INDUSTRIAL ECOLOGY (EAS 557 & CEE 586)
Winter Term 2020

SYLLABUS

Time	Tuesday and Thursday 2:30 – 4:00 pm
Location	1040 Dana (School of Natural Resources & Environment)
Instructor	Gregory Keoleian Director, Center for Sustainable Systems Peter M. Wege Professor of Sustainable Systems Professor, SEAS and Professor, Civil and Environmental Engineering Co-Director, Rackham Graduate Certificate Program in Industrial Ecology
Office	3504 Dana Bldg. School of Natural Resources and Environment
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Graduate Student Instructor	Stephen Hilton (sphilton@umich.edu)
Office	4046 Dana Bldg.
Office Hrs.	Monday 2:30–4:00 pm; Tuesday 10:00 –11:30 am; Wednesday 2:00– 3:00 pm; or by appointment
Graduate Student Instructor	Max Woody (maxwoody@umich.edu)
Office	4046 Dana Bldg.
Office Hrs.	Tuesday 11:30 am – 1:00 pm; Thursday 11:30 am – 2:00 pm; or by appointment

COURSE BACKGROUND

This course was first offered in the winter term of 1994 as part of an education/research project entitled "Interdisciplinary Education and Research on Industrial Ecology." Support for developing and teaching the course was provided through the AT&T Foundation's Industrial Ecology Faculty Fellowship Program. This was the first full semester Industrial Ecology course ever taught and has evolved over the years along with the field.

COURSE DESCRIPTION

Industrial ecology is the systematic analysis of global, regional and local material and energy flows and uses that are associated with products, processes, industrial sectors, and economies. Energy consumption, non-renewable and renewable materials consumption, air pollutant emissions, waterborne pollutant effluents and solid waste generation associated with human activities are tracked. These analyses are the core tools of industrial ecology, which seeks to design and manage products and services that meet human needs in a sustainable manner. Industrial Ecology provides a scientific foundation for advancing the "Circular Economy," which is framework gaining the attention of business and industry. This course is designed as an interdisciplinary course. Industrial designers, process engineers, natural resource managers and policy makers, business managers, environmental health professionals, regulators, and consumers each play a critical role in shaping the environmental profile of products. A framework is presented for analyzing multi-stakeholder interests and the consequences of their decisions and actions. Ecological, economic, social, political, and technological factors that influence the life cycle of a product system will be considered. This life cycle encompasses raw materials acquisition and processing, manufacturing, use, resource recovery, and the ultimate disposition and fate of residuals.

The course will provide you with analytical tools and methods for implementing principles of industrial ecology and the circular economy. . The practical applications covered in the course will be based largely on current research in the area of *life cycle assessment* (LCA) and *life cycle design.* Life cycle assessment is a comprehensive tool for identifying and evaluating the full environmental burdens associated with a product system from production through retirement. This methodology is used for comparative analyses of alternatives including materials (biobased vs petroleum based), energy systems (renewable and fossil fuels), consumer products and packaging, automotive component designs, and residential construction methods. Other analytical tools covered include ecological footprint analysis, carbon footprint analysis (life cycle assessment of greenhouse gases), and life cycle cost analysis. Life cycle design focuses on integrating environmental considerations into product design. The challenge is to align and meet performance, cost, legal, and cultural requirements while achieving environmental improvements.

COURSE FORMAT

Concepts, principles and methodologies will be introduced by lecture and discussed in a seminar format. Case studies will be used throughout the course to demonstrate concepts and principles, and to highlight accomplishments and practical limitations of life cycle assessment and life cycle design. Class participation is essential for understanding multi-disciplinary perspectives. There will be **student-led class discussions** once per week in conjunction with a **blog on special topics**. You are required to either: 1) Respond to four blog posts, or 2) Serve one time as a class discussion leader and respond to one blog post. Sign-ups will be done via the Course Wiki spreadsheet, which can be accessed in the Collaborations tab on Canvas.

In conjunction with this course, we will schedule optional field trips to industrial sites to complement the course material and provide you with the opportunity to visit industrial facilities.

COURSE RESOURCES

1. Reference textbooks

Environmental Life Cycle Assessment: Measuring the Environmental Performance of Products. American Center for Life Cycle Assessment: Vashon Island, Washington, 2014.

Life Cycle Assessment: Quantitative Approaches for Decisions that Matter. H. Scott Matthews, Chris T. Hendrickson and Deanna H. Matthews, 2015.

Life Cycle Assessment: Inventory Guidelines and Principles (EPA 600/R-92/245). Cincinnati, OH: U.S.EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, February 1993.

Guidelines for Life-Cycle Assessment: "A Code of Practice." Society of Environmental Toxicology and Chemistry, 1993.

Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and Allied Signal (EPA/600/R-95/107). Keoleian, G., Koch, J., Menerey, D. and Bulkley, J. Cincinnati, OH: U.S.EPA, Office of Research and Development, National Risk Management Research Laboratory, July 1995.

Life Cycle Design Guidance Manual: Environmental Requirements and the Product System. (EPA/600/R-96). Keoleian, G. and Menerey, D. Cincinnati, OH: U.S. EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, January 1993.

Green Products by Design: Choices for a Cleaner Environment (OTA-E-541) U.S. Congress, Office of Technology Assessment, 1992.

Industrial Ecology. Graedel, T.E. and Allenby, B., Prentice Hall: Englewood Cliffs, NJ, 2nd Ed., 2003.

The Greening of Industrial Ecosystems. National Academy Press: Washington, DC, 1994.

Industrial Ecology and Global Change. Ed. R. Socolow, C. Andrews, F. Berkhout, and V. Thomas. Cambridge University Press, 1994.

