Massachusetts Institute of Technology

D-Lab

# D-LAB WASTE:
# LIFE CYCLE ASSESSMENT

# LIFE CYCLE ASSESSMENT (LCA)

A tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. LCA provides an adequate instrument for environmental decision support.

- UNEP

"Life Cycle Assessment." United Nations Environment Program.

The term *life cycle* indicates that every stage of the life cycle of the service, from resource extraction to ultimate end-of-life treatment, is taken into account.

For each operation within a stage, the inputs (raw materials, resources and energy) and outputs (emission to air, water and solid waste) are calculated and then aggregated over the life cycle by means of material and energy balances, drawn over the system boundary [4,6].

– Arena, Mastellone, & Perugini (2003)

Arena, Umberto, Maria Laura Mastellone, and Francesco Perugini. "The environmental performance of alternative solid waste management options: a life cycle assessment study." *Chemical Engineering Journal* 96, no. 1 (2003): p 207.

# EXAMPLES

- Biomass (corn, soy) in different manufacturing applications
- Waste management process
- Energy and environmental impact of product alternatives
- Different modes of transportation to inform new infrastructure

- Product, Process or Activity

# LIFE CYCLE ANALYSIS APPLIED TO WASTE MANAGEMENT

# HISTORY OF LCA – 1960S – 1970S

- Harold Smith presents concept of cumulative energy requirements for production of chemical intermediates and products – 1963
- Oil crisis of 1970s?
- Limits to Growth – MIT researchers for the Club of Rome (international think tank) with computer modeling --- economic collapse and major population decline by 2030.
- Blueprint for Survival
- Coca-Cola comparing different bottle types in the 1969; what had the greatest energy and enviornmental cost. No public.
- Known then as Resource and Environmental Profile Analysis




Vigon, B.W., D.A. Tolle, B.W. Cornaby, and H.C. Latham. *Life-Cycle Assessment: Inventory Guidelines and Principles*. Environmental Protection Agency: 1994.Page6.

# HISTORY OF LCA (1980S)

- No common methodology for LCA
- LCA used to analyze same products with different results
- Used to ‘greenwash’ or substantiate corporate claims

- Guinee, Jeroen B., et al. "Life cycle assessment: past, present, and future." *Environmental Science & Technology* 45.1 (2010): 90-96.
- Vigon, B.W., D.A. Tolle, B.W. Cornaby, and H.C. Latham. *Life-Cycle Assessment: Inventory Guidelines and Principles*. Environmental Protection Agency: 1994.Page6.

# HISTORY OF LCA (1990S)

- Age of harmonization and embracing LCA
- 1992 - Rio Earth Summit – United Nations Conference on Environment and Development == Sustainable development
- ISO (international Standards Organizaiton) comes out and promises to standardize LCA in response – development of ISO standards(14,000 family).
- SETAC (Society of Environmental Toxicology and Chemistry) has been involved in harmonizing the efforts of LCA

That said ISO – never sought to standardize LCA methods. “There is no single method for conducting LCA”

- Guinee, Jeroen B., et al. "Life cycle assessment: past, present, and future.” *Environmental Science & Technology* 45.1 (2010): 90-96.
- Vigon, B.W., D.A. Tolle, B.W. Cornaby, and H.C. Latham. *Life-Cycle Assessment: Inventory Guidelines and Principles*. Environmental Protection Agency: 1994.Page6.

# HISTORY OF LCA (2000S +)

- Age of Elaboration
- UNEP and SETAC launch the Lifecycle Initiative
- Lifecycle initiative --- to put lifecycle into practice and improve the tools; series of other governmental agencies (in Europe and US) promote LCAs and shared data.

- Opportunity to extend LCA to also include cost (Life Cycle Cost) and even beyond

