Design for Sustainability

Introduction to Life Cycle Assessment

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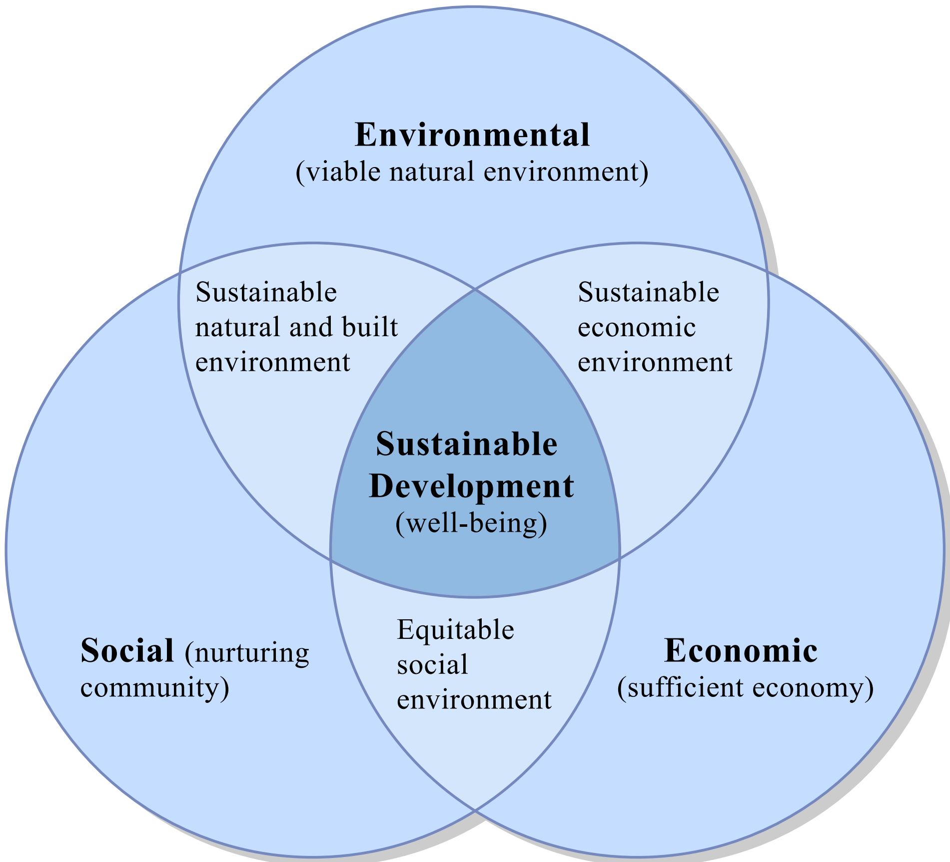
What is Sustainable Development?



The Concept of Sustainable Development

- **Original definition:**
  "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs"
  (Brundtland Commission 1987)

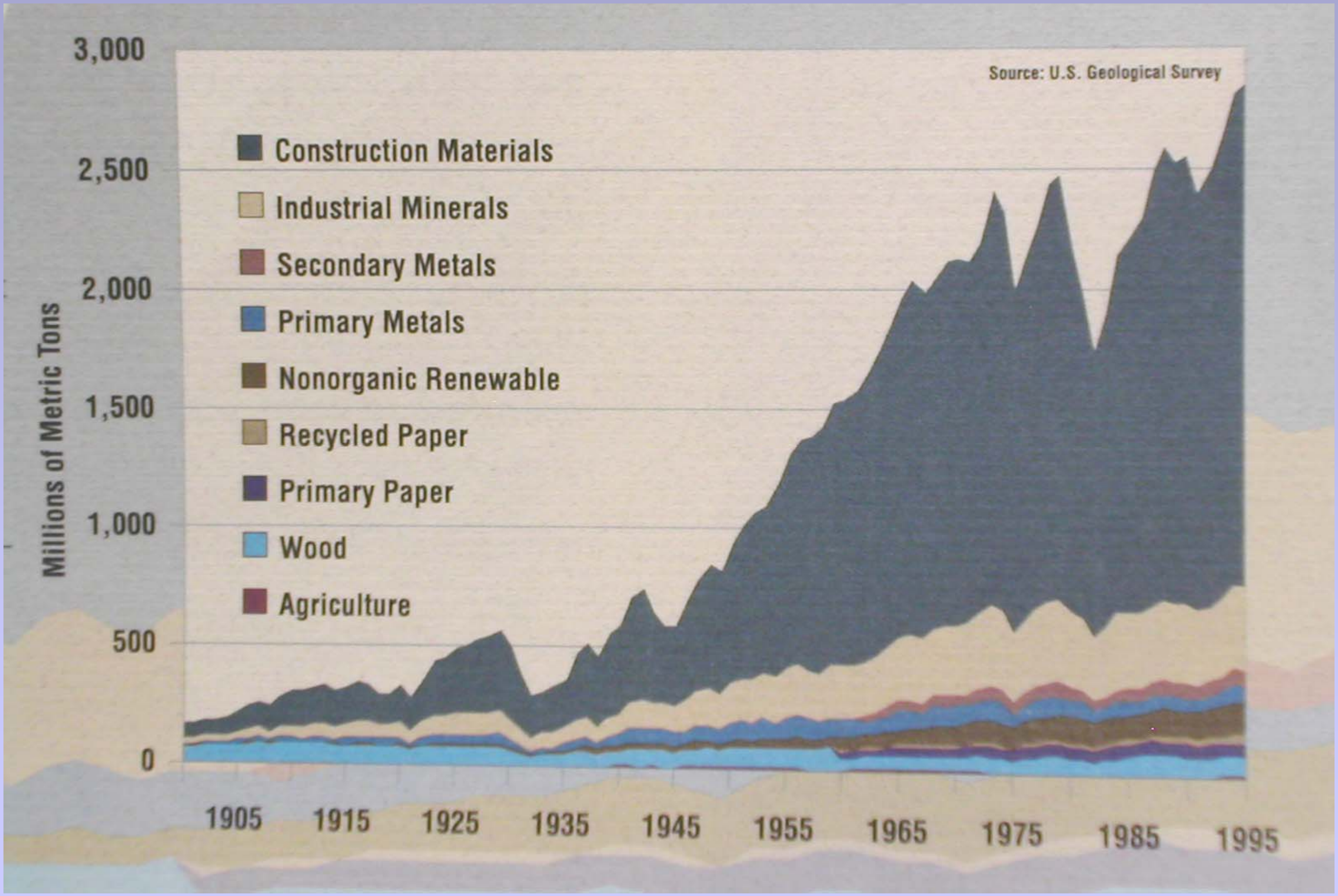
- **More recently:**
  "A dynamic process which enables all people to realize their potential and to improve their quality of life in ways which simultaneously protect and enhance the earth's life support systems"
  (Forum for the Future)

Figure by MIT OCW.

Challenges to make development sustainable

- **Differences in timescales:** bridging the gap between typical political and commercial timescales and the long view of sustainability
- **Dealing with economic market-technology 'failure':** learning why market economics and technology do not interact fast enough to produce sustainability - and changing the signals
- **Defining 'progress' to sustainability:** better indicators and sustainability measurements to drive better choices
- **Addressing the harder 'social dimension':** including 'social' components in projects; social objectives for products and projects; consulting properly with local communities
- **Understanding and engaging with real world complex systems:** changing our 'world view' to understand complex interactions and feedback loops, and changing to adopt the 'precautionary principle'

Use of Raw Materials in the U.S.



Construction and the Environment

US Primary Energy Consumption:

Buildings	**37%**
Industry	**36%**
Transportation	**28%**

Source: US Dept. of Energy (2002)

Construction and the Environment

In the United States, buildings account for:

37% of total energy use
(65% of electricity consumption)
30% of greenhouse gas emissions
30% of raw materials use
30% of waste output (136 million tons/year)
12% of potable water consumption

Source: US Green Building Council (2001)