Environmental Life-Cycle Assessment Ed. Mary Ann Curran, McGraw-Hill, New York, 1996

*Cradle to cradle**:** remaking the way we make things* McDonough, W. & Braungart, M. 2002. New York: North Point Press.

Factor four: doubling wealth, halving resource use von Weizsacker, Ernst U., Lovins, Amory, Lovins, Hunter, London : Earthscan Publications LTD, 1997.

Natural Capitalism: Creating the Next Industrial Revolution Hawken, P., Lovins, A. and Lovins, L.H., Little, Brown and Company: Boston, 1999.

Biomimicry: Innovation Inspired by Nature Benyus, J. M. Quill: New York, 1998.

2. Websites

Life Cycle Initiative (UNEP and SETAC): http://www.lifecycleinitiative.org/
Center for Sustainable Systems: http://css.umich.edu/
International Society for Industrial Ecology: https://is4ie.org/
Journal of Industrial Ecology: http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291530-9290

COURSE SCHEDULE

I. Industrial Ecology and Sustainability Frameworks

Jan. 9	**Industrial Ecology Framework**
Jan. 14	**Sustainability Framework**
Jan. 16	**Resource Sustainability Challenges and Opportunities**
Jan. 21	**Industrial Ecology and the Circular Economy**
Jan. 23	**Material Flow Analysis**

II. Life Cycle Assessment

Jan. 28	**Life Cycle Assessment (LCA): Components and Applications**
Jan. 30	**Life Cycle Inventory Analysis**
Feb. 4	**Energy and Transportation Modules**
Feb. 6	**Materials Production Phase: Non-renewable feedstocks**
Feb. 11	**Materials Production Phase: Renewable feedstocks**
Feb. 13	**Manufacturing Phase**
Feb. 18	**Use Phase**
Feb. 20	**End-of-Life Management Phase**

Feb. 25-Feb. 28 **Midterm Exam (take home)**

Feb. 25	**Life Cycle Impact Assessment I: Introduction, GWP and ODP**
Feb. 27	**Life Cycle Impact Assessment II: Other Environmental and Human Health Impacts**
Mar. 10	**Life Cycle Impact Assessment III: Water, Land Use, and Resource Depletion**

III. Life Cycle Design and Management

Mar. 12	**Life Cycle Design Framework and Design Requirements**
Mar. 17	**Design Strategies**
Mar. 19	**Life Cycle Costing**
Mar. 24	**Life Cycle Management and Green Supply Chains**
Mar. 26	**Life Cycle Framework for Environmental Marketing and Labeling**

IV. Sustainable Systems (Production and Consumption)

Mar. 31	**Sustainable Food Systems**
Apr. 2	**Sustainable Mobility**
Apr. 7	**Sustainable Buildings**

April 9	**Finalize term projects**
Apr. 14	**Industrial Ecology Symposium: Term Project Presentations**
Apr. 16	**Industrial Ecology Symposium: Term Project Presentations**
Apr. 16	**Term Project Papers Due and Peer Evaluation Forms Due**

April 21	**Course Review**

April 28	**Final Exam** (4:00 – 6:00 pm)

COURSE OUTLINE

I. Industrial Ecology and Sustainability Frameworks

Jan.9 **Industrial Ecology Framework**

Definition, Goals, Analytical Components, and Tools
IPAT Equation
  Population and Carrying Capacity
  Consumption Patterns
  Technology
Kaya Identity (IPAT Equation applied to carbon emissions)

Reading: Jelinski, L.W., T.E. Graedel, R.A. Laudise, D.W. McCall, and C. Kumar N. Patel. "Industrial Ecology: Concepts and Approaches." *Proceedings, National Academy of Sciences,* USA 89 (February 1992): pp. 793-797.
Frosch R.A. "Industrial Ecology of the 21st Century" *Sci. Amer*. (1995) Sept. 178-181.
Daily, Gretchen C. and Paul Ehrlich. "Population, Sustainability, and Earth's Carrying Capacity," *BioScience,* November 1992: pp. 761-764, 770, 771.

Other Resources:
Apple Environmental Responsibility Report 2019 Progress Report, Covering Fiscal Year 2018 https://www.apple.com/environment/pdf/Apple_Environmental_Responsibility_Report_2019.pdf
Raupach, M.R. et. al. "Global and regional drivers of accelerating CO2 emissions" *Proceedings National Academy of Sciences* June 12, 2007 vol. 104 no. 24 10288-10293.
Mihelcic, J.R. et al. 2003. Sustainability Science and Engineering: The emergence of a New Metadiscipline. *Environmental Science and Technology* 37:5314-5324.

Jan. 14 **Sustainability Framework**

Definitions and Drivers for Sustainability
Sustainability Indicators
  Ecological/Environmental – Ecological Footprint
  Economic – Genuine Progress Indicator (GPI)
  Social and Demographic – Equity
UN 17 Sustainable Development Goals

Reading: Wackernagel, M. and W. Rees, Chapter 3 in *Our Ecological Footprint*, New Society Publishers: Gabriola Island, B.C. Canada (1996) pp. 61-124.
Living Planet Report and Summary Booklet 2018 WWF (browse summary report) https://wwf.panda.org/knowledge_hub/all_publications/living_planet_report_2018/
UN 17 Sustainable Development Goals and 169 Targets https://sustainabledevelopment.un.org/sdgs (browse)
CSS Factsheet: Social Development Indicators http://css.umich.edu/factsheets/social-development-indicators-factsheet

Other Resources:
Green Economy Guidebooks, United Nations Department of Economic and Social Affairs, Division for Sustainable Development, 2012: https://sustainabledevelopment.un.org/content/documents/GE%20Guidebook.pdf
Ecological Footprint: https://www.footprintnetwork.org/resources/footprint-calculator/
Wackernagel, M., et al. Tracking the ecological overshoot of the human economy *Proceedings Natl. Acad. Sci.*(2002) 99(14): 9266-9271.
Costanza, R. et al. The value of the world's ecosystem services and natural capital. *Nature* (1997) 387: 253 - 260.
Genuine Progress Indicator 2006 Executive Summary:

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.
Socioeconomic data and maps (including environmental sustainability data): http://sedac.ciesin.columbia.edu/

Jan. 16 **Resource Sustainability Challenges and Opportunities**

Sustainability Thresholds (biodiversity, climate change, etc.)
Materials Resources
  Classification (renewable and non-renewable)
  Resource Scarcity – Minerals
  Consumption Patterns
Waste
  Air Pollutant Emissions
  Waterborne Pollutant Discharges
  Solid Waste (MSW, Industrial, Hazardous)
Energy Resources
  Classification (renewable and non-renewable)
  Production Data
  Consumption Data
Water Resources
Land Use and Intensity (per ha footprints)

Reading:

Kessler, Stephen. *Minerals Resources Economics and the Environment.* Macmillan College Publishing: New York, 1994: pp. 1-6, 321-323.
Advancing Sustainable Materials Management: Facts and Figures (browse)
  https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures
Center for Sustainable Systems Factsheets:
  http://css.umich.edu/factsheets
  US Environmental Footprint
  Greenhouse Gases
  Climate Change: Science and Impacts
  U.S. Energy System
  U.S. Renewable Energy
  U.S. Material Use
  U.S. Municipal Solid Waste
  U.S. Water Supply and Distribution

Other Resources:

Rockstrom J. et al. A safe operating space for humanity. *Nature* (24 September 2009) 461: 472-475 | doi:10.1038/461472a;
Monthly Energy Review
  http://www.eia.gov/totalenergy/data/monthly/
Air Quality and Emissions Trends:
  https://www.epa.gov/air-trends
Toxic Release Inventory
  http://www2.epa.gov/toxics-release-inventory-tri-program
Climate Watch: https://www.climatewatchdata.org/

UN Water Statistics – http://www.unwater.org/statistics/en/
World Health Organization Factsheets on Drinking Water and Sanitation
  https://www.who.int/en/news-room/fact-sheets/detail/drinking-water
  https://www.who.int/en/news-room/fact-sheets/detail/sanitation

Jan. 21 **Industrial Ecology and the Circular Economy**

Metaphor: Industrial and Natural Ecosystems
Ecosystem Classifications – Type I, II, III
Circular Economy Framework
Food Webs and Industrial Ecoparks
Biomimicry – Nature as a Model

Examples: Kalundborg, Bullet Trains, Velcro, Arsenic, Mercury

Reading: Ehrenfeld, John and Nicholas Gertler, “Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg,” *Journal of Industrial Ecology* (1997) 1(1): 67-79.
Eckelman, M. “Spatial Assessment of Net Mercury Emissions from the Use of Fluorescent Bulbs” *Environ. Sci. & Technol. (2008) 42(22) 8564-8570.*

Other Resources:

Janine M. Benyus *Biomimicry: Innovation Inspired by Nature* Quill: New York, 1998.
Biomimicry 101 https://biomimicry.org/#
Lovins, A.B., L.H. Lovins, P. Hawken. "A Road Map for Natural Capitalism." *Harvard Business Review*. May/June 1999: 145-158. (browse)
Fact Sheets from the Ecological Society of America: https://www.esa.org/publications/
Topics include acid deposition, acid rain, biodiversity, soil carbon sequestration, ecosystem services, global climate change
Journal of Industrial Ecology Volume 11, Number 1, Special Feature on Industrial Symbiosis.
A Report of the Interagency Workgroup on Industrial Ecology, Material and Energy Flows, August, 1998 (browse)
Cote, R.P. and E. Cohen-Rosenthal, "Designing eco-industrial parks: a synthesis of some experiences" *J. Cleaner Production* (1998) 6: 181-188.
Allenby, Braden R. "Achieving Sustainable Development through Industrial Ecology." *International Environmental Affairs* 4(1): 56-68.
Frosch, Robert A., and Nicholas E. Gallopoulos. "Strategies for Manufacturing." *Scientific American*, (September 1989): 144-152.
Ayres, Robert U. "Industrial Metabolism: Theory and Policy" in *The Greening of Industrial Ecosystems.* National Academy Press: Washington, DC (1994): 23-37.

Jan. 23 **Material Flow Analysis**

Material Flow Analysis
- Extraction
- In-use stock, net additions to stock, service life
- Discards, recycling, leakage

Natural vs Anthropogenic Pollutant Cycles

Examples: Aluminum, Copper, Silver, Cement, Mercury

Reading:

Graedel, T.E.; et. al. "The Contemporary European Copper Cycle: The Characterization of Technological Copper Cycles." *Ecological Economics*. 42 (2002), p. 9-26.
Johnson, J. et al. "Dining at the Periodic Table: Metals Concentrations as They Relate to Recycling" *Env. Sci. Technol.* (41) 5: 1759-65.
Nriagu, Jerome A. "A global assessment of natural sources of atmospheric trace metals," *Nature* 338 (March 2, 1989): 47-49.