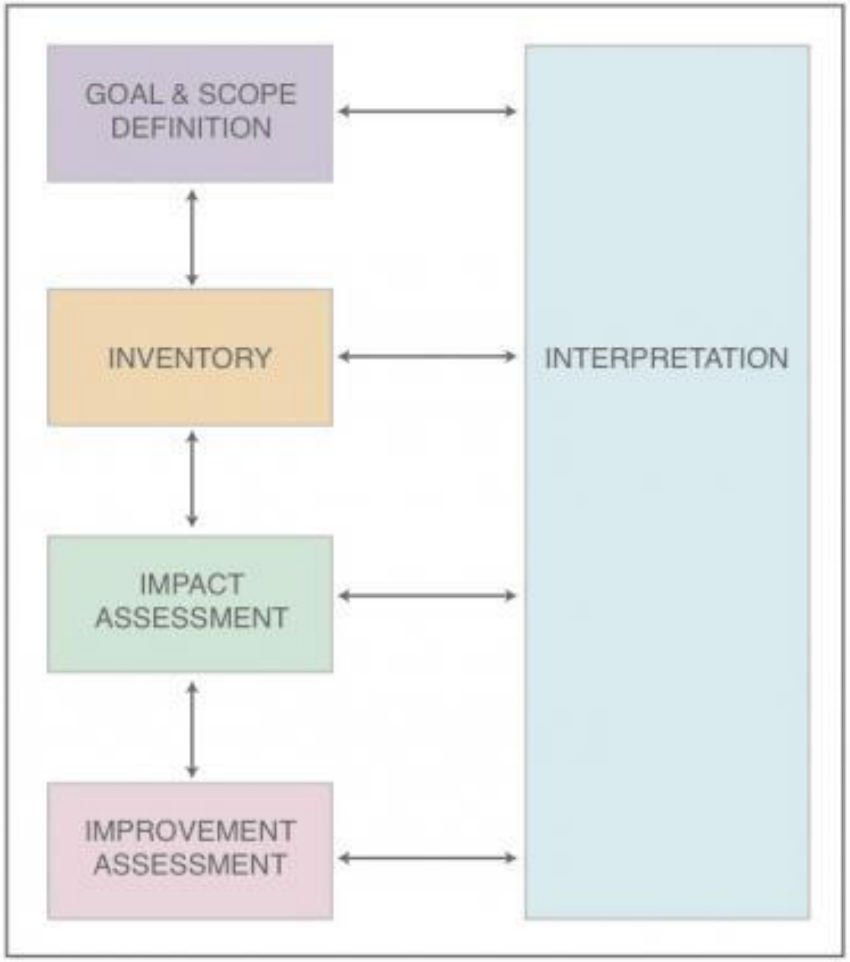
- Life Cycle Sustainability Analysis to broaden the scope to cover people, planet and prosperity.
- Go beyond a singular product to sector to economy
- Also be the physical relations (like the land/context and resources available), economic and behavioral relations

- Guinee, Jeroen B., et al. "Life cycle assessment: past, present, and future." *Environmental Science & Technology* 45.1 (2010): 90-96.
- Vigon, B.W., D.A. Tolle, B.W. Cornaby, and H.C. Latham. *Life-Cycle Assessment: Inventory Guidelines and Principles*. Environmental Protection Agency: 1994.Page6.

# LCA APPLIED TO WASTE MANAGEMENT

- First introduced in mid 1990s
- Often system based, focusing on a service
- Scope:
  - "Bin-to-grave" or "curbside to grave"
  - Starting point is waste
- Functional Unit
  - Tons of waste, ash, etc

# PHASES OF LCA




Source: Garman, J. (2011) based on ISO 14040

Courtesy of Dovetail Partners, Inc. Used with permission.

# GOAL + SCOPE

- Define the objective and system boundaries
- Identify the product, process or activity to be studied:
  - Material (plastic, paper, etc)
  - Waste source (households, industry, etc)
  - Solid waste unit (MSW, ash, compost)
  - Remanufacturing processes, energy recovery or disposal (compost, biogas, etc.)
- Function, functional unit or reference flow
- System boundaries
- Criteria for inputs/outputs
- Data quality requirements

# EXAMPLE OF FUNCTIONAL UNITS

- All activities linked with the disposal and recycling of **WEEE (waste of electrical and electronic equipment) accumulated over one year** (2004) in Switzerland.
- Amount of **communal waste generated annually in a selected rural area** in Austria
- Treatment and disposal of **1 ton of MSW** in Sao Paulo
- Collection and treatment of **566,000 tons of MSW**, which correspond to the annual generation in the district of Bologna for 2006
- **1 ton of product gas** produced from the assortment of waste materials in Singapore

Abeliotis, Konstadinos. *Life cycle assessment in municipal solid waste management*. INTECH Open Access Publisher, 2011.

