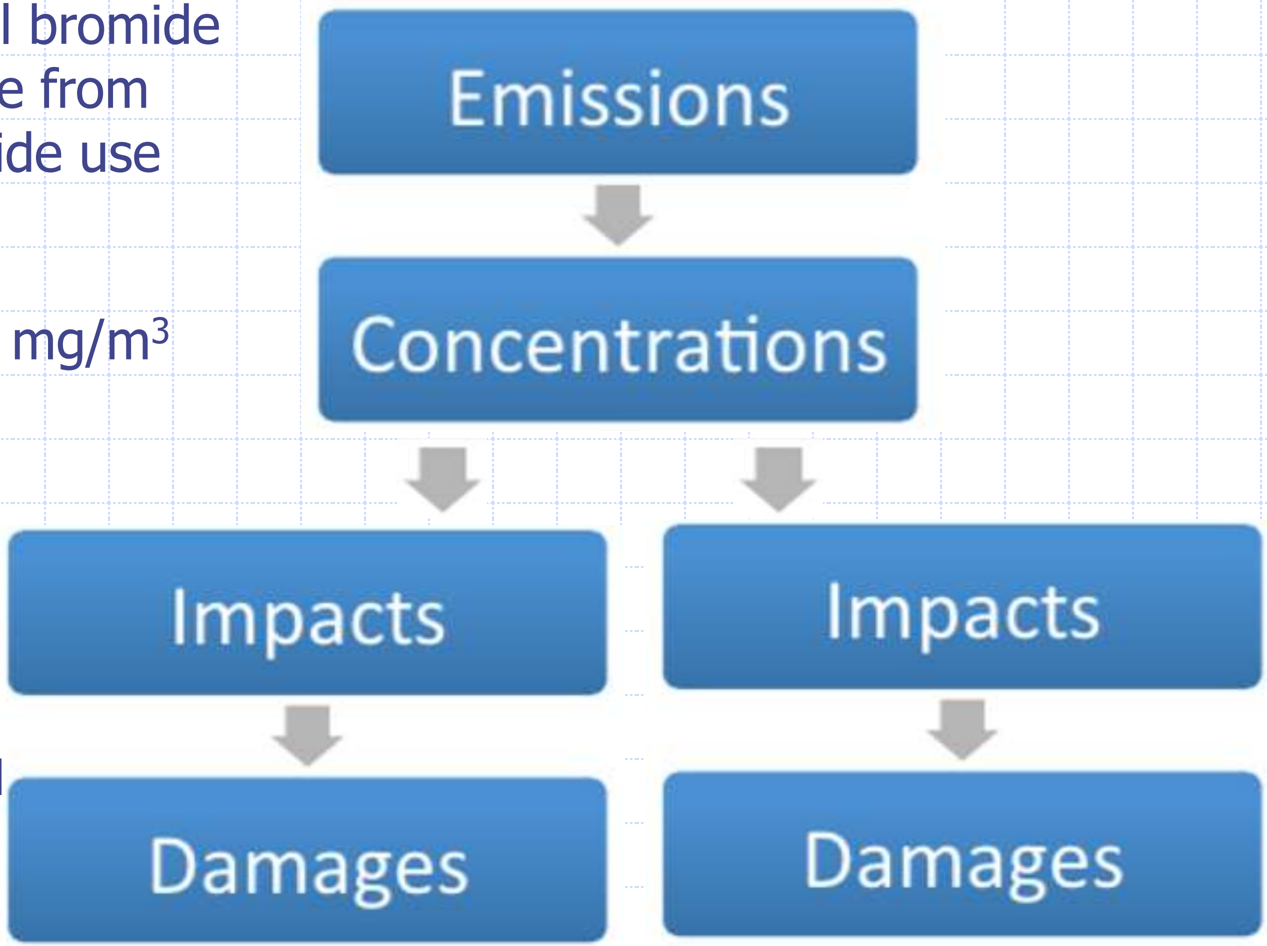
Rising sea level
Coral reef damage
Increased severe weather

Cause-Effect Chain
Specific to an emissions example

Similar chains could be drawn for resource depletion or land use

Methyl bromide release from pesticide use

CH_3Br mg/m^3



Increased radiative forcing

Loss of atmospheric ozone

Rising sea level
Coral reef damage
Increased severe weather

Increased skin cancer

Midpoints vs. Endpoints

- Typical LCI result is 'an emission, waste generation, etc.'
- An emission creates higher concentrations in environment
- Higher concentrations impact people or ecosystems exposed to those concentrations – leads to a midpoint
- Exposure potentially leads to health effects and damages – these are endpoints

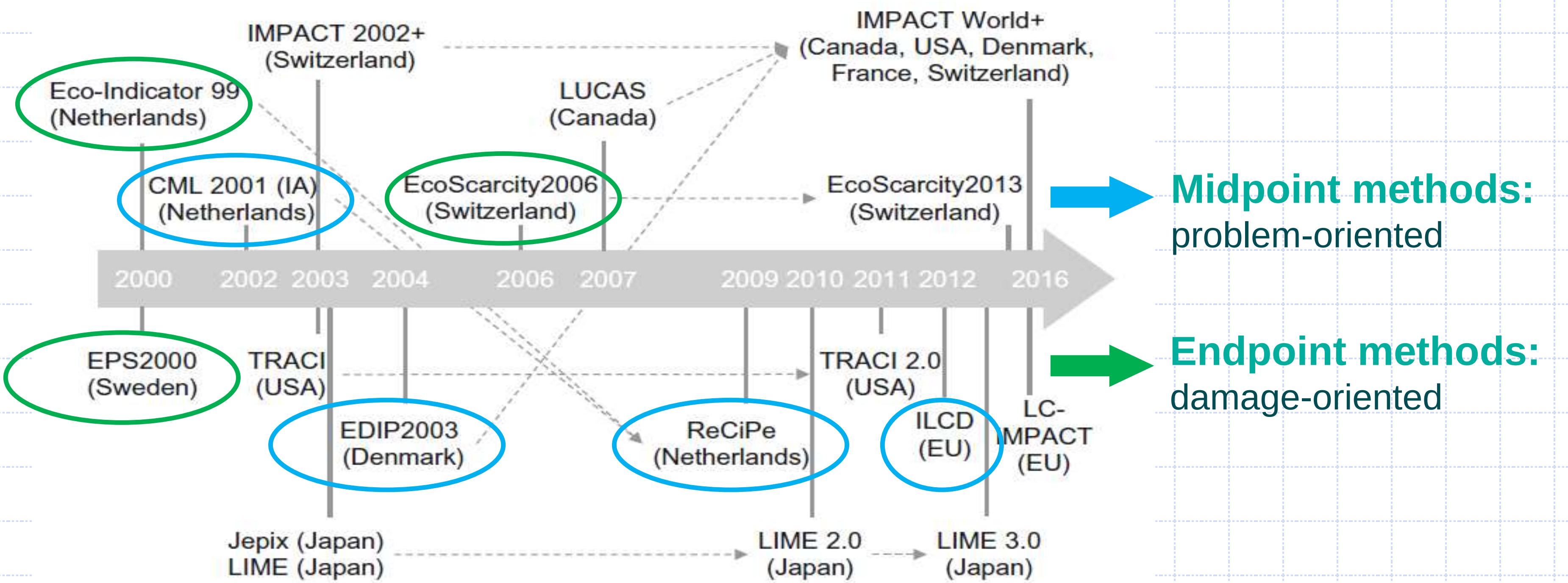


Fig. 10.1 LCIA methods published since 2000 with country/region of origin in *brackets*. *Dotted arrows* represent methodology updates (Rosenbaum 2017)