Other Resources:

Reck B.K. and T. E. Graedel "Challenges in Metal Recycling" *Science* 10 August 2012: 690-695.
Metals_Recycling_Rates_UNEP 110412-1
Gerst, M.D. and T.E. Graedel "In-Use Stocks of Metals: Status and Implications" *Env. Sci. Technol.* (42) 19: 7038-45.
R.J. Klee, T.E. Graedel Elemental Cycles: A Status Report on Human or Natural Dominance *Annual Review of Environment and Resources*, (2004) 29: 69-107.
USGS Material Flow Resources https://www.usgs.gov/centers/nmic
Use of Raw Materials in the United States From 1900 Through 2014 USGS Fact Sheet 2017-3062, December - 2017. https://pubs.usgs.gov/fs/2017/3062/fs20173062.pdf

II. Life Cycle Assessment

Jan. 28 **Life Cycle Assessment (LCA): Components and Applications**

Process Level LCA vs Economic Input-Output (EIO) LCA
Components: Goal Definition and Scoping, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), Life Cycle Interpretation
Functional unit of analysis

Cases: Mid-sized vehicles; Beverage Containers

Reading:

ISO 14040 International Standard, *Environmental management – Life cycle assessment – Principles and framework*, 2006-07-01.
Henrickson, C.; et. al. "Economic Input-Output Models for Environmental Life-Cycle Assessment." *Environmental Sci. & Tech.*, (1998) 32: 184A-191A.
Comparative Energy and Environmental Impacts for Soft Drink Delivery Systems, National Association of Plastic Container Recovery

Other Resources:

“International Standards for LCA” Chapter 2 in *Environmental Life Cycle Assessment* 2014.

Chapter 1: Life Cycle and Systems Thinking; Chapter 4: The ISO LCA Standard – Goal and Scope in *Life Cycle Assessment* Matthews et al. 2015.

Keoleian, G.A. et al. “LCI Modeling Challenges and Solutions for a Complex Product System: A Mid-Sized Automobile” *Total Life Cycle Conference Proceedings*, *P-339,* SAE International, Warrendale, PA, (1998) Paper No. 982169: 71-84.

Life Cycle Initiative (UNEP and SETAC): http://www.lifecycleinitiative.org/

An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications UNEP and SETAC 2013

Life Cycle Assessment: Inventory Guidelines and Principles (EPA 600/R-92/245). Cincinnati, OH: U.S. EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, February 1993.

Guidelines for Life-Cycle Assessment: A “Code of Practice.” Society of Environmental Toxicology and Chemistry, 1993.

Jan. 30 **Life Cycle Inventory Analysis**

System Boundaries
Process Flow Diagram
Input/Output Analysis
LCA Databases
LCA Software

Case: Diapers – Disposable vs. Reusable? Which means we need to model Washing Machines.

Reading: Vizcarra, A.T., Lo, K.V. and P.H. Lio. “A Life-Cycle Inventory of Baby Diapers Subject to Canadian Conditions.” *Environmental Toxicology and Chemistry,* Vol. 13 No. 10 (1994): 1707-1716.

Hendrickson, C.T. Lester B. Lave, H. and S. Matthews “Using the economic input-output life cycle assessment model” Chapt. 5 in *Environmental life cycle assessment of goods and services: an input-output approach* Washington, DC: Resources for the Future, (2006) 49-61.

Other Resources:

Chapter 8: LCA Screening via Economic Input-Output Models in *Life Cycle Assessment* Matthews et al. 2015.

Global Guidance Principles for Life Cycle Assessment Databases: A Basis for Greener Processes and Products UNEP/SETAC 2011

Hufschimidt, M. “Input-output Models” in: Environment Natural Systems, and Development. p. 287-300.

“Input Output Models for LCA” Chapter 7 in *Environmental Life Cycle Assessment* 2014

Feb. 4 **Energy and Transportation Modules**

- Energy
  - Primary energy
  - Feedstock, Process Fuels and Transportation Fuels
  - Electricity Generation
  - Emission Factors
- Transportation
  - Energy – Combustion and Precombustion (upstream processes)
  - Emission Factors

Reading: Energy Requirements and Environmental Emissions for Fuel Consumption– Appendix A Franklin Associates, 2000.

Life Cycle Assessment: Inventory Guidelines and Principles (EPA 600/R-92/245). Cincinnati, OH: U.S. EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, February 1993: pp. 46-50.

Other Resources:

Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model – Argonne National Laboratory https://greet.es.anl.gov/

Transportation Energy Data Book Oak Ridge National Laboratory: https://tedb.ornl.gov/

S. Kim and B.E. Dale “Life cycle inventory information of the United States electricity system” *Intl. J. LCA* (2005) 10(4): 294-304.

Feb. 6 **Materials Production Phase: Non-renewable feedstocks**

- Sourcing Issues (e.g., transport distance, production methods, grids, supply chain risks, social impacts)
- Processes
  - Acquisition – mining, drilling
  - Material Processing and Refinement – beneficiation, chemical reactions
- Material Production Energy
- Energy of Material Resources (e.g., plastics)

Examples: Al, Steel, Glass, Plastics, Cement

Reading: Kessler, Stephen. *Mineral Resources Economics and the Environment.* McMillan College Publishing: New York, 1994: pp. 164 – 174: 196-203.

Other Resources:

Flow Studies for Recycling Metal Commodities in the US
https://www.usgs.gov/centers/nmic/recycling-statistics-and-information
International Aluminum Institute:
http://www.world-aluminium.org/
Worldsteel Association: http://www.worldsteel.org/
Aluminum Association Inc.: http://www.aluminum.org
American Iron and Steel Institute: http://www.steel.org
Plastics Division of the American Chemistry Council (ACC): https://plastics.americanchemistry.com/Education-Resources//Alonso, E., J. Gregory, F. Field, and R. Kirchain "Material Availability and the Supply Chain: Risks, Effects, and Responses" Env. Sci. Technol. (2007) 41(19): 6649-56.

Feb. 11 **Materials Production Phase: Renewable feedstocks**

Sourcing of feedstock (e.g., agricultural, certified forests, urbanwood)
Processes
  Acquisition – Agricultural production, harvesting
  Material Processing and Synthesis – Refining, polymerization
Material Production Energy
Energy of Material Resources

Examples: PLA, PHA, coconut fibers (automotive), propanediol from corn (PDO), PE from sugar cane.