Embodied Energy vs. Operating Energy

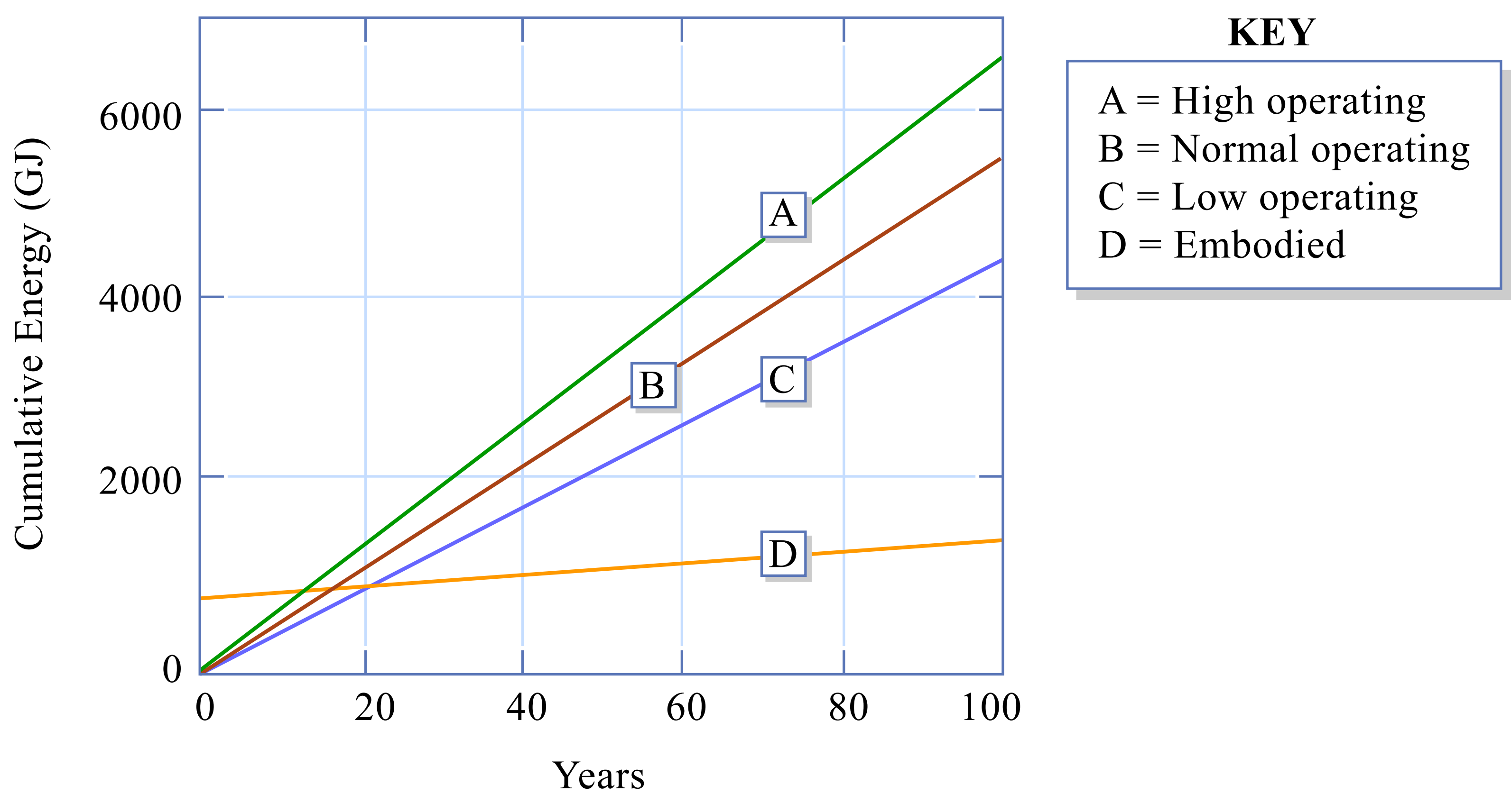


Figure by MIT OCW.

LEED Green Building Rating System

- Supported by the US Green Building Council
- Consensus-based rating system, crafted by professionals in the building profession
- Originally geared towards new (office space) construction, but now piloting modified rating schemes for homes, commercial interiors, renovations, and neighborhood development
- Building that participate in the rating system attain *Certified, Silver, Gold* or *Platinum* status based on points earned

LEED Categories

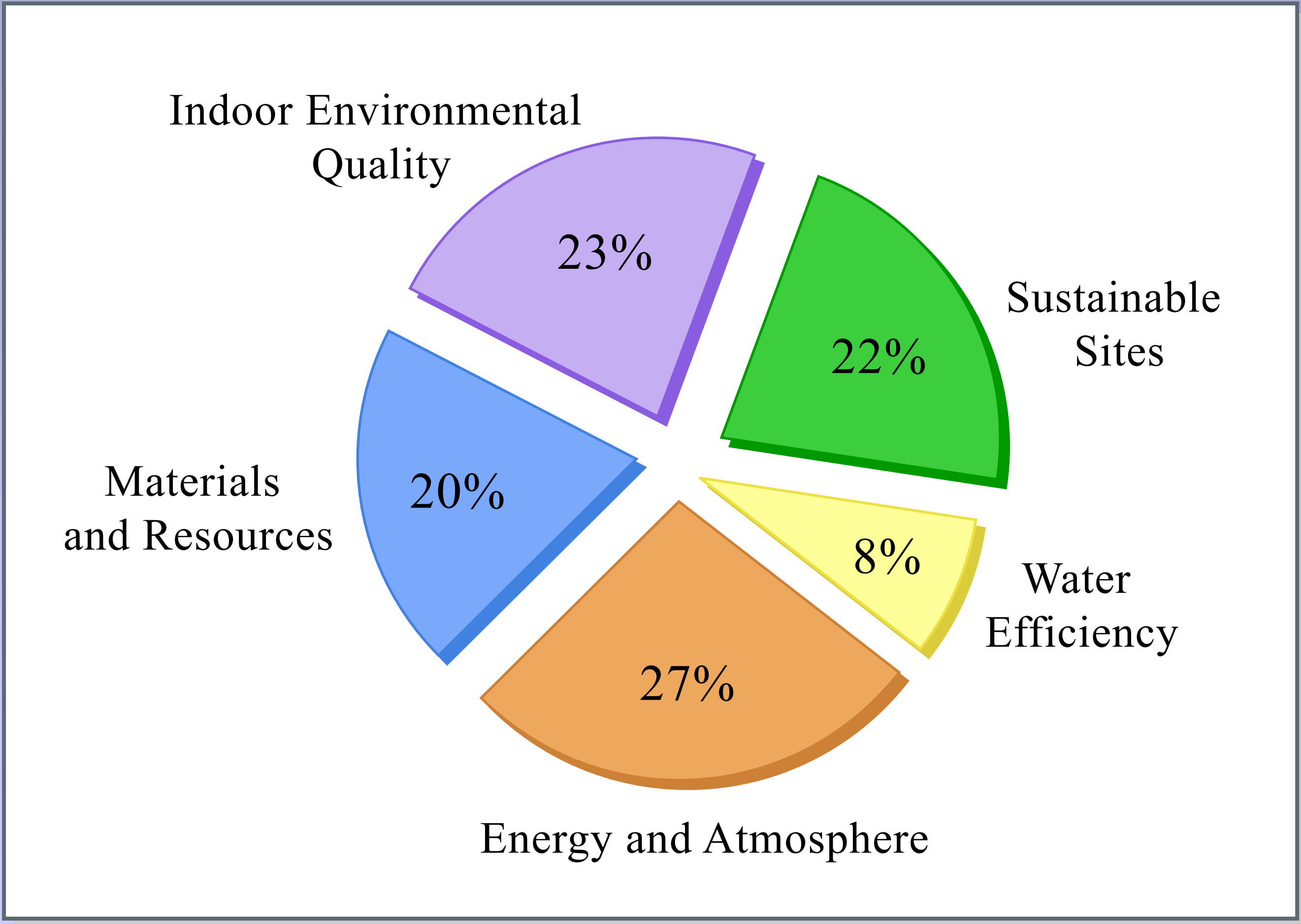


Figure by MIT OCW.

LEED Criticism

- Benefits
  - Raises consciousness of owners
  - Encourages integrated design
  - Facilitates discussions about the benefit of environmentally preferable building design strategies
  - Easily navigated; accessible to all building professionals
  - Constantly re-examined and updated
- Limitations
  - Equivalent point values are given to non-equivalent design strategies and improvements
  - Often reduced to a point optimization process
  - Evaluation mechanisms are often overly simplified and therefore misleading
  - Can only gain points for doing good, never lose points for inflicting harm

Life Cycle Assessment

An introduction to basic principles

Life Cycle Assessment – What is it?

- Life cycle assessment is the process of evaluating the total effects that a product has on the environment over its entire existence – starting with its production and continuing through to its eventual disposal.
- It is fundamentally a decision-making tool.