Commonly used life-cycle impact categories using midpoint modeling and example endpoints

Life-cycle impact	*Relevant inventory data*	*Midpoint modeling*	*Example endpoints*
Global impacts			
Global warming	Carbon dioxide (CO_2) Nitrogen dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl bromide (CH_3Br)	Converts release data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials	Polar melt Soil moisture loss Longer seasons Forest loss/change Change in wind and ocean patterns
Stratospheric zone depletion	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl bromide (CH_3Br)	Converts release data to trichlorofluoromethane (CFC-11) equilavents	Increased UV radiation Skin cancer Cataracts Crop damage Marine life damage Immune system depression Decreased resources for future generations
Regional impacts			
Photochemical smog	Nonmethane hydrocarbons (NMHC)	Converts release data to ethane (C_2H_8) equivalents	Decreased visibility Eye irritation Respiratory distress Vegetation damage
Acidification	Sulfur oxides (SO_x) Nitrogen oxides (NO_x) Hydrochloric acid (HCl) Hydrofluoric acid (HF) Ammonia (NH_3)	Converts data to hydrogen (H^+) ion equivalents	Building corrosion Vegetation damage Soil quality decrease
Eutrophication	Phosphate (PO_4^{3-}) Nitrogen oxide (NO) Nitrogen dioxide (NO_2) Nitretes Ammonia (NH_3)	Converts data to phosphate (PO_4^{3-}) equivalents	Excessive plant growth Oxygen depletion