Reading: Vink, E.T.H. Applications of life cycle assessment to NatureWorks^{TM} polylactide (PLA) production *Polymer Degradation and Stability* 80 (2003) 403–419.
Gerngross, Tillman U. "Can Biotechnology Move Us Toward a Sustainable Society?" Nature Biotechnology (June 1999) 17: 541-544.
"Growing Plastics" *Chemical and Engineering News* (2008) September 29: 21-25.
"Raw materials reality" *Chemical and Engineering News* (2006) December 11: 22- 23.

Other Resources:

Southeast Michigan's Reclaimed Wood Marketplace: http://www.urbanwood.org/
"Coconut Fibers" *High Tech Report 2001* DaimlerChrysler, p. 76-79.
"DuPont Tate & Lyle Bio Products Begin Bio-PDO™ Production in Tennessee" (press release)
S. Kim and B.E. Dale, "Life Cycle Assessment Study of Biopolymers (Polyhydroxy-alkanoates) Derived from No-Tilled Corn" *Intl. J. LCA* (2005) 10 (3) 200- 10.

Feb. 13 **Manufacturing Phase**

Manufacturing Processes (e.g., stamping, extrusion, molding)
Co-Product Allocation Rules

Cases: Steelcase office furniture, Steel vs HDPE Fuel Tanks

Reading: Boustead, I., 1997, Eco-profiles of the European Plastics Industry, Report 10: Polymer Conversion, Association of Plastics Manufacturers in Europe, May. (browse)
Life Cycle Assessment: Inventory Guidelines and Principles (EPA 600/R-92/245). Cincinnati, OH: U.S. EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, February 1993: pp. 55-59.
Keoleian, G., Spatari, S., Beal, R., Stephens, R., Williams, R. "Application of Life Cycle Inventory Analysis to Fuel Tank System Design" *Intl. J. LCA* (1998) 3(1): 18-28.

Other Resources:

"Unit Processes" Chapter 4 in *Environmental Life Cycle Assessment* 2014
Sullivan, J.L., Burnham, A. and Wang, M., 2010, *Energy Consumption and Carbon Emissions Analysis of Vehicle and Component Manufacturing*, ANL/ESD 10-6.

Feb. 18 **Use Phase**

Processes
  Operation (use)
  Service (maintenance, repair)

Cases: Cups – Paper, Plastic or Ceramic?
Lightweighting Cars
Wireless technologies

Readings: Hocking, M.B. “Paper Versus Polystyrene: A Complex Choice.” *Science* (1991) 251: 504-5.
Wells, H.A., Neil McCubbin, Red Cavaney, Bonnie Camo, and M.B. Hocking. “(Letters) Paper versus polystyrene: Environmental impact.” *Science* 252, no. 7 June (1991): 1361-1363.
Hocking, M.B. “Disposable Cups Have Eco Merit,” *Nature* 369, 12 May (1994): 107.
Toffel, M.W. and Horvath, A. “Environmental implications of wireless technologies: news delivery and business meetings.” Environ. Sci. & Technol. (2004) 38(11): 2961-70.

Other Resources:
Green Vehicle Guide US EPA http://www.epa.gov/greenvehicles/

Feb. 20 **End-of-Life Management Phase**
Options
- Remanufacturing
- Recycling
- Waste to Energy
- Landfill Disposal

Recycling Allocation
Examples: Packaging, Cars, Tires, Grocery Bags

Reading: *Life Cycle Assessment: Inventory Guidelines and Principles* (EPA 600/R-92/245). Cincinnati, OH: U.S. EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, February 1993, pp. 87-91.
Keoleian, G.A. and Spitzley, D. “Guidance for Improving Life-cycle Design and Management of Milk Packaging” *Journal of Industrial Ecology* (1999) 3(1): 111-126.

Other Resources:
van Haaren, R.,et al. “The State of the Garbage in America” *BioCycle* (2010) 51(10): 16-23.
Life Cycle Assessment for Three Types of Grocery Bags – Recyclable Plastic; Compostable, Biodegradable Plastic; and Recycled, Recyclable Paper, conducted by Boustead Consulting & Associates Ltd. for the Progressive Bag Alliance (Amer. Chem. Council), 2007.
Managing the End of Life of Tires - World Business Council for Sustainable Development 2008.
EPA WARM (Waste Reduction Model): https://www.epa.gov/warm

Mid-term Exam Period (3 day take home) start taking your exam between Feb. 25 – 28

Feb. 25 **Life Cycle Impact Assessment I: Introduction, GWP and ODP**
Methodology
- Classification
- Characterization
- Valuation

Impact Potentials – GWP and ODP
Greenhouse Gases: CO_2, CH_4, N_2O, CF_4, C_2F_6, SF_6, CFC substitutes
Case example: aluminum

Reading: *Guidelines for Life-Cycle Assessment: A “Code of Practice.”* Society of Environmental Toxicology and Chemistry (1993) pp. 26-30.
Life-Cycle Impact Assessment: A Conceptual Framework, Key Issues, and Summary of Existing Methods (EPA-452/R-95-002) U.S.EPA Office of Air Quality Planning and Standards, July 1995, pp. 3-1 – 3-8.
Bare, J.; “TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts.” *Journal of Industrial Ecology.* (2003) 6(3-4): 49, 56-68.
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2017 (published 2019), developed by the U.S. Government to meet annual U.S. commitments under the United Nations Framework Convention on Climate Change (UNFCCC). *(browse executive summary)*

Other Resources:
Chapter 10: Life Cycle Impact Assessment in *Life Cycle Assessment* Matthews et al. 2015.
Carbon Footprint Calculators: e.g., https://coolclimate.org/index
Ozone Depletion site at EPA: https://www.epa.gov/ozone-layer-protection
Basic Ozone Layer Science: https://www.epa.gov/ozone-layer-protection/basic-ozone-layer-science
Bare, J. et al.; “Development of the method and U.S. normalization database for life cycle impact assessment and sustainability metrics.” *Env. Sci. Tech.* (2006) 40(16): 5108-5115.
McMillan, C. and G.A. Keoleian “Not all Primary Aluminum is Created Equal: Life Cycle Greenhouse Gas Emissions from 1990 to 2005” *Environ.Sci. and Technol.* (2009) 43 (5): 1571–1577.