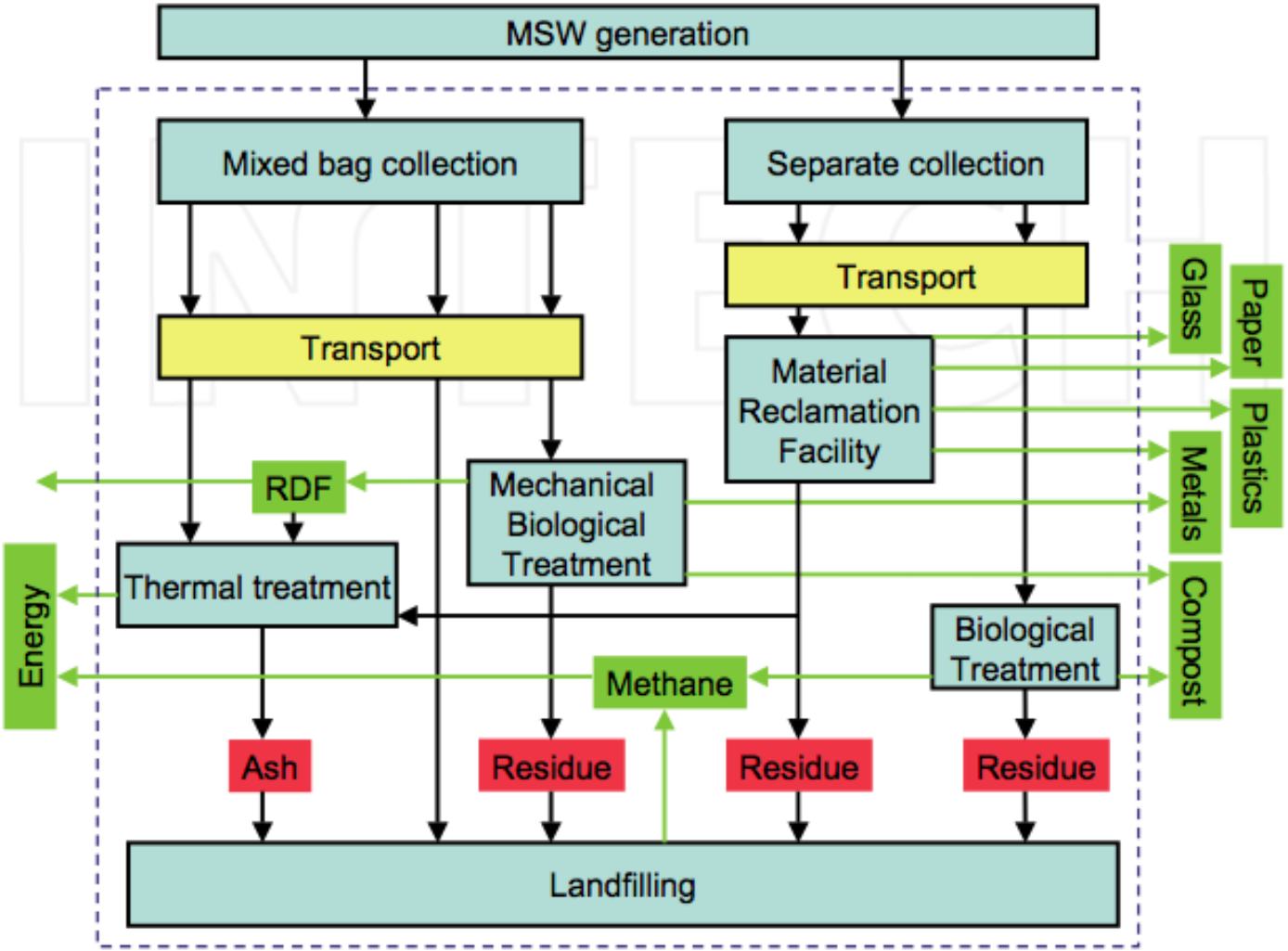



Fig. 1. The complete life cycle of MSW



Konstadinos Abeliotis (2011). "Life Cycle Assessment in Municipal Solid Waste Management." *Integrated Waste Management.* Volume I, Mr. Sunil Kumar (Ed.), InTech, DOI: 10.5772/20421.

# INVENTORY ANALYSIS CALCULATION

**Direct Burdens with WM operations**

**+ Indirect Burdens**

providing materials and energy to WM operations

**- Minus: Avoided Burdens**

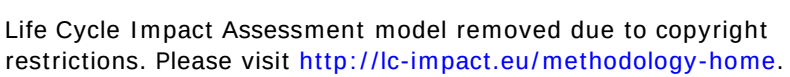
Economic activities displaced by materials

**Key Inputs:** Electricity, fossil fuels, water, raw materials
**Key Outputs:** air emissions, water discharges, solid wastes, resource use

# IMPACT ASSESSMENT INDICATORS

Each of these indicators/impacts is connected to something that wants to be changed.

The final goal is figuring out how these indicators impact the actual work/process.



# IMPACT ASSESSMENT STEPS

- **Classification:**
  - What does this emission contribute to?
- **Characterization:**
  - **How much does it contribute?**
- **Normalization:**
  - Is that much?
- **Valuation:**
  - Is it important?