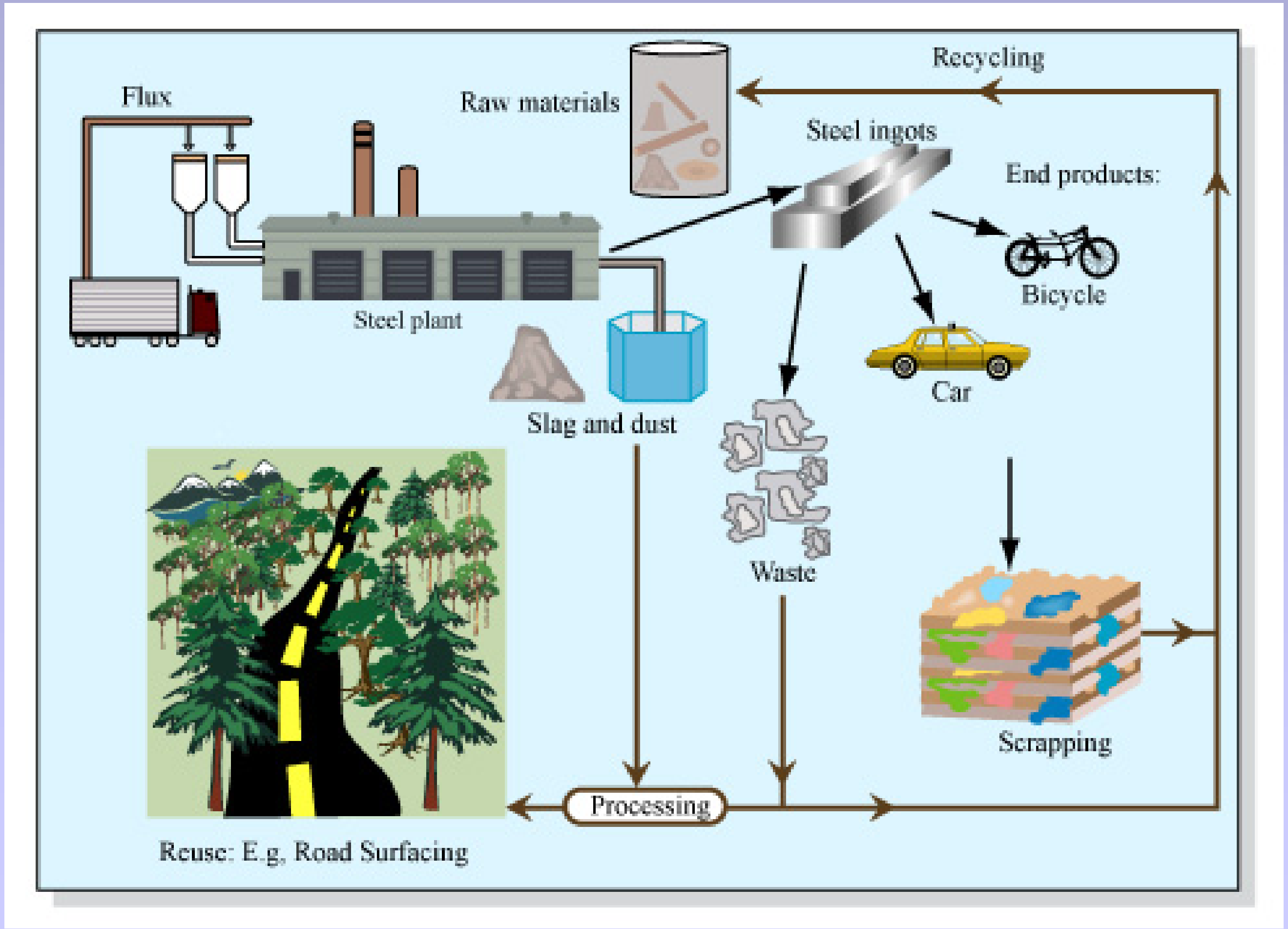


Figure by MIT OCW.

Image from: Svenska Mineral

Life Cycle Assessment – What is it?

- It accounts the energy and resource inputs, as well as the polluting outputs to land, water and air that result from the production of a product.
- It is an extremely complex environmental assessment tool that requires massive amounts of data which are often hard to find or expensive to purchase.
- It is still a method in progress:

> *"There is no single method for conducting LCA studies. Organizations should have flexibility to implement LCA practically as established in this International Standard, based upon the specific application and the requirements of the user."*
>
> (ISO 14040:1997)

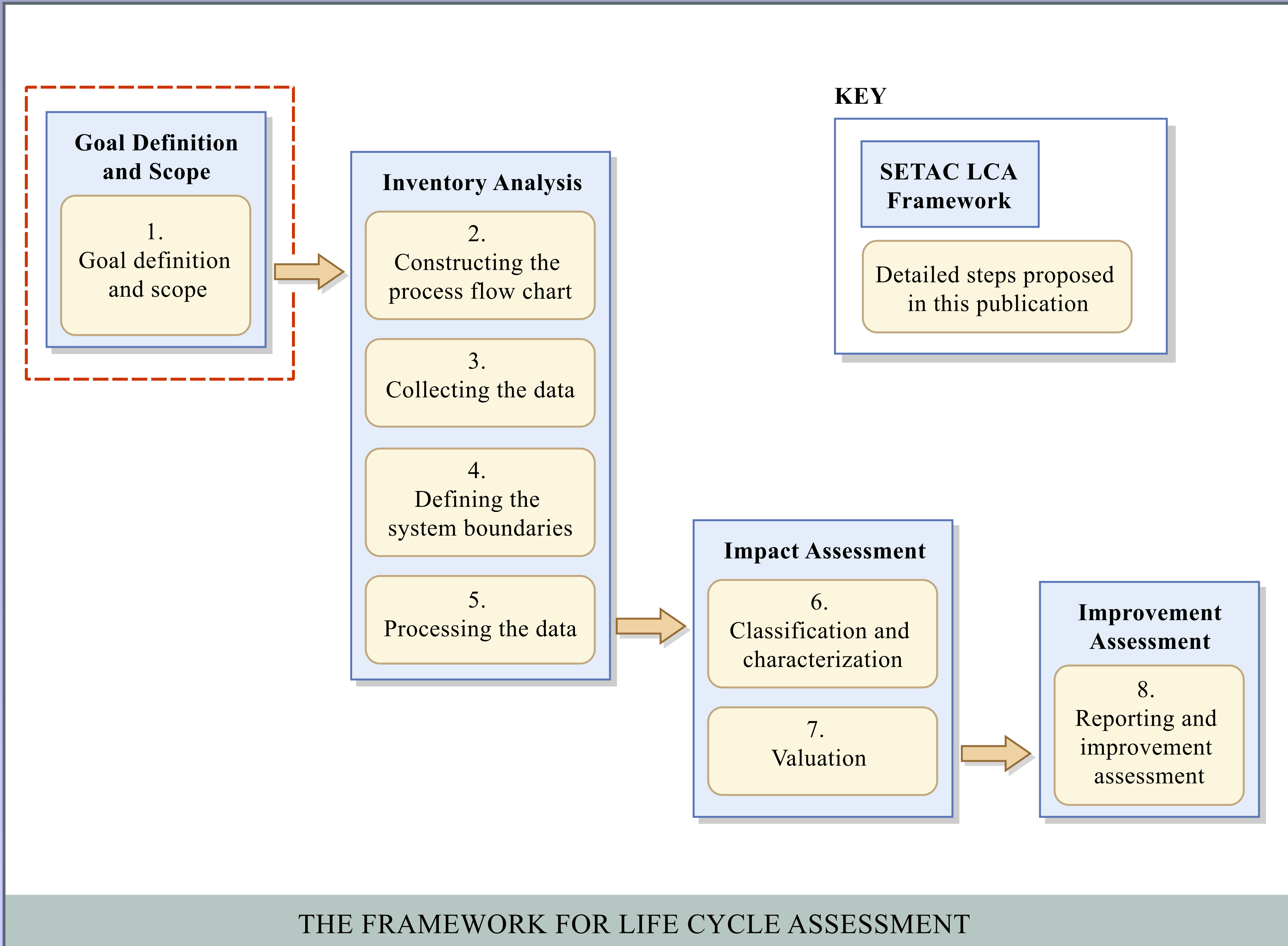


Figure by MIT OCW.

Diagram from: “Life Cycle Assessment: What It Is and How To Do It” Published by the United Nations Environmental Programme

Goal Definition and Scope

- What is being studied?
- Who is the intended audience?

- What is the functional unit to be examined?
- What are the data requirements?
- Are there any potentially critical assumptions to be made?

What is being studied and for whom?

- LCAs can be used privately, as a design tool within product development.
  - comparative and iterative
  - “quick-and-dirty”

- LCAs can be published for the purposes of eco-labeling.
  - attempt at absolute classification (it is actually a comparative assessment within a larger field)
  - require better data quality and precise calculations

Establishing the functional unit

- The functional unit is the comparison criterion or metric used in LCA
    - It is a comparison of product functions instead of product types or brands.
    - It often includes some indication of time.