Feb. 27 **Life Cycle Impact Assessment II: Other Environmental and Human Health Impacts**
Impact Potentials continued – Acidification, Smog, and Others
Human Health and Ecosystem Health
 Intake fraction
 Human Toxicity Potential (HTP)
 Critical Volume Approach
 Environmental Defense (ED)- Scorecard

Readings: "Life Cycle Impact Assessment" Chapter 11 in *Environmental Life Cycle Assessment* 2014
Bennett, D.H. McKone, T.E. Evans, J.S. Nazaroff, W.W. Margni, M.D. Jolliet, O. Smith, K.R. 2002. Defining Intake Fraction *Environmental Science and Technology* May 1, 2002 / Volume 36, Issue 9 / pp 206 A–211 A.
"Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES – LCA" *Chemosphere* (2000) 41: 541-573.

Other Resources:
Environmental Defense Scorecard: http://www.scorecard.org/
Bennett, D.H. Margni, M.D. McKone, T.E. Jolliet, O. Intake Fraction for Multimedia Pollutants: A tool for Life Cycle Analysis and Comparative Risk Assessment. *Risk Analysis* (2002) 22(5): 905-918.
Crettaz, P. Pennington, D. Rhomberg, L. Brand, K. Jolliet, O. Assessing Human Health Response in Life Cycle Assessment Using ED10s and DALYs: Part 1 – Cancer Effects. *Risk Analysis* (2002) 22(5): 931-946.

Feb 29 – Mar. 8 Winter Break

Mar. 10 **Life Cycle Impact Assessment III: Water, Land Use and Resource Depletion**
Water Footprint and Water Stress Index
Land Use
Resource Depletion Impact
Social LCA
Other topics: Material Criticality Issues: scarcity, substitutability, supply risk and Conflict Minerals

Reading: Pfister, S., A Koehler, S. Hellweg "Assessing the Environmental Impacts of Freshwater Consumption in LCA" *Environ. Sci. Technol*. (2009) 43: 4098–4104.
Guidelines for Social Life Cycle Assessment of Products UNEP/SETAC 2009 (browse)
CSS Factsheet: Critical Materials http://css.umich.edu/factsheets/critical-materials-factsheet
Conflict Minerals Initiative: Raise Hope for Congo (browse site) https://enoughproject.org/about/past-campaigns/rhfc
Social Hotspots Databasehttps://www.socialhotspot.org/about-shdb.html (browse)

Other Resources:
Water Risk Assessment Maps WWF http://waterriskfilter.panda.org/en/Explore/Map
DOE, Critical Materials, U. S. Department of Energy Critical Materials Strategy, December 2010. (focus on critical materials for batteries) http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf
Gruber, P., P. Medina, G. Keoleian, S. Kesler, M. Everson, T. Wallington, "Global Lithium Availability: A Constraint for Electric Vehicles?" *Journal of Industrial Ecology* (2011) 15(5): 760-775.

III. Life Cycle Design and Management

Mar. 12 **Life Cycle Design Framework and Design Requirements**
Life Cycle Management
 Multistakeholders
 Internal Elements: Environmental Management Systems, Corporate sustainability
 External Factors: Consumer preferences, Government regulations
Life Cycle Design Process
 Needs Analysis
 Specification of Requirements
 Selection and Synthesis of Design Strategies
 Design Evaluation

Reading: Keoleian, G.A. "Life-Cycle Design" in *Environmental Life-Cycle Assessment*. Ed. Mary Ann Curran, McGraw-Hill: New York, 1996: pp. 6.1-6.34.

McDonough, B.; "Applying the Principles of Green Engineering to Cradle-to-Cradle Design." *Environmental Science and Technology*. December 1, 2003. p. 434-441.
Measuring Intangibles ROBECOSAM's Corporate Sustainability Assessment Methodology (browse)

Other Resources:

Life-Cycle Design Guidance Manual: Environmental Requirements and the Product System. (EPA/600/R-92/226). Cincinnati, OH: U.S. EPA, ORD, Risk Reduction Engineering Laboratory, Jan. 1993.
Keoleian, G., Koch, J., Menerey, D. and Bulkley, J. *Life-Cycle Design Framework and Demonstration Projects: Profiles of AT&T and Allied-Signal* (EPA/600/R-95/107), Cincinnati, OH: U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory, July 1995.
Design for Sustainability: A Step by Step Approach UNEP 2009.
US Environmental Protection Agency: http://www.epa.gov/lawsregs/
China State Environmental Protection Administration: http://english.mee.gov.cn/Japan Environmental Laws**:** http://www.env.go.jp/en/laws/
European Commission – Environmental Policies**:** http://ec.europa.eu/environment/waste/index.htm

Mar. 17 **Design Strategies**

Product Life Extension
Material Oriented Strategies
  Material Recycling
  Material Selection
  Material Intensiveness
Process Oriented Strategies
Distribution Oriented Strategies

Reading: Chapter 5 "Design Strategies" in *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System.* (EPA/600/R-92/226). Cincinnati, OH: U.S. EPA, Office of Research and Product Development, Risk Reduction Engineering Laboratory, January 1993, pp. 61-96. (browse on canvas)
Anastas PT, Zimmerman JB "Design through the 12 principles of green engineering" *Environmental Science & Technology* 37 (5): 94A-101A MAR 1 2003.
Kim, H.C., G.A. Keoleian, Y.A. Horie, "Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost" *Energy Policy* (2006) 34: 2310–2323.