# LCA LIMITATIONS

- Public health, hygiene, procedure safety
- Not all risk factors are incorporated:
  - Pathogenic (virus, bacteria, etc)
  - Eco-toxicological (dose-response relationship)
- Land-use
- Dismenity effects
- Destruction of natural habitat

Source:
Arena, Umberto, Maria Laura Mastellone, and Francesco Perugini. "The environmental performance of alternative solid waste management options: a life cycle assessment study." *Chemical Engineering Journal* 96.1 (2003): 207-222.

# LCA LIMITATIONS

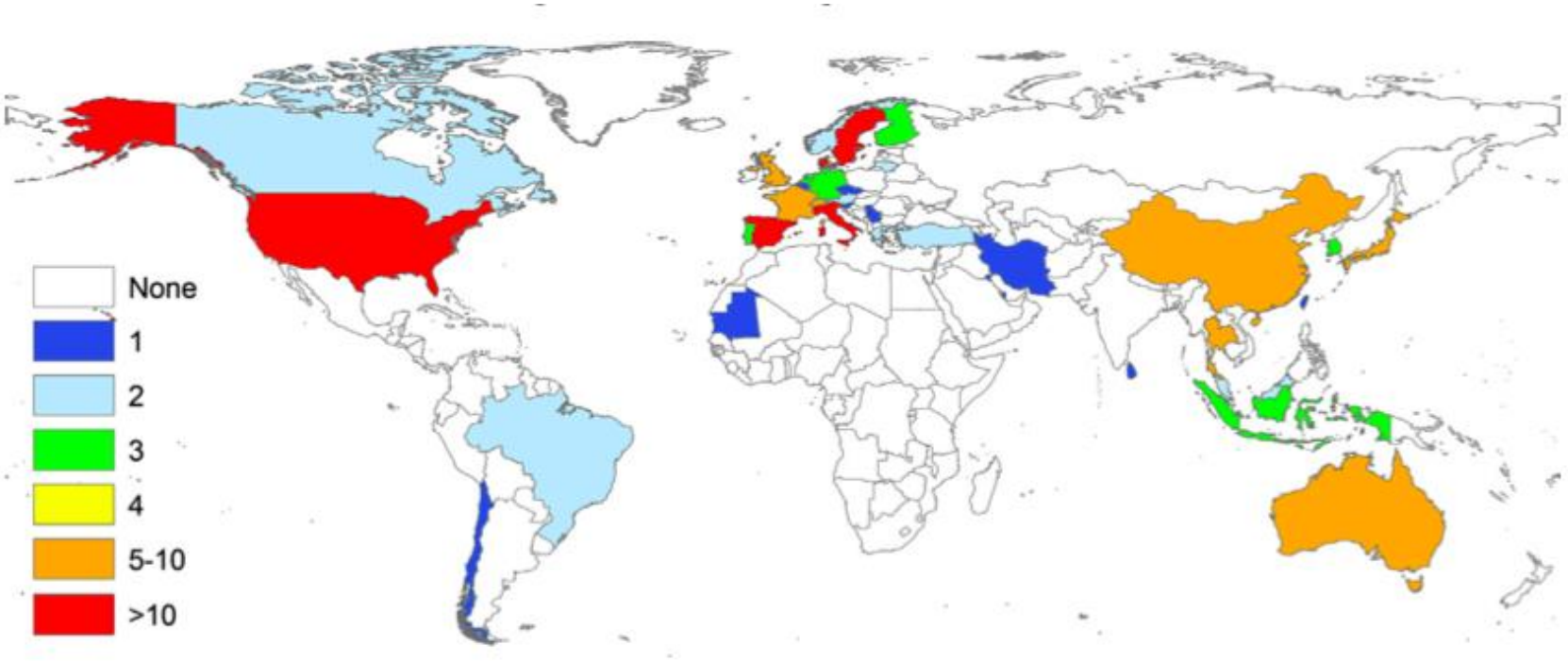
- Does not differentiate impacts by time they occur
- Outcome does not reflect:
  - Changing conditions of WM (population, generation, composition)
  - Policy changes
- Not as strong at evaluating site-specific issues (i.e., water consumption)

# LCA LIMITATIONS

- Requires relevant data – from literature, databases, or through surveys
- Costly ($50k+ for product analysis)
- Reliability of results

# REVIEW OF LCA STUDIES OF SWMS

## (LAURENT, ET. AL)






Laurent, Alexis, et al. "Review of LCA studies of solid waste management systems–Part I: Lessons learned and perspectives." *Waste management* 34.3 (2014): 573-588.