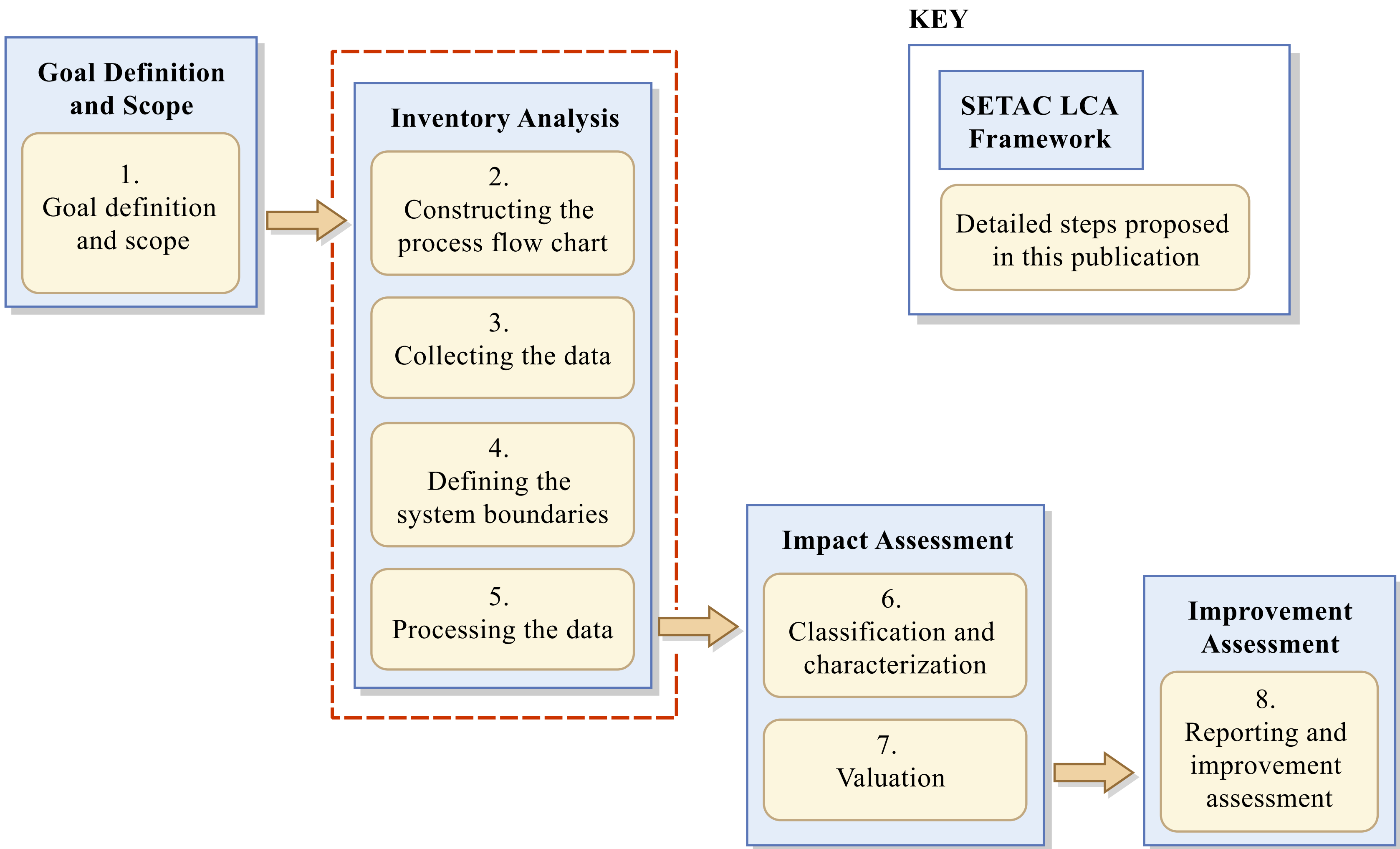
Life Cycle Assessment relies on well-formulated functional units to establish sensible comparative baselines against which to compare various product or project alternatives.

Data quality requirements

- Time-related coverage
- Geographical coverage
- Technological coverage
- Precision, completeness and representativeness
- Consistency
- Clearly stated sources and factors of uncertainty

Critical assumptions

- Location
  - Is the data local, regional, worldwide?
- Transport mechanism
  - Are materials being transported by truck, ship, rail, air?
  - How far are materials being transported?
- Equipment efficiency
  - Is the data based on state-of-the-art equipment or average-performing equipment?
- Levels of aggregation of data



THE FRAMEWORK FOR LIFE CYCLE ASSESSMENT

Figure by MIT OCW.

Diagram from: “Life Cycle Assessment: What It Is and How To Do It” Published by the United Nations Environmental Programme

Constructing a Process Flow Chart

- Helps identify scope of investigation
  - Locates critical processes
  - Locates “hidden” flows

Gypsum Production Flow Chart

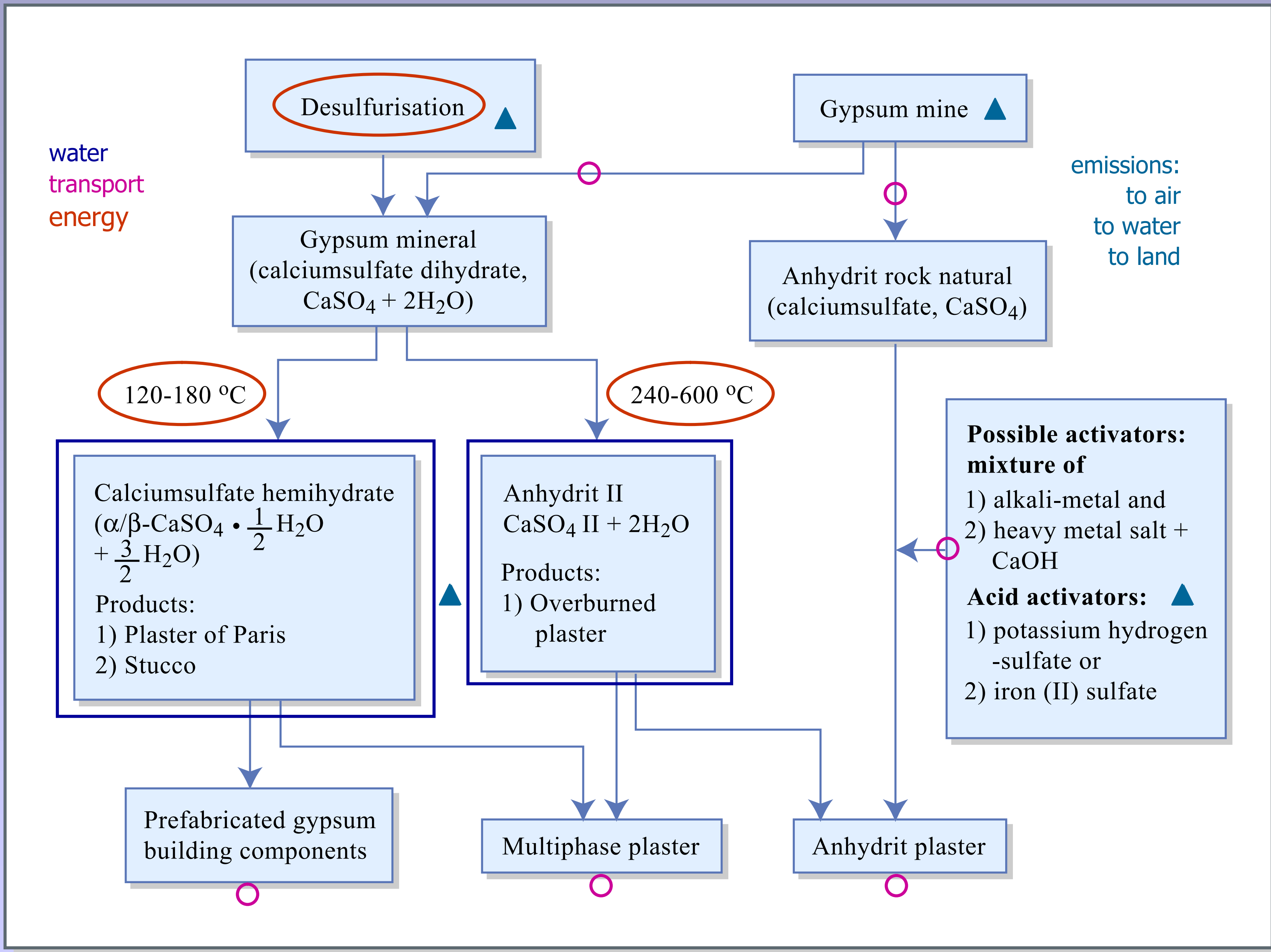


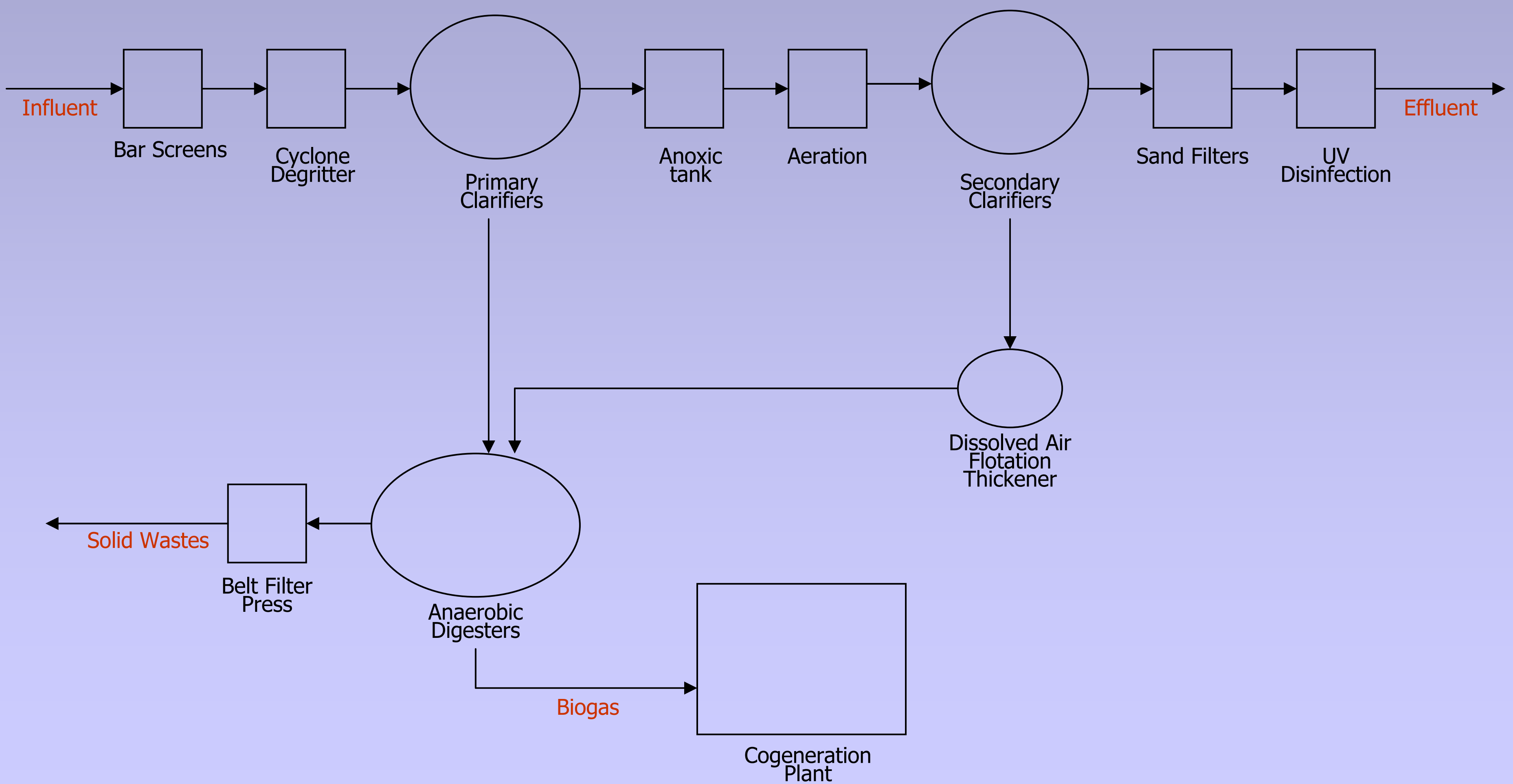
Figure by MIT OCW.