Other Resources:

von Weizsacker, Ernst U., Lovins, Amory, Lovins, Hunter, *Factor four: doubling wealth, halving resource use* London : Earthscan Publications LTD, 1997.
Herman, R., S.A. Ardekani, J.H. Ausubel, "Dematerialization," *Technology and Environment*, National Academy Press: Washington, (1989): pp. 50-69.
De Kleine, R., G.A. Keoleian, J.C. Kelly "Optimal replacement of residential air conditioning equipment to minimize energy, greenhouse gas emissions, and consumer cost in the US" *Energy Policy* (2011) 39(6): 3144-3153.

Mar. 19 **Life-Cycle Costing**

Purchase, ownership, disposition
Private and social costs

Cases: Compact Fluorescent Light Bulbs, Appliances, Cars

Reading: "Economics and the Environment" Chapt. 13 in *Introduction to Engineering and the Environment* E. Rubin, McGraw-Hill: New York (2001) p. 544-588.
Lund, Robert T. "Life-Cycle Costing: A Business and Societal Instrument." *Management Rev.* 67, no. 4 (1978): 17-23.

Other Resources:

Chapter 3: Life Cycle Cost Analysis in *Life Cycle Assessment* Matthews et al. 2015.
"Life-Cycle Cost Analysis (LCCA)" by Sieglinde Fuller, National Institute of Standards and Technology (NIST): http://www.wbdg.org/resources/life-cycle-cost-analysis-lcca
Weitzman, M. L. (1998) "Why the Far-Distant Future Should be Discounted at the Lowest Possible Rate." *Journal of Environmental Economics and Management* 38: 201-208.
Hellweg, S., Hoffstetter, T. B., and Hungerbulher, K. "Should Current Impacts be Weighted Differently than Impacts Harming Future Generations?" *International Journal of Life Cycle Assessment,* (2003) 8(1): 8-18.

Mar. 24 **Life Cycle Management and Green Supply Chains**

Environmental Accounting
  Internal costs: conventional, hidden, liability, less tangible costs; external costs
  Activity Based Accounting and Cost allocation
Revisit Sourcing Decisions

Extended Producer Responsibility
E Waste

Reading *Life Cycle Management: How business uses it to decrease footprint, create opportunities and make value chains more sustainable*, UNEP/SETAC 2009.
Sustainability Consortium https://www.sustainabilityconsortium.org/product-categories/ (browse)
SASB (Sustainability Accounting Board Standards) Materiality Map https://www.sasb.org/standards-overview/materiality-map/ (browse)
"A Green Supply Chain" *Chemical & Engineering News* (2010) August 2: 16- 22. (browse)
O'Rourke, D. "The science of sustainable supply chains" *Science* (2014) 344 (6188): 1124-1127.

Other resources:
Responsible Sourcing Tool (human trafficking in your supply chain) http://www.responsiblesourcingtool.org/
Adhitya, A., I. Halim,and R.Srinivasan "Decision Support for Green Supply Chain Operations by Integrating Dynamic Simulation and LCA Indicators: Diaper Case Study" *Environ. Sci. Technol.* (2011), 45: 10178–10185
The Lean and Green Supply Chain: A Practical Guide for Material Managers and Supply Chain Managers to Reduce Costs and Improve Environmental Performance (January 2000) (EPA 742-R-00-001, pp.58. (browse)
"Environmental Cost Accounting" Chapt. 12 in *Green Engineering: Environmentally Conscious Design of Chemical Processes* D.T. Allen and D.R. Shonnard Eds. Prentice Hall (2002) p. 397-416.
Forging a Better Supply Chain *C&E News* (2012): June 25: 12-18.
Producing usable materials from e-waste *Environ. Sci. & Technol.* (2008) Sept. 15: 6782.
Lifset R. and T. Lindhqvist "Producer Responsibility at a Turning Point" *J. Ind. Ecol.* (2008) 12(2): 144-47.
Seuring, S and Muller "Literature review and conceptual framework for sustainable supply chain management" *Journal of Cleaner Production* 16 (2008) 1699–1710.

Mar. 26 **Life Cycle Framework for Environmental Marketing and Labeling**
First Party Environmental Marketing
Third Party Environmental Labeling
    Mandatory
    Voluntary (Report Cards, Seals of Approval, Single Attribute Certification)

Case: Green Seal, Blue Angel, Green Cross

Reading: *Environmental Labeling Issues, Policies, and Practices Worldwide* December 1998 EPA 742-R-98-009 p 1-4, 9-14.
Sins of Greenwashing: https://www.ul.com/insights/sins-greenwashing

Other Resources:
Lyon, T.P. and Montgomery, A.W. (2015) "The Means and End of Greenwash." *Organization & Environment*, 28(2), 223-249.
"LCA Based Product Claims" Chapter 19 in *Environmental Life Cycle Assessment* 2014
"Communicating LCA Results" Chapter 18 in *Environmental Life Cycle Assessment* 2014
FTC Guides for the Use of Environmental Marketing Claims- new guides released October 2012
https://www.ftc.gov/policy/federal-register-notices/guides-use-environmental-marketing-claims-green-guides
Magerholm Fet A. and C. Skaar "Eco-labeling, Product Category Rules and Certification Procedures Based on ISO 14025 Requirements" (2006) *Int J LCA* 11(1): 49 – 54.