# REVIEW OF LCA STUDIES OF SWMS

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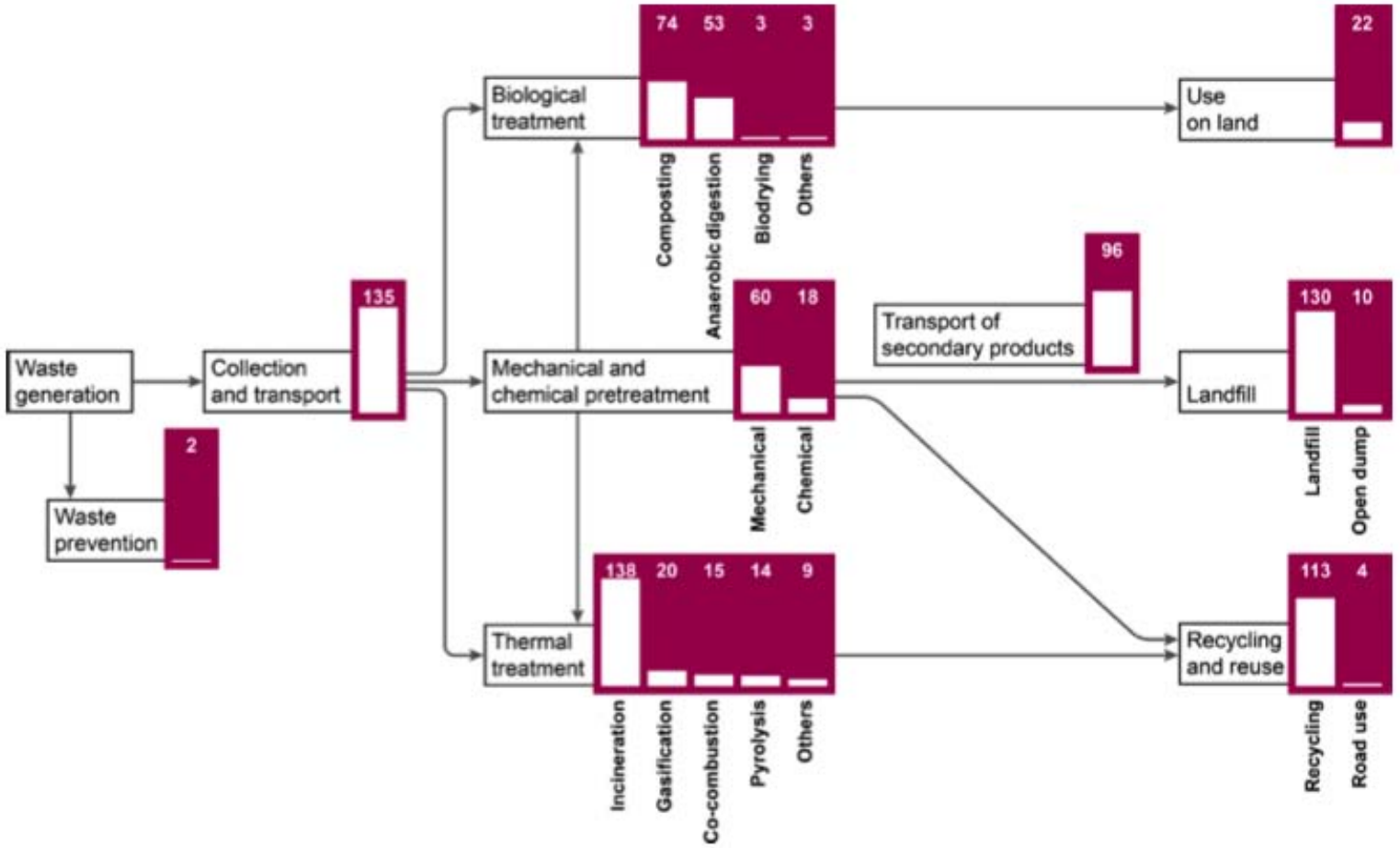




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# HOW DO WE MEASURE REFUSAL?

- Requires info on waste system and the upstream product system
- Refusing waste may be associated with other behavior changes which need to be measured (rebound effects)
  - Decrease in unsolicited mail = more internet time
- Currently no consensus on how to measure this

Laurent, Alexis, et al. "Review of LCA studies of solid waste management systems–Part I: Lessons learned and perspectives." *Waste management* 34.3 (2014): 573-588.