Continua >

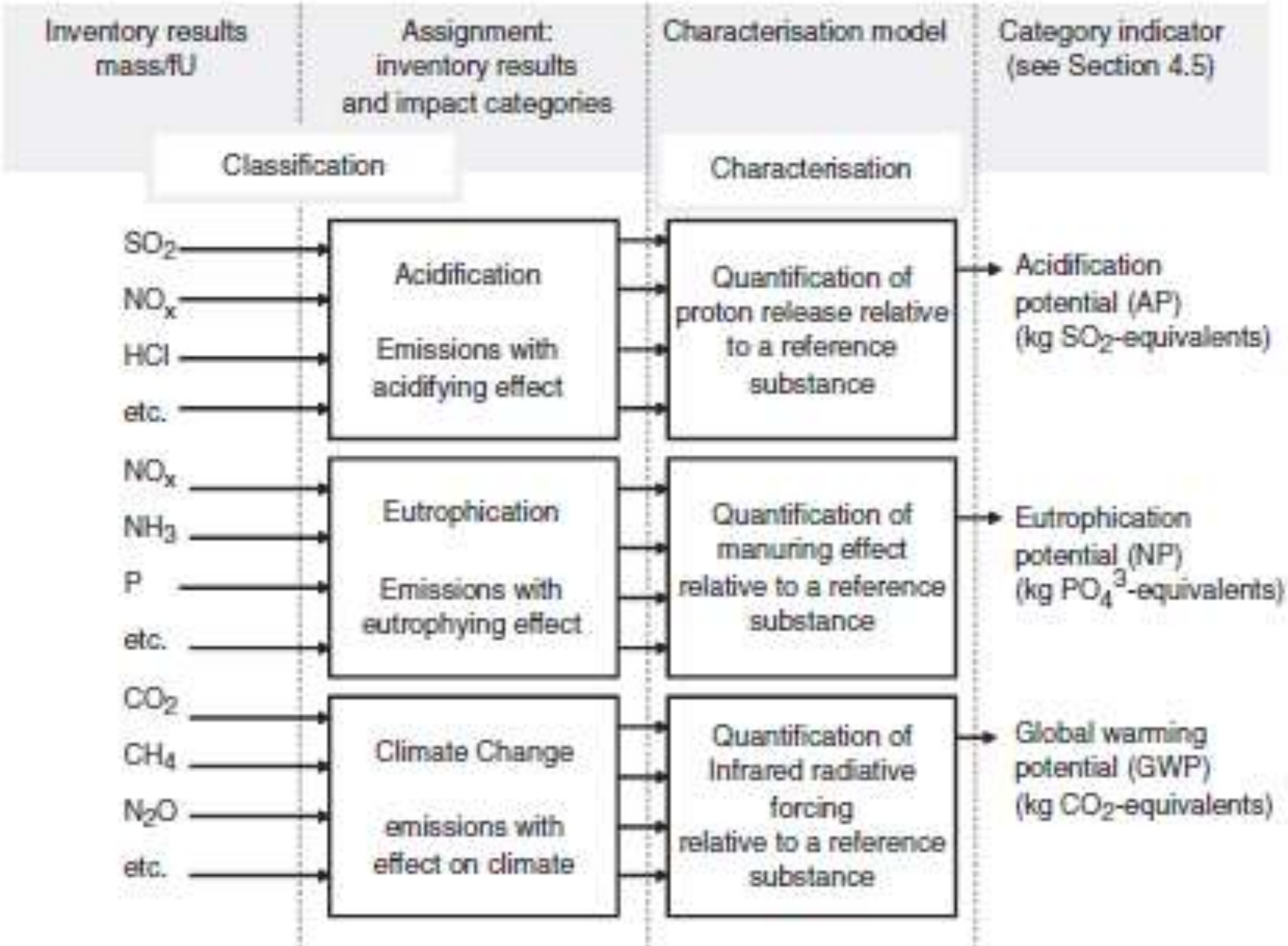
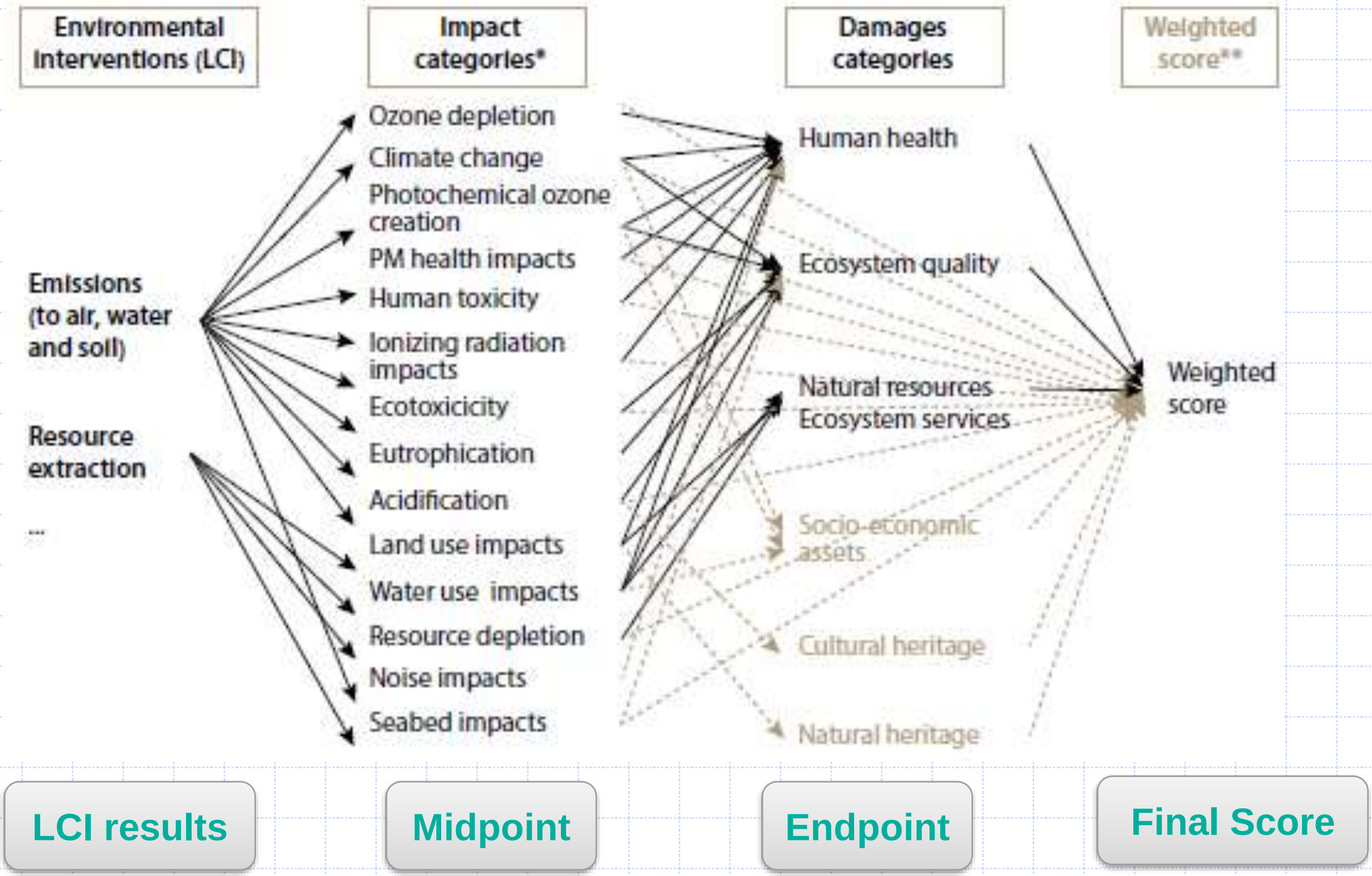
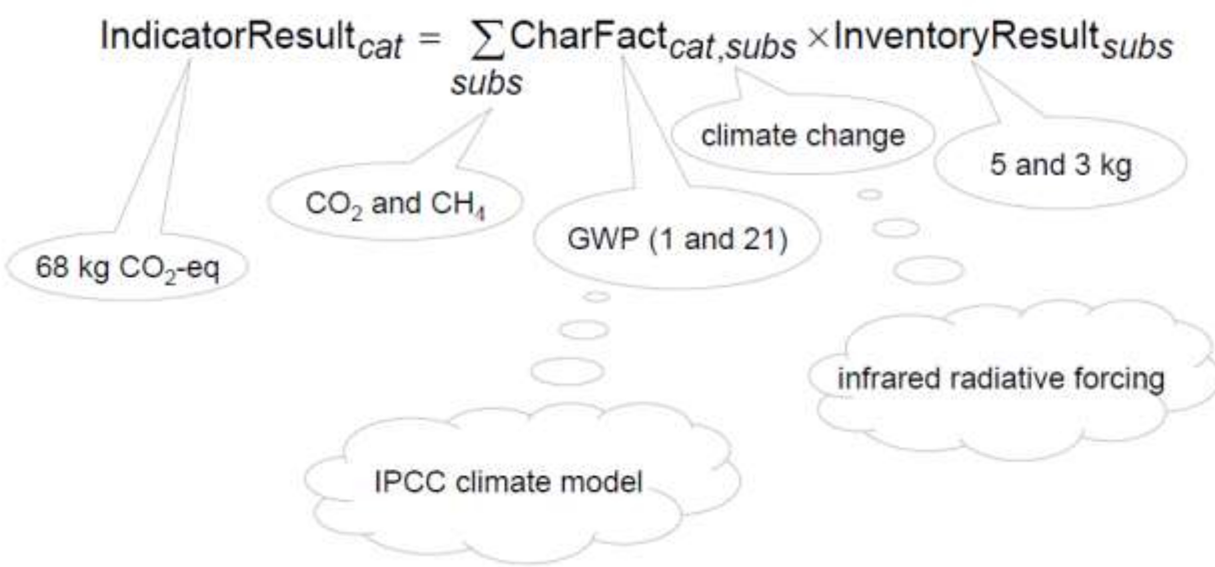


Figure 4.2 Principle of classification and characterisation in the phase life cycle impact assessment.