Constructing a Process Flow Chart

- Helps identify scope of investigation
  - Locates critical processes
  - Locates “hidden” flows

- Helps identify nature and amount of data required

Wastewater Treatment Facility Diagram



Constructing a Process Flow Chart

- Helps identify scope of investigation
  - Locates critical processes
  - Locates “hidden” flows
- Helps identify nature and amount of data required in the assessment
- Helps identify logical system boundaries

Assigning project boundaries

- In principle, the analysis boundaries should include all resource extractions and environmental emissions related to a product.
  - Practically, the boundaries of an analysis cannot capture the complete picture.

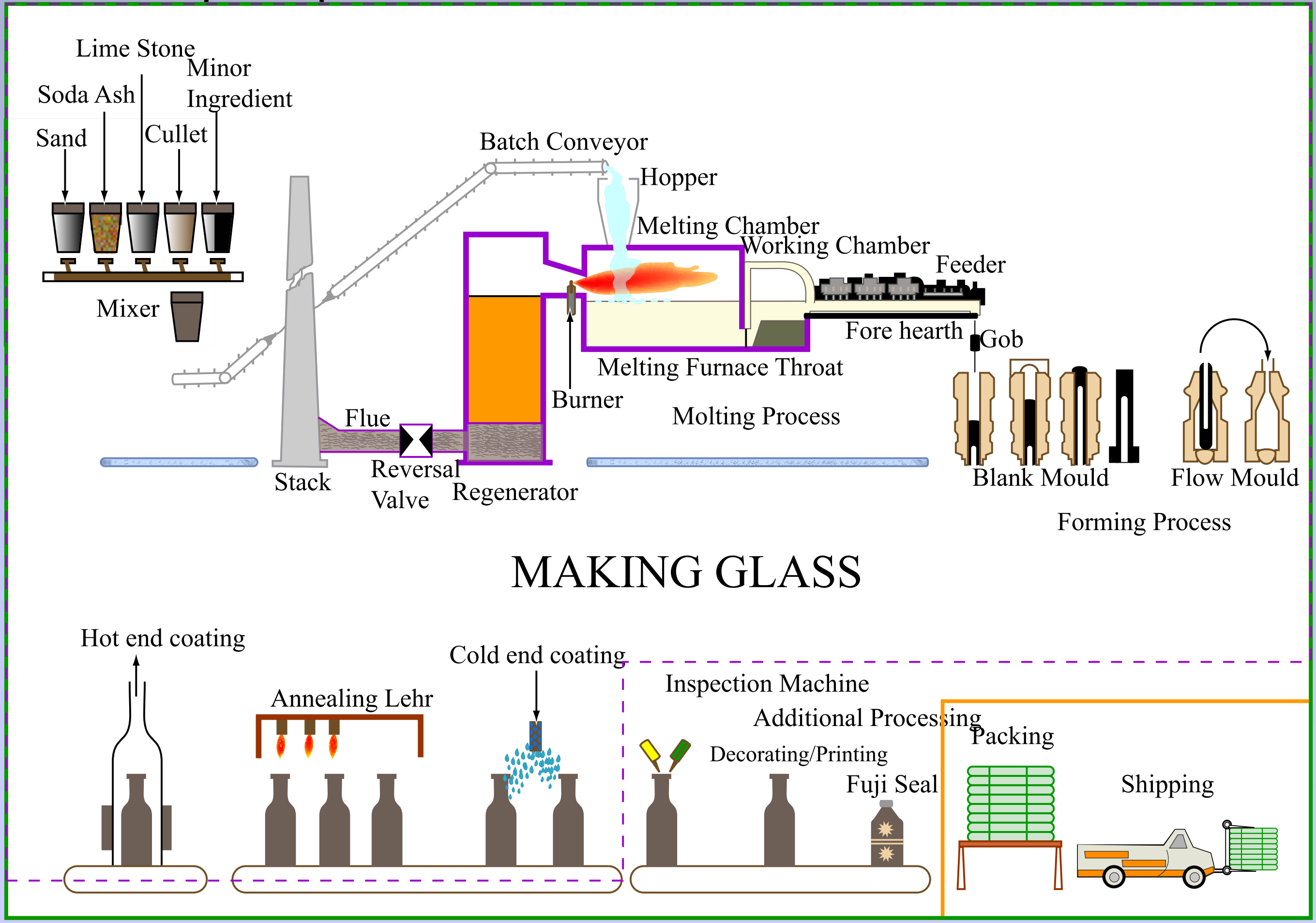


Figure by MIT OCW.

Collecting and Processing Data

- This is the most time and effort intensive portion of an LCA.
- Allocation procedures must be established when looking at systems that have multiple product flows.
- The calculation of energy flows and resulting extractions and emissions must take into account the different fuels used.

Data Sources

- Eco-invent Database
  - Fees
  - Extensive European data on full range of building products, energy production, transport, etc.
  - Data manipulated within the SimaPro user interface
  - Franklin database (US equivalent) currently under development
- Athena CMI
  - Fees
  - Canadian data with good range of building products
  - The Athena Institute also provides a user interface for evaluation of data
- BEES (NIST)
  - Free
  - North American data on a small handful of building products
  - <u>Very</u> limited in scope
- EIOLCA (Carnegie Mellon)
  - Free
  - Highly aggregated North American data
  - Limited in scope, breadth, and transparency of output data