# FINDINGS

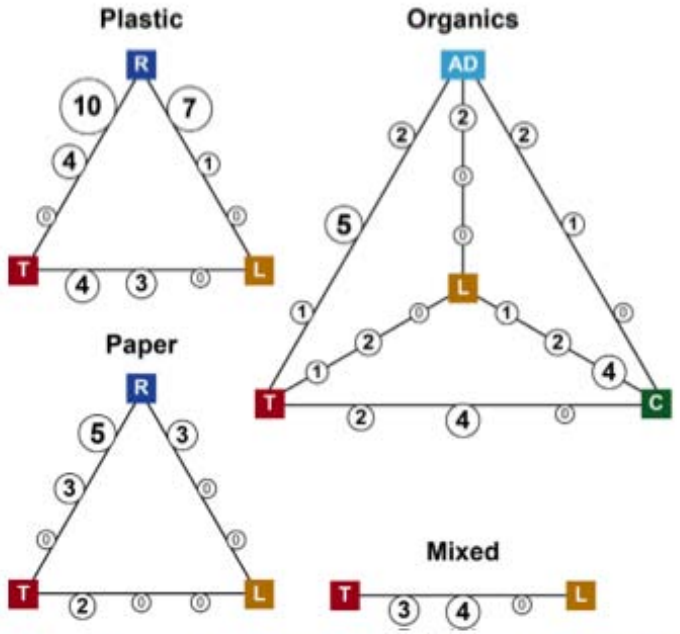


**Fig. 5.** Comparative analysis of key findings for selected waste treatment technologies applied to manage paper, plastic, organic and mixed waste fractions (total of 34 studies). The nodes "R" stand for recycling, "L" for landfilling, "T" for thermal treatment, "C" for composting, "AD" for anaerobic digestion. For each pair comparison, three circled numbers are indicated, representing the number of studies concluding on the better environmental performance (i.e. lower overall environmental impact) of one waste treatment technology over another (numbers closer to each of the two nodes), or reaching either inconclusive results or results with similar environmental burden (numbers in the middle). The size of the circles is proportional to the number of studies.



In General:

Paper: Recycling > Thermal > Landfill

Organics: Thermal/Compost/Anerobic Digestion > Landfill

Plastic: Recycling > Thermal > Landfill

Mixed Waste: Thermal > Landfill

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# WHAT'S GENERALIZABLE?