From LCI to LCIA: structure of LCIA framework



Environmental impact categories : example



Compartment	Substance	Result	unit
Air	Carbon dioxide, fossil	5	kg
Air	Sulfur dioxide	2	g
Air	Methane	10	g
Air	Ammonia	5	kg
Water	Nitrate	8	kg
Air	Nitrogen dioxide	15	g
Air	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	2	g
Soil	Carbon dioxide, to soil or biomass stock	1,5	kg

Characterization Factor «carbon dioxide, fossil» = 1 kg CO_2 eq. / kg

Characterization factor «Methane» = 28 kg CO_2 eq. / kg

Result Global Warming Potential

= 5 x 1 + 0,010 x 28 = 5,28 kg CO_2 eq.

carbon dioxide, fossil

Methane

LCIA is…

- Complicated!
- Many studies stop at LCI stage (not full LCA)!
- Others focus on straightforward impacts
  - Cumulative energy demand
  - GHG
  - Water requirements
- LCIA tools (TRACI, ReCiPe, etc.) do most of the work
  - No need to be intimidated
  - Tools convert detailed inventory information into estimates of associated impacts

ISO 14040: 5.4.1 General

ISO 14040: 4.4.1 General

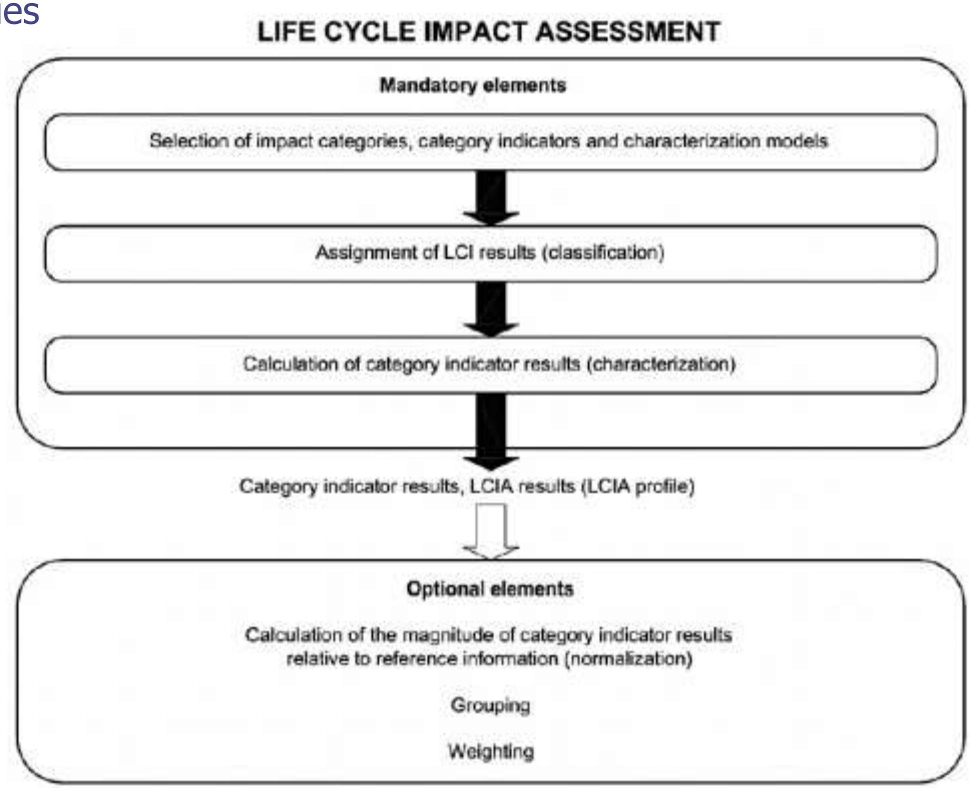
ISO requirements for LCIA - ISO says…

- Impact assessment phase evaluates significance of potential environmental impacts using LCI results
  - Associates inventory data with impact categories and indicators, in order to understand impacts
- Provides information for Interpretation phase
  - Have goal and scope objectives been met?
- Impact choices, modelling and evaluation can introduce subjectivity
  - Transparency is critical
  - Assumptions must be clearly described and reported

- Coordinate LCIA with other LCA phases to account for possible omissions and sources of uncertainty:
  - Is quality of LCI data/results sufficient to conduct LCIA in accordance with goal and scope?
  - Has system boundary and data cut-off decisions been sufficiently reviewed to ensure availability of LCI results necessary to calculate LCIA indicator results?
  - Is environmental relevance of LCIA results decreased due to LCI functional unit calculation, system wide averaging, aggregation and allocation?

Impact Assessment in the ISO LCA Framework (LCIA)

- Mandatory Elements:
  - Selection (impact categories, their indicators, and characterization models)
  - Classification (assigning LCI results to categories)
  - Characterization (calculation of category results)
    - at least get things into correct categories
- Optional Elements:
  - Normalization
    - (comparing to reference info)
  - Grouping
    - (sorting/ranking impact categories)
  - Weighting
    - (with numerical factors/value choices)
  - Data Quality Analysis
    - (uncertainty/sensitivity)



(Source: ISO 14040:2006)

Mandatory

Selection

- Select and explain:
  - Impact categories
  - Their indicators
  - Expected characterization models and methods to be used
- ISO says to "choose impact categories consistent with scope" and "reference your work"
  - No prescribed categories/impacts that must be included (e.g., global warming)
- ISO says impact assessment should encompass "a comprehensive set of environmental issues"
  - Study should not be narrowly focused
- Methods should be geographically relevant to your scope
- Climate change, ozone depletion, respiratory inorganics, human toxicity, ionizing radiation, ecotoxicity, ozone formation, acidification, terrestrial eutrophication, aquatic eutrophication, land use, resource consumption…

Next, Classification

Your inventory of flows can now be organized

Outputs to Nature	Acids, unspecified	water	unspecified	No	kg	6.10E-05
	BOD5, Biological Oxygen Demand	water	unspecified	No	kg	6.10E-15
	Calcium, ion	water	unspecified	No	kg	5.80E-06
	CFCs and HCFCs, unspecified	air	unspecified	No	kg	6.70E-10
	Chloride	water	unspecified	No	kg	7.60E-06
	COD, Chemical Oxygen Demand	water	unspecified	No	kg	4.60E-05
	Dinitrogen monoxide	air	unspecified	No	kg	2.20E-07
	Dissolved solids	water	unspecified	No	kg	1.00E-05
	Fluoride	water	unspecified	No	kg	7.90E-07
	Iron	water	unspecified	No	kg	1.60E-08
	Mercury	air	unspecified	No	kg	2.10E-08
	Mercury	water	unspecified	No	kg	6.10E-10
	Metallic ions, unspecified	water	unspecified	No	kg	6.90E-05
	Methane	air	unspecified	No	kg	1.70E-05
	NMVOC, non-methane volatile organic compounds, unspecified origin	air	unspecified	No	kg	4.70E-05
	Oils, unspecified	water	unspecified	No	kg	3.90E-07
	Particulates, unspecified	air	unspecified	No	kg	4.50E-04
	Phenol	water	unspecified	No	kg	3.90E-10
	Sodium, ion	water	unspecified	No	kg	1.96E-03
	Sulfate	water	unspecified	No	kg	1.75E-03
	Suspended solids, unspecified	water	unspecified	No	kg	1.30E-04