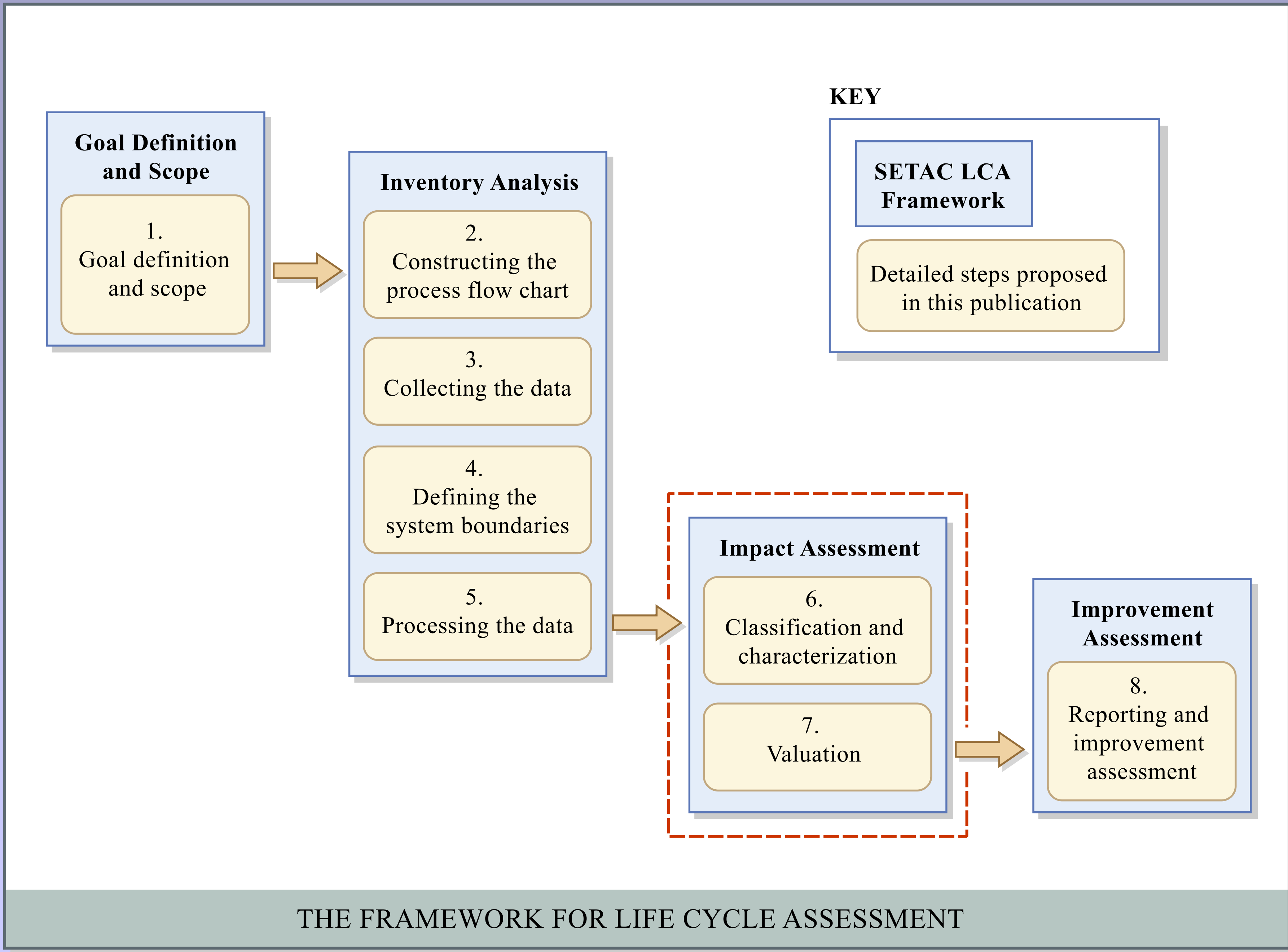


Figure by MIT OCW.

Diagram from: "Life Cycle Assessment: What It Is and How To Do It" Published by the United Nations Environmental Programme

Classification

- Classification categories
  - Abiotic depletion
    - result of extraction of non-renewable raw materials
  - Energy depletion
  - Global warming
    - effects of CO_2 and other greenhouse gases
  - Photochemical oxidant creation
    - smog
  - Acidification
    - result of nitrogen and sulphur oxide releases into atmosphere
  - Human toxicity
  - Ecotoxicity (aquatic and terrestrial)
  - Nutrification
    - addition of nutrients to soil and water, resulting in reduction of oxygen
  - Ozone depletion

Characterization

- Inventory data inputs and outputs assigned to relevant impact categories

- Characterization: components of each impact category are aggregated to one representative type

Acidification Potential is unequally affected by NOx, ammonia, and SO_2

the AP index is represented in *kg of SO_2/kg,* where:

1 kg of NOx is considered equivalent to *0.7 kg SO_2*
1 kg of NH_3 is considered equivalent to *1.9 kg SO_2*

Characterization Equivalency Factors

	ADP	EDP	GWP	POCP	AP	NP	ODP
Acetylene				0.168			
Ammonia					1.9	0.35	
Ammonium						0.33	
Benzene				0.189			
Cadmium	1.9×10^{-9}						
Carbon Dioxide			1				
Chemical Oxygen Demand						0.022	
Chlorobenzene							
CFC-12			7100				1
Halon-1202							1.3
Hexane				0.421			
Hydrocarbons				0.377			
Lead	1.3×10^{-11}						
Methane			11	0.007			
Mercury	1.8×10^{-7}						
Nitrate						0.1	
Nitrite						0.13	
Nitrogen						0.42	
Nitrogen Oxides					0.7	0.13	
Nitrous Oxide			270				
Phospate						1	
Sulphur Dioxide					1		
Trichloromethane			25				
Copper	2.9×10^{-12}						
Crude Oil		42.3(/kg)					
Natural Gas		35.7(/m3)					
Tin	2.3×10^{-10}						
Zinc	6.8×10^{-12}						

Multiple outputs affect each environmental impact category

Multiple impact categories can be affected by a single output

The result of this step is a series of indices (one per category) that describe the product in question

Normalization

- Which is more harmful?
  - Global warming potential = 250kg CO_2 equivalent
  - Nutrification potential = 149kg PO_4^{-3} (phosphate) equivalent

Normalization is a process by which the environmental index is "scaled" to some regional or global referent.

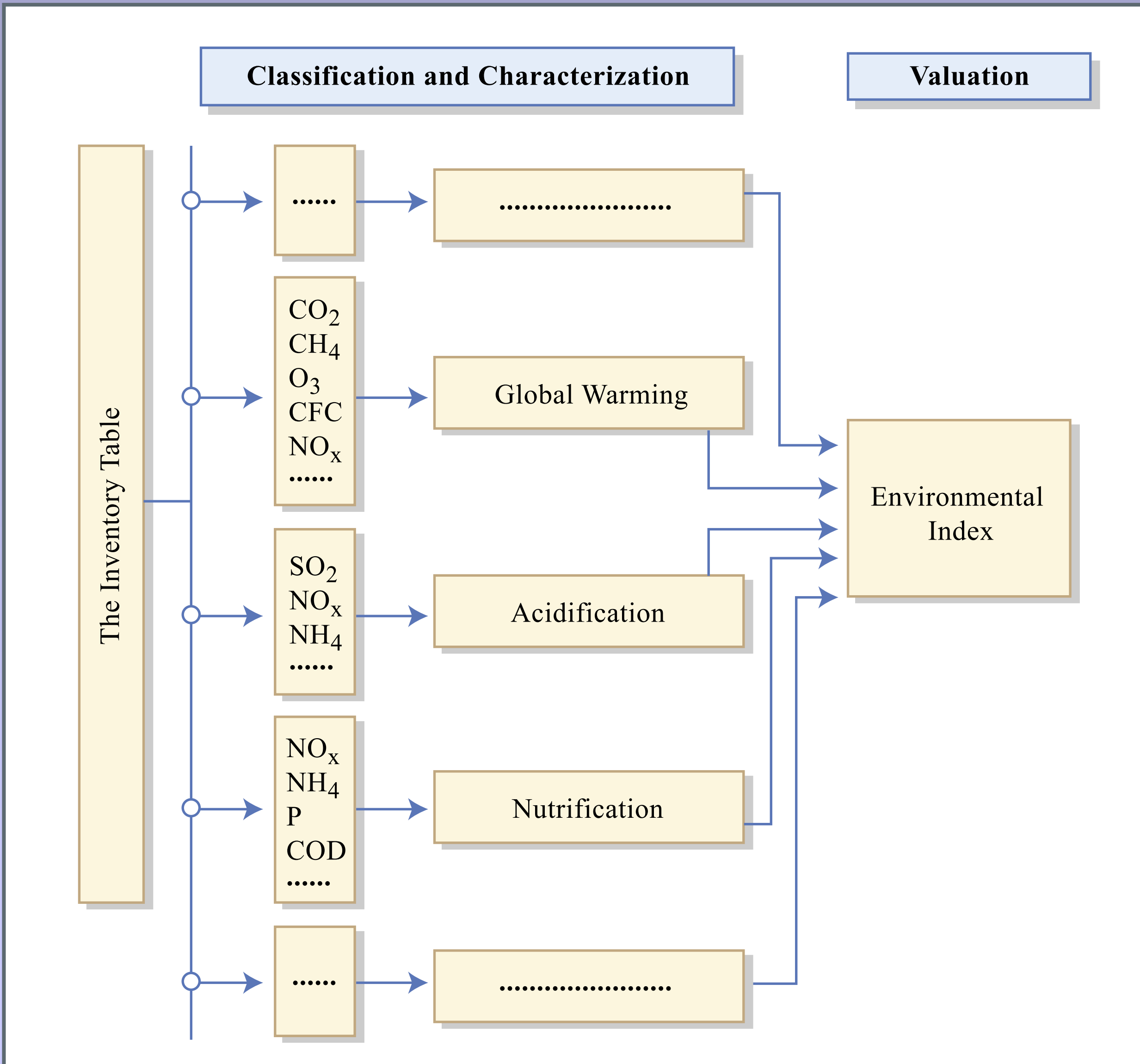
- Which is more harmful?
  - Global warming potential = 250kg/37.7x10^{12} kg CO_2 equivalent

    6.6×10^{-12}
    relative to global CO2 production
  - Nutrification potential = 149kg/74.8x10^{9} kg phosphate equivalent

    1995×10^{-12}
    relative to global Phosphate production

Valuation and Interpretation

- Subjective weighing process
  - Affected by location, politics, interests, opinions
- End result is a single environmental index, which simplifies all of the data into one value
  - Loss of transparency
  - Loss of specificity
  - Gain in comparability
- Known sets of weighing factors:
  - EPS system
  - Ecopoints
  - NSAEL factors
  - etc.