IV. Sustainable Systems (Production and Consumption)

Mar. 31 **Sustainable Food Systems**
Sustainability Indicators for the US Food System
    Environmental, Economic, and Social
Material Flows and Food Waste
Life Cycle Energy Consumption
Aurora Organic Dairy: Life Cycle Greenhouse Gas Emissions

Reading: Heller, M. and G. Keoleian "Assessing the sustainability of the U. S. food system: A life cycle perspective" *Agricultural Systems* (2003) 76: 1007-1041.
CSS Factsheet: US Food System http://css.umich.edu/factsheets/us-food-system-factsheet

Other Resources:
Heller, M.C., and G.A. Keoleian, "Greenhouse Gas Emission Estimates of U.S. Dietary Choices and Food Loss." *Journal of Industrial Ecology* (2015) 19(3): 391–401.
Agricultural Ecosystems: Facts and Trends – World Business Council for Sustainable Development 2008

Weber, C. and H.S. Matthews "Food-Miles and the Relative Climate Impacts of Food Choices in the United States" *Environ. Sci. Technol.* (2008) 42: 3508-3513.
de Boer, I.J.M. (2003) Environmental impact assessment of conventional and organic milk production *Livestock Production Science* (2003) 80: 69–77.
Jones, A. An Environmental Assessment of Food Supply Chains: A Case Study on Dessert Apples. *Environmental Management*. (2000) 30(4): 560-76.

Apr. 2 **Sustainable Mobility**
Trends, Technology, Environmental Impacts, Economics, Policy
Plug-In Hybrid Electric Vehicles (PHEV) LCA

Reading: Keoleian, G.A. and D.V. Spitzley. "Life Cycle Based Sustainability Metrics." Chapter 7 in *Sustainability Science and Engineering: Defining Principles* (Sustainability Science and Engineering, Volume 1), M.A. Abraham, Ed. Elsevier, 2006: 127-159.
Mobility 2030: Meeting the challenges to sustainability; World Business Council for Sustainable Development (browse)
CSS Factsheet: Personal Transportation http://css.umich.edu/factsheets/personal-transportation-factsheet
CSS Factsheet: Autonomous Vehicles http://css.umich.edu/factsheets/autonomous-vehicles-factsheet
Other Resources:
Michalek, J., M. Chester, P. Jaramillo, C. Samaras, C.Shiau, L. Lave "Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits" *PNAS* (2011) 108 (40):16554-16558.
Kromer, M.A. and J.B. Heywood A Comparative Assessment of Electric Propulsion Systems in the 2030 US Light-Duty Vehicle Fleet *SAE Technical Paper Series* 2008-01-0459.
Mobility for Development – Facts and Figures and Executive Summary; World Business Council for Sustainable Development (2009)
Mobility 2001 Report: Overview; World Business Council for Sustainable Development (browse)

Apr. 7 **Sustainable Buildings**
Trends, Technology, Environmental Impacts, Economics, Policy
House LCA

Reading: Keoleian, G.A., Blanchard, S. and P. Reppe "Life Cycle Energy, Costs, and Strategies for Improving a Single Family House" *Journal of Industrial Ecology* (2000) 4(2): 135-156.
Wilson, A. and J. Boehland, "Small is Beautiful: U.S. House Size, Resource Use, and the Environment" *J. Ind. Ecol.* (2005) 9 (1-2): 277-287.
CSS Factsheet: Residential Buildings http://css.umich.edu/factsheets/residential-buildings-factsheet

Other Resources:
Mazor, M.H., J.D. Mutton, D.A.M. Russell, G.A. Keoleian, "Life Cycle Greenhouse Gas Emissions Reduction From Rigid Thermal Insulation Use in Buildings" *Journal of Industrial Ecology* (2011) 15(2): 284-99.
Scheuer, C., G. Keoleian, and P. Reppe. "Life Cycle Energy and Environmental Performance of a New University Building." *Energy and Buildings* (2003) 35: 1049-1064.
BEES 4.0 Building Products Database NIST https://www.nist.gov/services-resources/software/bees LEED (Leadership in Energy and Environmental Design) https://new.usgbc.org/
ACEEE (American Council for an Energy-Efficient Economy) http://aceee.org/

Apr. 9 **Finalize term projects**
Apr. 14 **Industrial Ecology Symposium: Term Project Presentations**
Apr. 16 **Industrial Ecology Symposium: Term Project Presentations**
Apr. 16 **Term Project Papers Due and Peer Evaluation Forms Due**

Apr. 21 Course Review

April 28 **Final Exam** (4:00 – 6:00 pm)

COURSE REQUIREMENTS AND EVALUATION

Class participation*	10 %
Assignments	20 %
Term Project	20 %
Mid-Term Exam	25 %
Final Exam	25 %

* Class participation = the Sustainable Systems blog/class discussion leader (4%), active participation in the class including Q/A, sharing news and info (3%), and attendance based on two excused absences and -0.5%/each 2 additional absences (3%).

Term Project

A term project will be assigned on Jan. 21 and project groups will be formed to facilitate interdisciplinary collaboration. Your group will choose a product and apply industrial ecology principles and tools to assess the environmental impacts associated with the product and identify opportunities for improvement. The term project includes a group paper and presentation.

Exams

Midterm	The midterm will be a take home exam which takes roughly 6 hours total to complete. You have a three day period to complete the exam starting anytime between February 25 and 28. Exams will be distributed enclosed in unsealed envelopes. Note the start time on the envelope, and when you finish, seal up the exam in the envelope provided and note the end time. For example, if you start the exam at 3pm on Tuesday, February 25 you must seal it up in the envelope before 3pm on Friday, February 28. The last possible day to submit is Monday, March 2. Late exams will be marked down. You will be allowed to use your notes for this exam, but may NOT work with other students as this is a violation of academic integrity.
Final	April 28, 4:00 – 6:00 pm