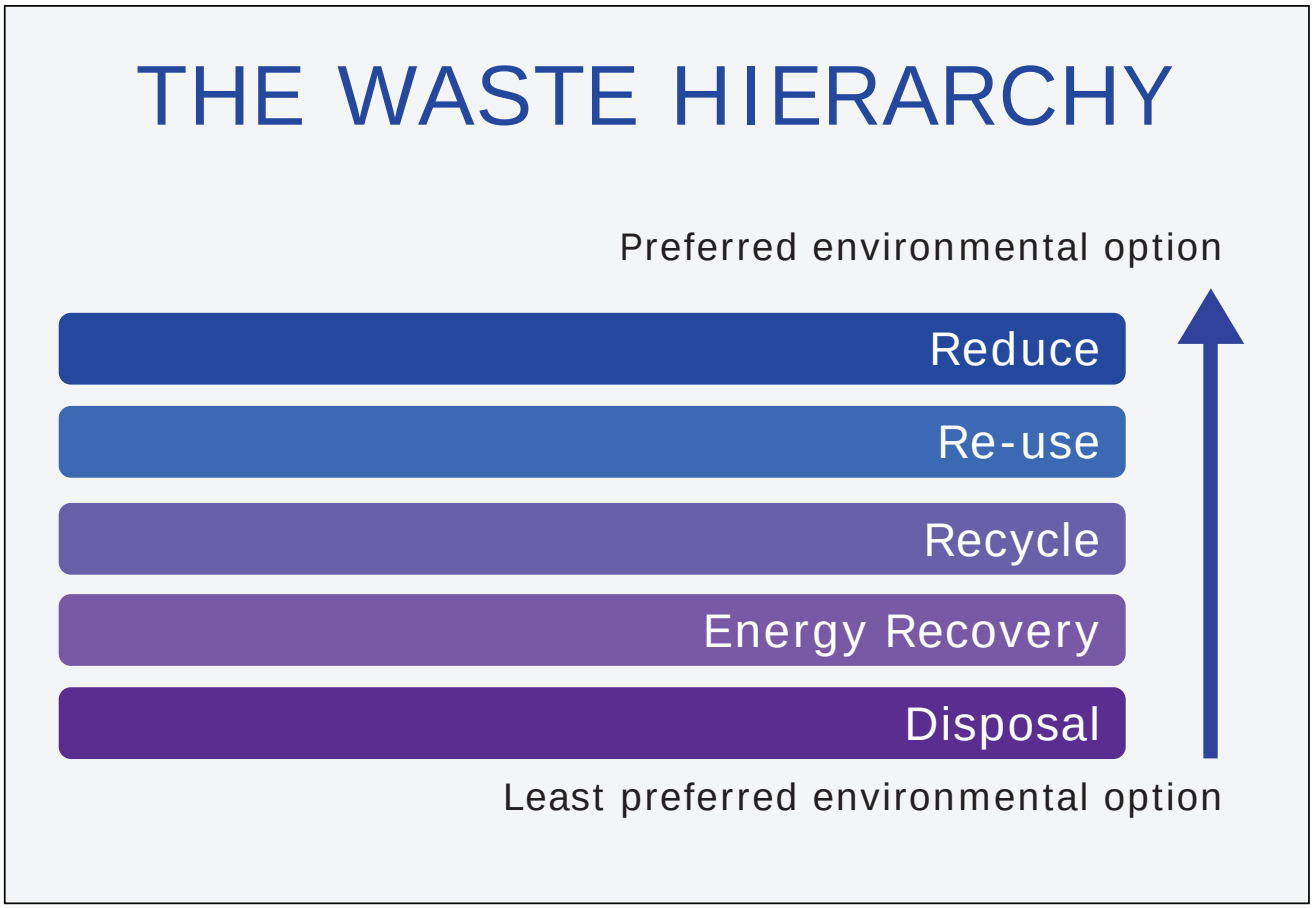



Image by MIT OpenCourseWare.