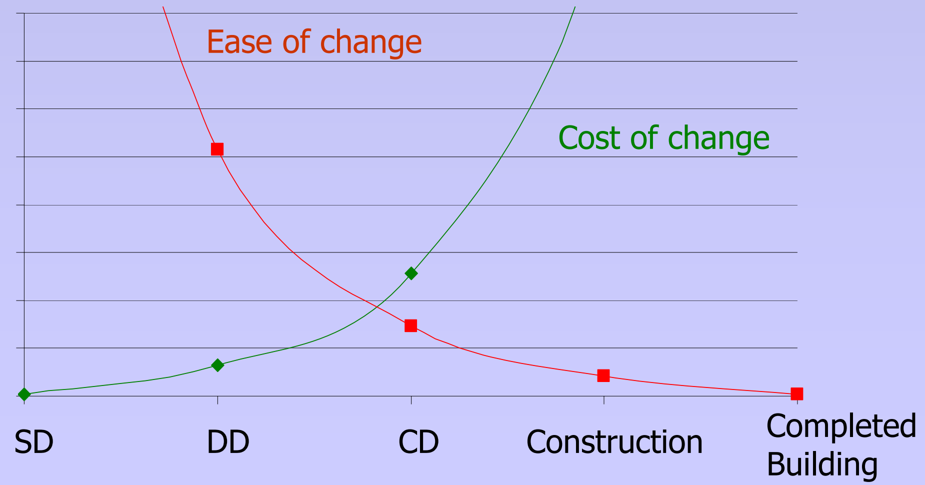


The Steps Involved in Impact Assessment

Figure by MIT OCW.

Why use LCA?

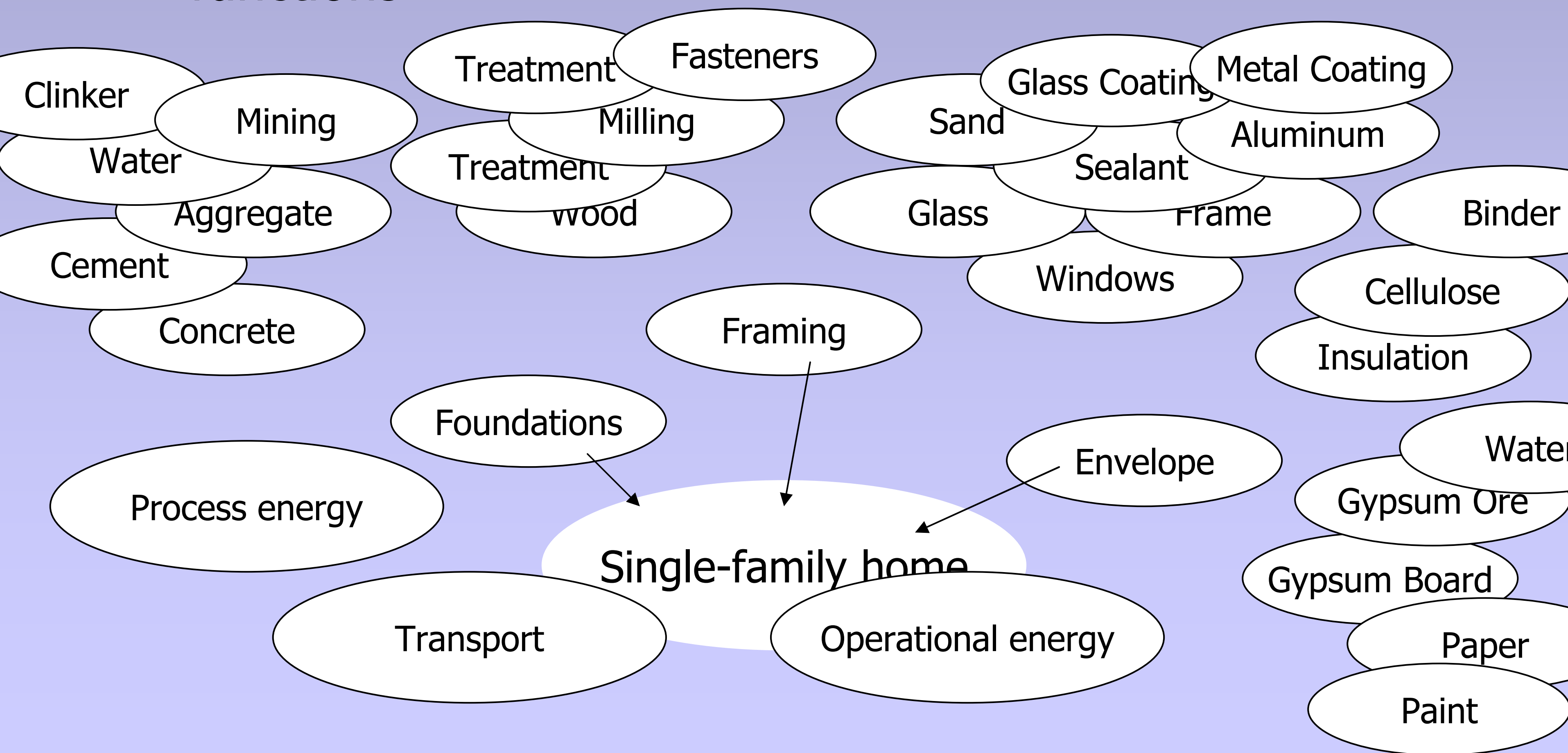
- It is quantitative.
  - LCA provides an objective, scientific, numerical basis for decision-making.
  - Enhances the reproducibility and consequent credibility of an environmental assessment.
- It is integrative.
  - By looking at a product or product function from cradle to grave, the LCA process avoids problem shifting.
  - It encourages early interdisciplinary collaborations



Evaluating the Built Environment

(or, why people don't tend to use LCA for buildings and infrastructure)

- The built environment is a collection of products and functions.



Some Challenges of using LCA to assess the Built Environment

- Comparable products may have radically different LCA outputs due to method of production, distance from job site, machinery used in production and installation, etc.
  - Often producers are reluctant to reveal disaggregated data as it may reveal trade secrets
- Data does not yet exist reliably in aggregated form
- The method of construction can affect the longevity and end of life options of a product, thereby potentially rendering an LCA misleading (if it exists at all)

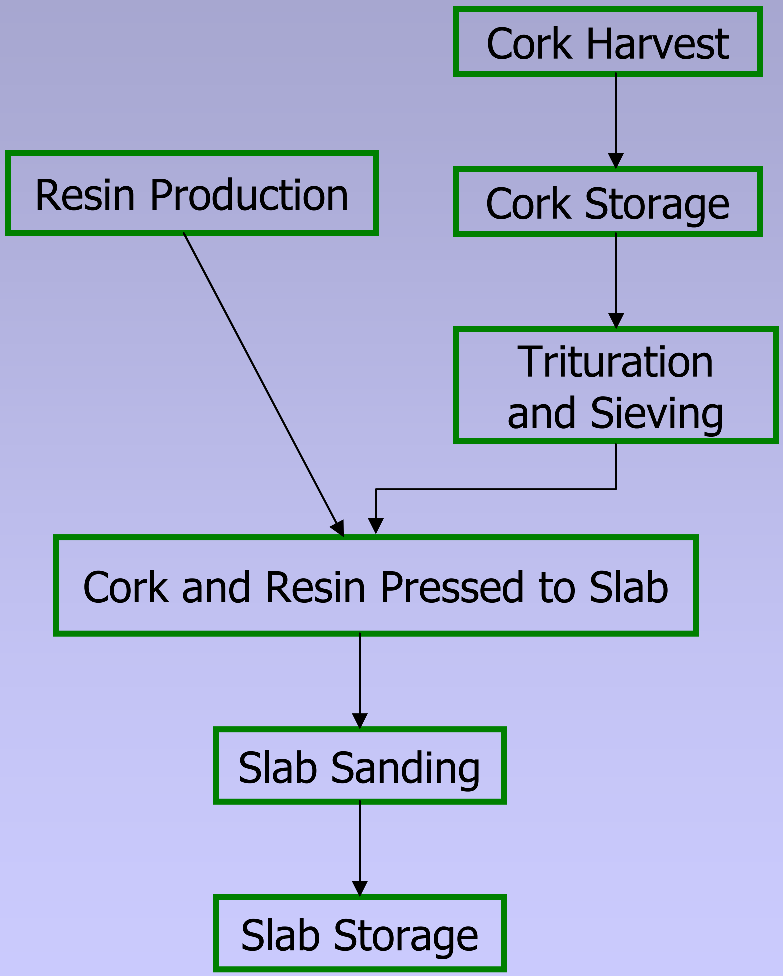
Many of these challenges can be addressed to some degree by selecting appropriate scope and assessment boundaries that minimize sensitivity and error