Classification

- Taking huge list of inventory flows and making smaller more manageable piles
  - GHGs all in one pile. Ozone depleters, etc.
  - ‘copy’ (not ‘move’) into these piles
  - Why? Some in several piles, e.g., NOx (toxic, acidic, eutrophication)

Mandatory

Classifying Greenhouse Gases

- IPCC (100-year) method Example

Name	Chemical Formula
Carbon dioxide	CO_2
Methane	CH_4
Nitrous oxide	N_2O
CFC-11	CCl_3F
CFC-12	CCl_2F_2
CFC-13	$CClF_3$
CFC-113	CCl_2FCClF_2
CFC-114	$CClF_2CClF_2$
CFC-115	$CClF_2CF_3$
Halon-1301	$CBrF_3$
Halon-1211	$CBrClF_2$
Halon-2402	$CBrF_2CBrF_2$
Carbon tetrachloride	CCl_4
Methyl bromide	CH_3Br
Methyl chloroform	CH_3CCl_3
HCFC-22	$CHClF_2$
HCFC-123	$CHCl_2CF_3$
HCFC-124	$CHClFCF_3$
HCFC-141b	CH_3CCl_2F
HCFC-142b	CH_3CClF_2
HCFC-225ca	$CHCl_2CF_2CF_3$
HCFC-225cb	$CHClFCF_2CClF_2$

Figure 10-7: (Abridged) List of Substances Classified into IPCC (2007) LCIA Method

Classifying Energy Demand

- Cumulative Energy Demand (CED) LCIA Method

Category	Subcategory	Included Energy Sources
Non-renewable resources	fossil	hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat
	nuclear	uranium
	primary forest	wood and biomass from primary forests
Renewable resources	biomass	wood, food products, biomass from agriculture, e.g. straw
	wind	wind energy
	solar	solar energy (used for heat & electricity)
	geothermal	geothermal energy (shallow: 100-300 m)
	water	run-of-river hydro power, reservoir hydro power

Figure 10-8: Energy Sources Classified into Cumulative Energy Demand (CED) LCIA Method (Source: Hischier 2010)

Mandatory

Classification of Initial Inventory

Flux	Compartment	Unit	Option A	Option B
Carbon dioxide, fossil (CO_2)	Air	Kg	5	2
Sulfur dioxide (SO_2)	Air	Kg	2	5
Oil			10	8

Classification: Climate Change Impact Category (IPCC)				
Flow	Compartment	Units	Option A	Option B
Carbon dioxide, fossil	air	kg	5	2
Classification: Energy Impact Category (CED)				
Crude oil		kg	10	8

- Where is SO_2?
- What if one of our flows belonged in two categories?

Classification Issues

- Depending on scope, you might have no flows (or too few) to classify into your LCIA methods
  - Ex 1: you want to study global warming but you have no GHG emissions in inventory
  - Ex 2: your inventory is too narrow to support a robust LCIA effort (e.g., only have fossil CO_2 emissions not methane, etc.)
- If so, "impact results" will be zero or less than expected due to data gaps, not representative of product system
- This is why process matrix methods are so useful – they basically ensure you have sufficient flows (done by SW)
- Classification by hand can introduce errors
  - Variation in naming conventions
  - Scope of methods
  - Misclassification
- Mostly handled by software, matching by Chemical Abstract System (CAS) Numbers
  - e.g., formaldehyde is 50-00-0
- Many classification issues can be avoided by keeping your scope broad

Next step: Characterization

- Transforms classified flows into impact category indicators via characterization factors
  - Impact categories could include: resources, ecosystems, human health
  - Indicators convert multiple flows (maybe with different units) into a single common unit
  - Allows for comparison
- Characterization factors are available from separate scientific studies on impact assessment
  - Not done for a single LCA study
  - We'll use existing factors (and don't need to create them)

Characterization

- GHGs – obvious example. Use GWP weights! (e.g., CO_2-equivalents or CO_2e)
  - CO_2 : 1 kg of CO_2 = 1 kg of CO_2e
  - CH_4 : 1 kg of CO_2 = 28 kg of CO_2e
  - N_2O : 1 kg of CO_2 = 265 kg of CO_2e
  - Sum up individual effects (units CO_2e)

- For many studies the only LCIA done is global warming (e.g., "carbon footprinting")

$$Characterized\ flow = flow\ (inventory\ unit) * char.factor\ \left(\frac{characterized\ units}{inventory\ unit}\right)$$

IPCC 5th Assessment Report

- Not just a single set of values!

Name	Chemical Formula	Characterization Factor (kg CO_2-eq / kg of substance)	
		20 years	100 years
Carbon dioxide	CO_2	1	1
Methane	CH_4	84	28
Methane, fossil	CH_4	85	30
Nitrous oxide	N_2O	264	265
CFC-11	CCl_3F	6,900	4,660
CFC-12	CCl_2F_2	10,800	10,200
CFC-13	$CClF_3$	10,900	13,900
CFC-113	CCl_2FCClF_2	6,490	5,820
CFC-114	$CClF_2CClF_2$	7,710	8,590
CFC-115	$CClF_2CF_3$	5,860	7,670
Halon-1301	$CBrF_3$	7,800	6,290
Halon-1211	$CBrClF_2$	4,590	1,750

LCIA 'Model' Example

Table 1 — Example of terms

Term	Example
Impact category	Climate change
LCI results	Greenhouse gases
Characterization model	IPCC [a] model
Category indicator	Infrared radiative forcing (W/m^2)
Characterization factor	Global warming potential for each greenhouse gas (kg CO_2-equivalents/kg gas)
Indicator result	kg of CO_2-equivalents
Category endpoints	Coral reefs, forest, crops
Environmental reference	Degree of linkage between category indicator and category endpoint
NOTE Further examples are provided in ISO/TR 14047 [1].	
[a] Intergovernmental Panel on Climate Change.	

Source: ISO 14044 (2006)

- Should have a comprehensive set of impact categories/ indicators
- Your own "values" should not bias your model

Environmental impact categories: how to choose

- Table reports a typical result of Inventory analysis

Flux	Compartment	Unit	Option A	Option B
Carbon dioxide, fossil (CO_2)	Air	Kg	5	2
Sulfur dioxide (SO_2)	Air	Kg	2	5
Oil			10	8

- Statement "A is always better then B" is not always obvious
  - Particularly in different scenarios
- In presence of more fluxes (CO_2, SO_2, oil) which one should be chosen?