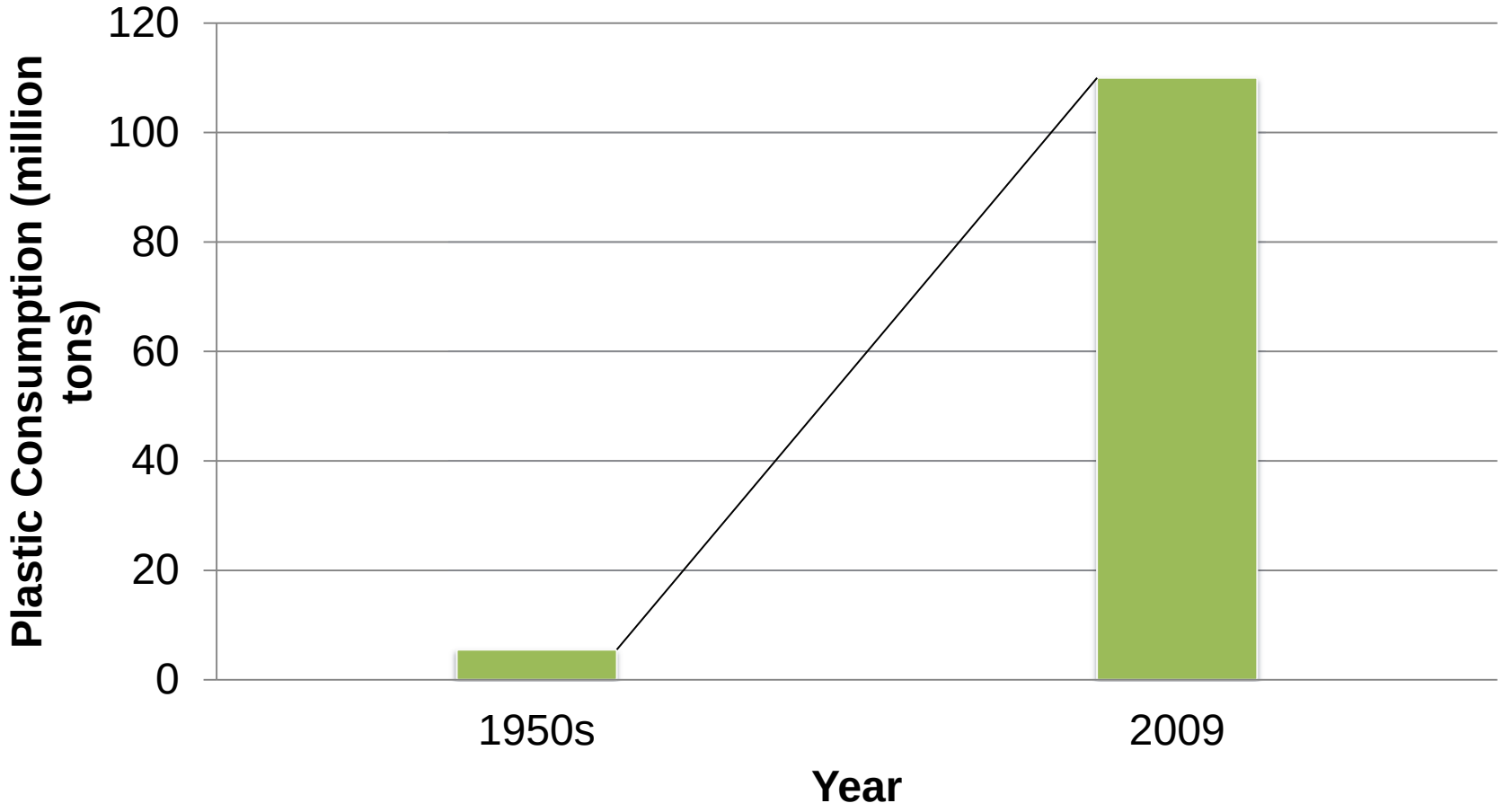
# OPPORTUNITIES IN LCA RESEARCH ON WM

- Sharing findings of existing LCA
- LCA application:
  - In developing countries
  - Beyond household waste (construction and demolition, industry, etc)
  - Extending material scope (plastic, paper, metals, glass)
  - To waste prevention

# THE PLASTIC AGE

i-D. “The Plastic Age: A Documentary feat. Pharrell Williams (Full Film).” 15 April 2015. Youtube.

# PLASTIC CONSUMPTION (IN MILLION TONS)




Cho, Renee. "What Happens to All That Plastic?" *State of the Planet: Earth Institute*. Columbia University.. 31 January 2012.

# SUSTAINABILITY METRICS: LCA AND GREEN DESIGN IN POLYMERS (TABONE, ET. AL)

12 Polymers

- Petrolum/Fossil Fuels (7)
  - PET
  - HDPE
  - LDPE
  - PP
  - PC
  - PVC
  - GPPS
- Biopolymers (2)
  - PLA made via a general process (PLA-G)
  - PLA made via Nature Works (PLA-NW)
- Polyhydroxyalkanoate (2)
  - PHA from corn grain (PHA-G)
  - PHA from corn stove (PHA-S)
- Hybrid bio/petroleum (1)
  - B-PET

Tabone, Michaelangelo D., James J. Cregg, Eric J. Beckman, and Amy E. Landis. "Sustainability metrics: life cycle assessment and green design in polymers." *Environmental Science & Technology* 44, no. 21 (2010): 8264-8269.

# SUSTAINABILITY METRICS: LCA AND GREEN DESIGN IN POLYMERS (TABONE, ET. AL)

- Functional Unit: 1 Liter of pellets
- Scope: Cradle-to-gate (production, not disposal or use)
- Impact categories:
  - Acidifcation
  - Carcinogenic human health hazards
  - Ecotoxicity
  - Eutrophication
  - Global Warming Potential
  - Noncarcinogenic human health hazards
  - Ozone depletion
  - Respiratory effects
  - Smog
  - Nonrenewable energy use (NREU)

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# YOUR TURN

- Product, Service or Process
- Define:
  - Boundary, functional unit, process
- For each step indicate:
  - Inputs: energy, raw materials, water
  - Outputs: emissions, waste materials, products

# RESOURCES

Limits to Growth: http://www.smithsonianmag.com/science-nature/looking-back-on-the-limits-of-growth-125269840/?no-ist
LCA: http://www.lifecycleinitiative.org/
LC-Impact: http://lc-impact.eu/methodology-home
Arena, Umberto, Maria Laura Mastellone, and Francesco Perugini. "The environmental performance of alternative solid waste management options: a life cycle assessment study." *Chemical Engineering Journal* 96.1 (2003): 207-222.
Laurent, Alexis, et al. "Review of LCA studies of solid waste management systems–Part I: Lessons learned and perspectives." *Waste management* 34.3 (2014): 573-588.
Laurent, Alexis, et al. "Review of LCA studies of solid waste management systems–Part II: Methodological guidance for a better practice." *Waste management* 34.3 (2014): 589-606.
Barlaz, Morton A. Professor and Head, Department of Civil, Construction and Environmental Engineering at NC State University. “Life Cycle Analysis, Part I” http://people.engr.ncsu.edu/barlaz/teaching.html

**Plastics:**
National Plastics Resource & Museum (no longer open) http://library.syr.edu/digital/guides/n/npc_mus.htm
Resin Identification Codes: http://speccrew.com/ไม่มีหมวดหมู่/resin-identification-codes-plastic-recycling-codes/
History of plastics: http://www.plasticsindustry.org/AboutPlastics/content.cfm?ItemNumber=670&navItemNumber=1117
Plastic Disclosure Project http://www.plasticdisclosure.org
Biodegradable Plastic: Its Promises: http://dujs.dartmouth.edu/applied_sciences/biodegradable-plastic-its-promises-and-consequences#.ViRsTOmKUz8
Container Recycling Institute: http://www.container-recycling.org/index.php/factsstatistics/plastic

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