Life Cycle Assessment

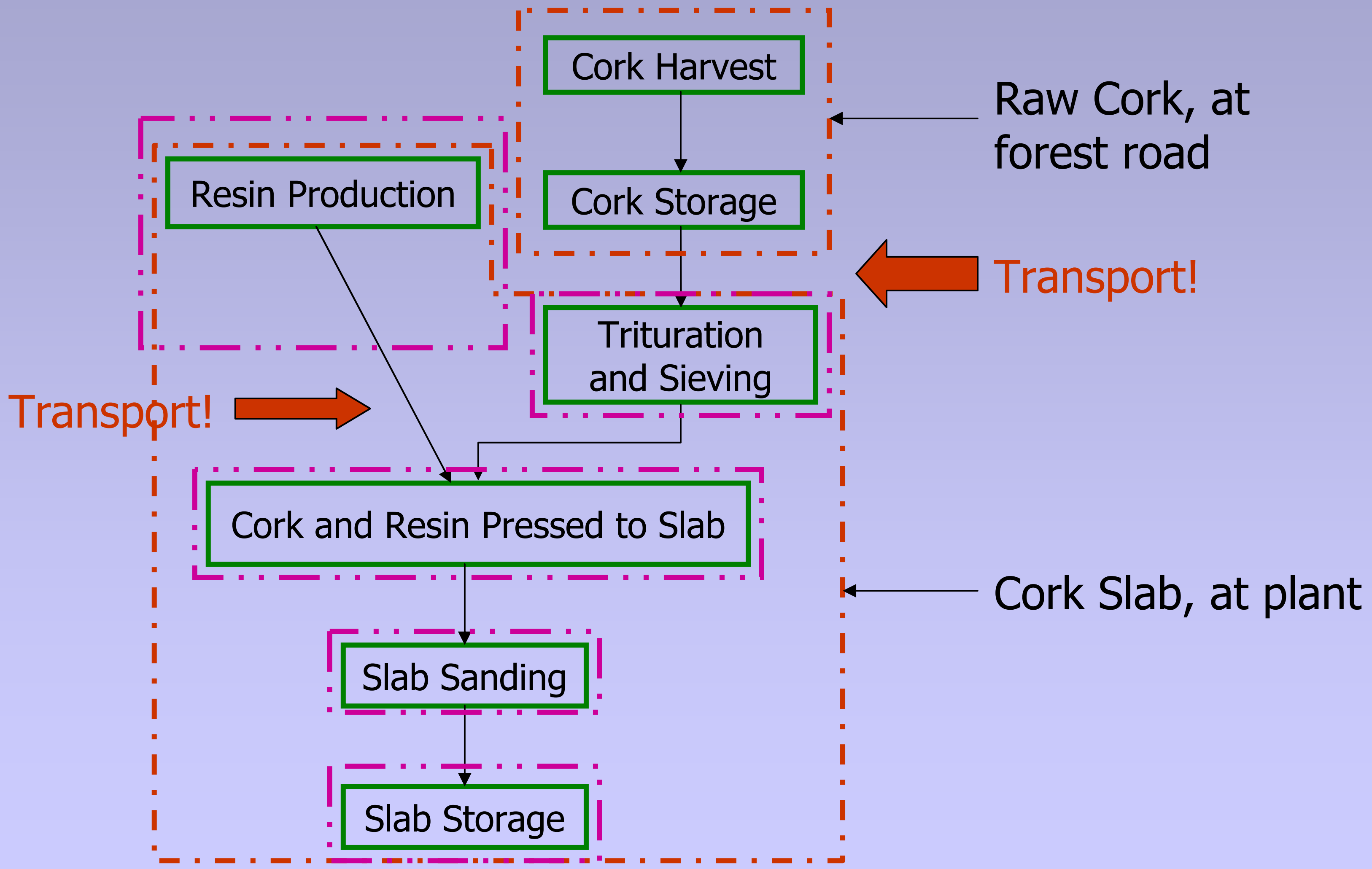
A quick example

Example: Cork

- Touted to be an environmentally preferable product in building
    - Flooring
    - Insulation
- It is considered a rapidly renewable resource.
- Characteristics:
    - Low density (lightweight)
    - High elasticity
    - Low thermal and electrical conductivity
    - High resistance to wearing
- Often combined with binders that have potentially negative effects on the environment.



System and Data Boundaries



Data Acquisition

(source: ecoinvent database)

					Matrix-ID	2127			2128			
					Dataset-ID	2488			2489			
					Name	raw cork, at forest road			residual wood, hardwood, under t			res
					Location	RER			RER			RE
					Unit	kg			m3			m3
					Infrastructure	0			0			
					Ecocat	wooden materials			wooden materials			woo
					Ecosubcat	extraction			extraction			ext
Datas	Matrix	Name	Unit	Ecocat	Ecosubcat	MeanValue	MinValue	MaxValue	MeanValu	MinValue	MaxValue	Me
2529	1	Acetaldehyde	kg	air	high population density	5.6E-10	0	0	5.65E-07	0	0	4.
2533	2	Acetaldehyde	kg	air	unspecified							
2534	3	Acetic acid	kg	air	high population density	4.21E-09	0	0	3.98E-06	0	0	3.
2538	4	Acetic acid	kg	air	unspecified	4.35E-09	0	0	3.59E-06	0	0	3.
2544	5	Acetone	kg	air	high population density	5.92E-10	0	0	6.63E-07	0	0	5.
2545	6	Acetone	kg	air	low population density	1.89E-10	0	0	1.28E-07	0	0	1.
2549	7	Acrolein	kg	air	high population density	1.92E-11	0	0	4.5E-08	0	0	3.
2550	8	Acrolein	kg	air	low population density	2.33E-13	0	0	1.58E-10	0	0	1.
2555	9	Actinides, radioactive, unspecified	kBq	air	low population density	8.36E-13	0	0	7.54E-10	0	0	6.
2560	10	Aerosols, radioactive, unspecified	kBq	air	low population density	7.29E-11	0	0	6.07E-08	0	0	5.
2564	11	Aldehydes, unspecified	kg	air	high population density	3.09E-11	0	0	3.5E-08	0	0	3.
2565	12	Aldehydes, unspecified	kg	air	low population density	4E-11	0	0	3.3E-08	0	0	2
2569	13	Aluminum	kg	air	high population density	4.42E-09	0	0	1.78E-05	0	0	1.
2570	14	Aluminum	kg	air	low population density	3.98E-10	0	0	1.11E-06	0	0	9.
2573	15	Aluminum	kg	air	unspecified	1.58E-07	0	0	0.000293	0	0	0.0
2579	16	Ammonia	kg	air	high population density	3.85E-08	0	0	2.24E-05	0	0	1.
2580	17	Ammonia	kg	air	low population density	6.84E-07	0	0	0.000149	0	0	0
2583	18	Ammonia	kg	air	unspecified	0.0000007	0	0	0.000245	0	0	0.0
2584	19	Ammonium carbonate	kg	air	high population density	2.53E-12	0	0	1.72E-09	0	0	1.
2589	20	Antimony	kg	air	high population density	6.87E-13	0	0	2.64E-09	0	0	2.
2590	21	Antimony	kg	air	low population density	5.01E-11	0	0	1.35E-07	0	0	1.
2593	22	Antimony	kg	air	unspecified	2.33E-13	0	0	9.66E-11	0	0	8.
2595	23	Antimony-124	kBq	air	low population density	1.03E-12	0	0	7.04E-10	0	0	6.
2600	24	Antimony-125	kBq	air	low population density	1.08E-11	0	0	7.34E-09	0	0	6.
2605	25	Argon-41	kBq	air	low population density	0.0000104	0	0	0.0158	0	0	

There are a little over 1000 emission categories listed per product!

- Emissions to air
- Emissions to water
- Emissions to land
- Resource use
- Land use
- Waste generation
- Etc.

Data Processing

- Identify economic flows
  - Process products
  - "Goods and Services"

Raw Cork, at forest road
Transport truck
Etc.

- Identify environmental flows
  - Natural resources; raw materials
  - Emissions to land, air, and water

Formaldehyde
Waste heat
Etc.

Next Steps

- LCA assumes linearity
- Input/output accounting results in a set of simultaneous equations
  - As long as some mechanism has been implemented to deal with the problem of allocation, there should be as many equations as there are unknown variables.
- Solving the equations gives the total environmental impact of the production of *1 kg cork slab, at plant*
  - This is easily done in spreadsheet format

Simple Matrix Formulation

Processes in Columns

Products in Rows

		Cork Slab (kg)				
Economic Flows	Cork Slab (kg)	1				
	Raw Cork (kg)	-1.06				
	Melamine resin (kg)	-0.056				
	Urea-formaldehyde (kg)	-0.056				
	Phenole-formaldehyde (kg)	-0.028				
	Wood Chips (MJ)	-6				
	Electricity (kWh)	-1				
	Transport by 32t truck (tkm)	-3.45				
Environmental Flows	Waste Heat (MJ)	3.6				
	Formaldehyde (kg)	0.00014				
	Landfill (kg)	0.00371				

Simple Matrix Formulation

		Cork Slab (kg)	Raw Cork (kg)	Melamine Resin (kg)	Electricity (kWh)	◆ ◆ ◆
Economic Flows	Cork Slab (kg)	1				
	Raw Cork (kg)	-1.06				
	Melamine resin (kg)	-0.056				
	Urea-formaldehyde (kg)	-0.056				
	Phenole-formaldehyde (kg)	-0.028				
	Wood Chips (MJ)	-6				
	Electricity (kWh)	-1				
	Transport by 32t truck (tkm)	-3.45				
	◆					
Environmental Flows	Waste heat to air(MJ)	3.6				
	Formaldehyde to air (kg)	0.00014				
	Sandpaper to landfill (kg)	0.00371				
	◆					
	◆					
	◆					

A

B

Simple Matrix Formulation

$$As = f$$

A is the Economic matrix
s is the Scale vector
f is the Economic flow vector

$$Bs = g$$

B is the Environmental matrix
s is the Scale vector
g is the Environmental profile

Questions?