- Difficult to prefer one over the other
- Next step: Summarize LCIA results for GHG and CED

LCIA Profile (aka category indicator results)

- Summary of all indicator category values
- Using IPCC and CED values, our inventory is...
  - Recall IPCC GWP of 1 for CO_2, CED 45.8 MJ-eq. for crude oil (fossil category)

Characterization: Climate Change (IPCC 2013)			
Indicator	**Units**	**Option A**	**Option B**
Equivalent releases CO_2	kg CO_2 equiv.	5	2
Characterization: Energy (CED)			
Non-renewable fossil	MJ-eq.	458	366
Non-renewable nuclear	MJ-eq.	0	0
Non-renewable forest	MJ-eq.	0	0
Non-renewable total	MJ-eq.	458	366
Renewable total	MJ-eq.	0	0

Figure 10-12: LCIA Profile of Hypothetical Example

Exercise: Expand Example Profile

Flux	Compartment	Unit	Option A	Option B
Carbon dioxide, fossil (CO_2)	Air	Kg	5	2
Sulfur dioxide (SO_2)	Air	Kg	2	5
Oil			10	8

CO_2 and Crude oil are done – now add SO_2 to the profile using following info

Flow	Acidification Air (kg H+ moles eq / kg substance)	Human Health - Criteria Air (kg PM10 eq / kg substance)
Sulfur dioxide	50.8	0.167

Figure 10-23: Excerpted Characterization Factors for Sulfur Dioxide

Exercise: Expand Example Profile

Characterization: Climate Change (IPCC 2013)			
Indicator	**Units**	**Option A**	**Option B**
Equivalent releases CO_2	kg CO_2 equiv.	5	2
Characterization: Energy (CED)			
Non-renewable fossil	MJ-eq.	458	366
Non-renewable nuclear	MJ-eq.	0	0
Non-renewable forest	MJ-eq.	0	0
Non-renewable total	MJ-eq.	458	366
Renewable total	MJ-eq.	0	0

Characterization: Acidification Air

Characterization: Human Health – Criteria Air

Exercise: Expand Example Profile

Characterization: Climate Change (IPCC 2013)			
Indicator	**Units**	**Option A**	**Option B**
Equivalent releases CO_2	kg CO_2 equiv.	5	2
Characterization: Energy (CED)			
Non-renewable fossil	MJ-eq.	458	366
Non-renewable nuclear	MJ-eq.	0	0
Non-renewable forest	MJ-eq.	0	0
Non-renewable total	MJ-eq.	458	366
Renewable total	MJ-eq.	0	0
Characterization: Acidification Air			
SO_2	kg H+ moles eq	101	254
Characterization: Human Health – Criteria Air			
SO_2	kg PM10 eq	0.33	0.84

Then, compare results for Options A and B

Is A preferable over B?

- It depends (as usual)
  - Discuss
- Are these results significant?
  - Magnitude
- Are they significantly different?
  - Uncertainty
- Are there model parameters which impact choice?
  - Scenarios
- Other things to think about?

Intermediate Summary

- Those are the mandatory elements (selection, classification, characterization)
  - Makes sense. If conducting LCIA, need to do at least these things
- Many studies are only LCI
- Likewise, many studies stop LCIA HERE (i.e., don't do optional steps)

- If stop here, then need to interpret results (as done with inventory step)
  - Don't just discuss numbers, talk about tradeoffs!

- Next (optional)
  - **Classification** of flows related to specific impact
  - **Characterization** of impacts, i.e. calculation of contribution to final score

Optional
  - **Normalization** → Divide the values of the impact category by a reference number (year, region, person, …)
  - **Grouping** → Group similar impacts into the same contribution
  - **Weighting** → Assign a specific parameter to weight differently various contribution

According to ISO 14040-44

Optional Step – Normalization

- "Normalizes" against (divide by) reference value
  - Reference values specific to each impact
- Provides some perspective
  - Global warming impact is 50 tons. Is that significant?
- Can be a helpful way to validate results
- ISO does not provide these values
  - But others have generated values that often used
  - Integrated into software
- Various ways to normalize:
  - Total effect of a person per year
  - Total in a country or region
  - Total per-capita
  - Against another option being studied (A vs B)
- Downside – normalizing on total effects generally yields negligible values
  - Alternative: adjust scale, normalize against hourly rate? Regional rates? Etc.

Optional Step – Grouping

- Sorting and/or ranking the characterized LCIA results (or normalized, optional)
  - Sorting along dimensions of the values, spatial scales, etc.
  - Ranking based on hierarchy to place the impacts into context with each other
  - (e.g., subjectively-defined high-medium-low impacts)
- Relies on value choices and thus is subjective
  - Could be inconsistent with what others choose
- More useful with multiple impact categories
  - Look at these first, then those

Optional Step – Weighting

- Most subjective of optional elements
- Weighting factors to allow for rolling up effects to a single (or a few) impact scores
- Comparative weighting of effects against each other (via relative importance of the effect)

Evaluation, Reporting and iteration

- Evaluation & reporting
  - Last LCIA step
  - Include all intermediate profile results
    - Transparency
    - Gives greatest future utility (comparison to other studies)
- Iterate through interpretation
  - Are results consistent with goal and scope?
  - Is inventory robust enough to support impact assessments?

LCIA Limitations

- Scientific method combined with values
- Lack of comprehensive focus/boundary
- Category indicators not equally important or precise
- Lack of complete data
- All of this very subjective compared to LCI
- Uncertainty!!

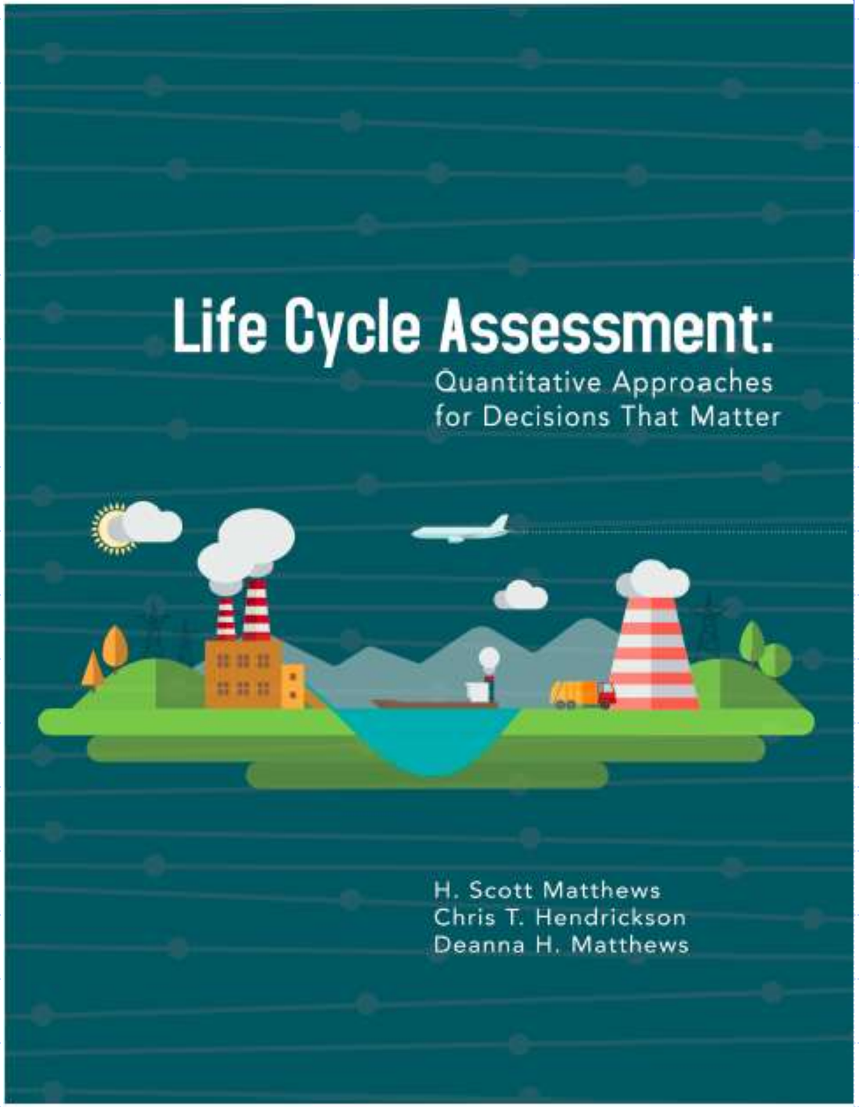
- This is a major area of research right now

Agenda

- Life cycle thinking
- Quantitative methods and life cycle cost analysis
- The ISO LCA standard
- Life cycle inventory
  - Data needs and data quality
  - Data sources
  - Handling multifunction systems (disaggregation and allocation)
  - Uncertainty
  - Input-output LCA
- Impact assessment
- Conclusions

Putting All the Pieces Together

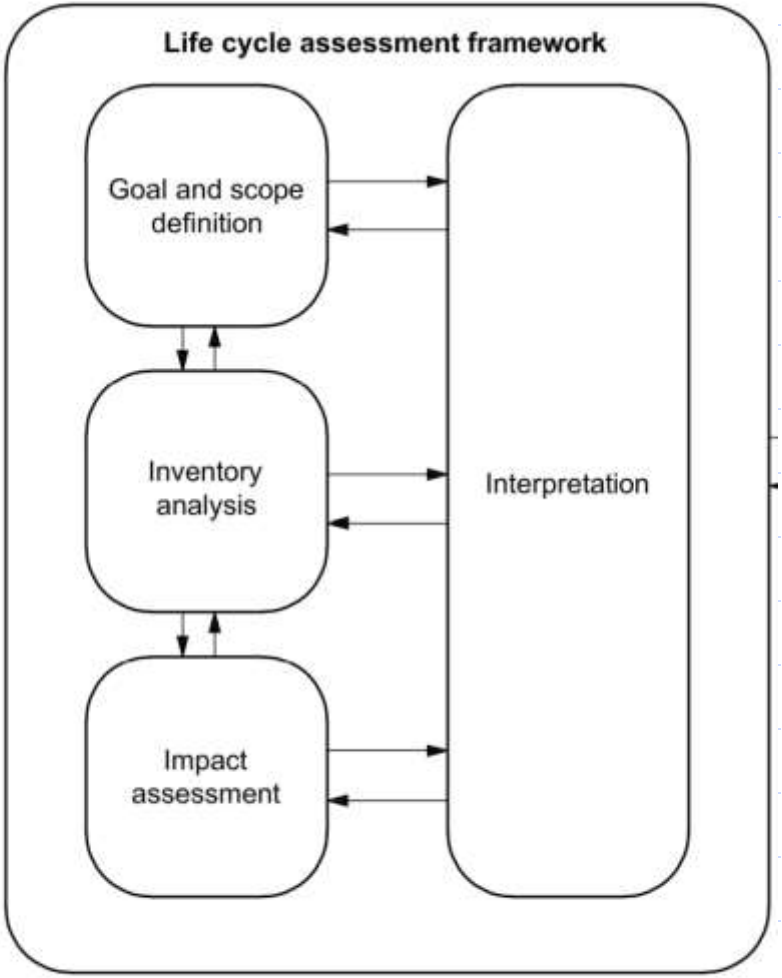
- LCA for Big Decisions
  - Recall title of LCA book…
- Easy to do small scale LCIs/LCAs
  - low chance for messing up and it mattering
- Recall initial LCA examples mentioned: zero emission electric vehicles, bottled versus tap water, etc.
  - Several of these were "big decisions"!
  - What have we learned from attacking these questions?



In summary …

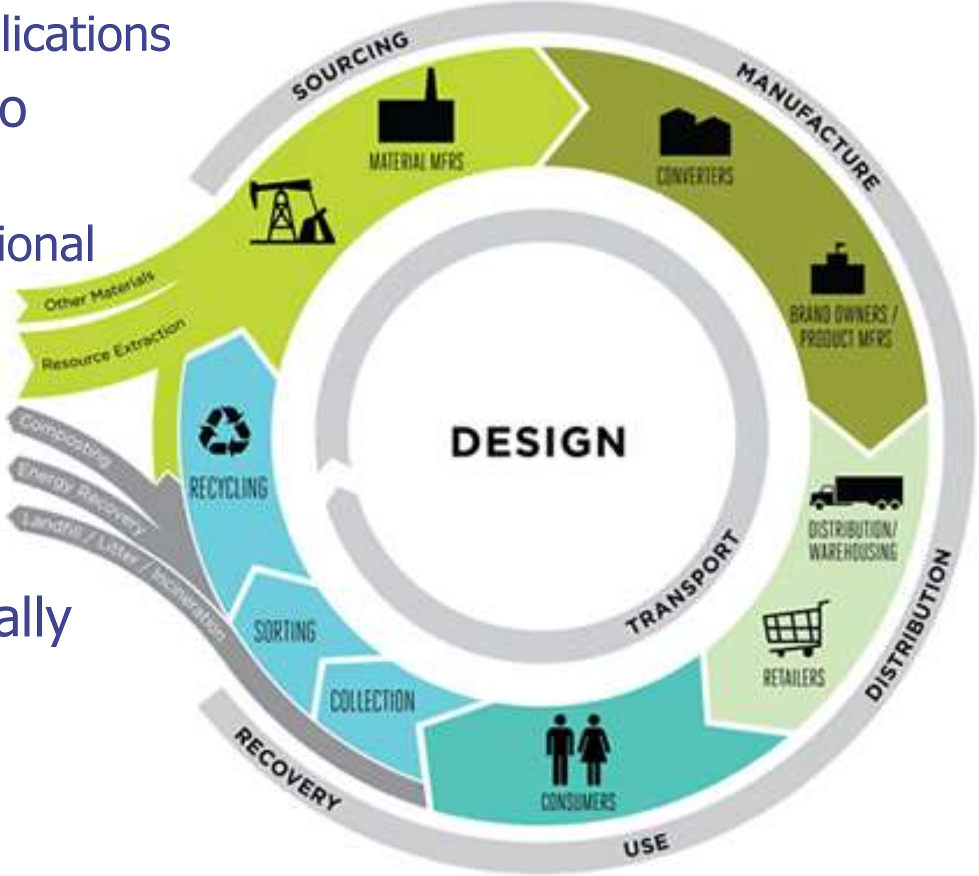
- Rigorous attention to data and quality
- Careful uncertainty assessment
- Context/Perspective important
- Carefully read and study ISO standard

- → Can we bring rigorous LCA methods to help inform big decisions?
  - YES



In conclusion

- LCA is a well developed high profile tool
  - LCA practice is increasingly being harmonized
  - It has a broad spectrum of applications
- LCA has clear limitations it is no "super-tool2:
  - There is a strong need of additional tools in the life cycle context
  - When augmented by tools that monitor economic and social performance, LCA supports sustainable analysis
- LCA and certification are mutually supported activities



Appendix: EPD

EPD, Feedstock energy e CED per il computo delle energie

- Esempio di flussi energetici = Comulative Energy Demand methods

Category	Subcategory	Included Energy Sources
Non-renewable resources	fossil	hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat
	nuclear	uranium
	primary forest	wood and biomass from primary forests
Renewable resources	biomass	wood, food products, biomass from agriculture, e.g. straw
	wind	wind energy
	solar	solar energy (used for heat & electricity)
	geothermal	geothermal energy (shallow: 100-300 m)
	water	run-of-river hydro power, reservoir hydro power

Figure 10-8: Energy Sources Classified into Cumulative Energy Demand (CED) LCIA Method (Source: Hischier 2010)

EPD, Feedstock energy e CED per il computo delle energie

THE INTERNATIONAL EPD® SYSTEM

Categorie di impatto	Fattori di caratterizzazione	Riferimenti
Acidification potential (kg SO2 eq.)	AP, CML 2001 non-baseline (fate not included), Version: January 2016.	Hauschild & Wenzel (1998)
Eutrophication potential (kg PO43- eq.)	EP, CML 2001 baseline (fate not included), Version: January 2016.	Heijungs et al. (1992)
Global warming potential (kg CO2 eq.)	GWP100, CML 2001 baseline Version: January 2016.	IPCC (2013) *Updated January 2016*
Photochemical oxidant formation potential (kg NMVOC eq.)	POFP, LOTOS-EUROS as applied in ReCiPe 2008	Van Zelm et al 2008 ReCiPe 2008
Water Scarcity Footprint (WSF) (m3 H2O eq)	AWARE Method: WULCA Characterization model for WSF 2015, 2017.	Boulay et al(2017)
Abiotic depletion potential – Elements (kg Sb eq.)	ADPelements, CML 2001, baseline	Oers, et al (2002)
Abiotic depletion potential – Fossil fuels (MJ, net calorific value)	ADPfossil fuels, CML 2001, baseline	Oers, et al (2002)

PARAMETER		UNIT	NON-CONSTRUCTION PRODUCTS: UPSTREAM/CORE/DOWNSTREAM/TOTAL				CONSTRUCTION PRODUCTS: A1/A2/A3, ETC.			
Global warming potential (GWP)	Fossil	kg CO_2 eq.								
	Biogenic	kg CO_2 eq.								
	Land use and land transformation	kg CO_2 eq.								
	TOTAL	kg CO_2 eq.								
Acidification potential (AP)		kg SO_2 eq.								
Eutrophication potential (EP)		kg PO_4^{3-} eq.								
Formation potential of tropospheric ozone (POCP)		kg C_2H_4 eq.								
Abiotic depletion potential – Elements		kg Sb eq.								
Abiotic depletion potential – Fossil fuels		MJ, net calorific value								
Water scarcity potential		m^3 eq.								

Table 4. Indicators describing potential environmental impacts.

https://www.environdec.com/Creating-EPDs/Steps-to-create-an-EPD/Perform-LCA-study/Characterisation-factors-for-default-impact-assessment-categories/

EPD, Feedstock energy e CED per il computo delle energie

EPD®

THE INTERNATIONAL EPD® SYSTEM

PARAMETER		UNIT	NON-CONSTRUCTION PRODUCTS: UPSTREAM/CORE/DOWNSTREAM/TOTAL				CONSTRUCTION PRODUCTS: A1/A2/A3, ETC.			
Primary energy resources – Renewable	Use as energy carrier	MJ, net calorific value								
	Used as raw materials	MJ, net calorific value								
	TOTAL	MJ, net calorific value								
Primary energy resources – Non-renewable	Use as energy carrier	MJ, net calorific value								
	Used as raw materials	MJ, net calorific value								
	TOTAL	MJ, net calorific value								
Secondary material		kg								
Renewable secondary fuels		MJ, net calorific value								
Non-renewable secondary fuels		MJ, net calorific value								
Net use of fresh water		m^3								

Table 5. Indicators describing use of primary and secondary resources

Da calcolare con il CED – Comulative Energy Demand

Flussi di materia ed energia uscenti dal sistema prodotto

Da calcolare con ReCiPe 2008 «water deplation»

Attenzione alla feedstock energy nei polimeri!!

https://www.environdec.com/Creating-EPDs/

EPD, Feedstock energy e CED per il computo delle energie

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PARAMETER	UNIT	NON-CONSTRUCTION PRODUCTS: UPSTREAM/CORE/DOWNSTREAM/TOTAL	CONSTRUCTION PRODUCTS: A1/A2/A3, ETC.
Hazardous waste disposed	kg		
Non-hazardous waste disposed	kg		
Radioactive waste disposed	kg		

Table 6. Indicators describing waste production.

Da calcolare con il modello EDIP 2003 utilizzando i flussi di rifiuti

PARAMETER	UNIT	NON-CONSTRUCTION PRODUCTS: UPSTREAM/CORE/DOWNSTREAM/TOTAL	CONSTRUCTION PRODUCTS: A1/A2/A3, ETC.
Components for reuse	kg		
Material for recycling	kg		
Materials for energy recovery	kg		
Exported energy, electricity	MJ		
Exported energy, thermal	MJ		

Table 7. Indicators describing output flows.

Tipologia di energia e di rifiuti dei rifiuti uscenti dal sistema prodotto

https://www.environdec.com/Creating-EPDs/