INDUSTRIAL ECOLOGY (NRE 557 & CEE 586)
Winter Term 2015

SYLLABUS

Time  
Tuesday and Thursday 2:30 – 4:00 pm

Location  
1040 Dana (School of Natural Resources & Environment)

Instructor  
Gregory A. Keoleian  
Director, Center for Sustainable Systems  
Peter M. Wege Endowed Professor of Sustainable Systems  
Professor, SNRE and Professor, Civil and Environmental Engineering  
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Tuesday 4:00 – 5:00 pm; Thursday 4:00 – 5:00 pm

Graduate Student Instructor  
Brett Simon (bssimon@umich.edu)

Office  
4th Floor Commons Dana Bldg.

Office Hrs.  
Monday 3:30 – 5:30 pm; Friday 1:30 pm – 3:30 pm; or by appointment

COURSE BACKGROUND
This course was first offered in the winter term 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 foundation of industrial ecology, which seeks to design and manage products and services that meet human needs in a sustainable manner.

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. 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 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 two blog posts. Sign-ups will be done via the Wiki tool in Ctools.
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**

2. **Websites**
   - Center for Sustainable Systems: [http://www.css.snre.umich.edu/](http://www.css.snre.umich.edu/)
   - International Society for Industrial Ecology: [http://www.is4ie.org/](http://www.is4ie.org/)

**COURSE OUTLINE**

1. **Industrial Ecology and Sustainability Frameworks**

   Jan. 8  **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:

   Other Resources:
Jan. 13 **Sustainability Framework**
Definitions and Drivers for Sustainability
Sustainability Indicators
- Ecological/Environmental – Ecological Footprint
- Economic – Genuine Progress Indicator (GPI)
- Social and Demographic – Equity

*Living Planet Report and Summary Booklet* 2014 WWF (browse summary report)
Genuine Progress Indicator (browse):
http://genuineprogress.net/genuine-progress-indicator/

**CSS Factsheet: Social Development Indicators**
http://css.snre.umich.edu/css_doc/CSS08-15.pdf

Other Resources:
Genuine Progress Indicator:
Maryland Genuine Progress Indicator: http://www.green.maryland.gov/mdgpi/indicators.asp
Elkington, J., Chapter 2 in *The Chrysalis Economy*. pp. 11-25.

Jan. 15 **Resource Sustainability Challenges and Opportunities**
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)

*Municipal Solid Waste in the United States Facts and Figures*(browse)
http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm
Center for Sustainable Systems Factsheets:
http://css.snre.umich.edu/facts
*US Environmental Footprint*
*Greenhouse Gases*
*Climate Change: Science and Impacts*
*U.S. Energy System*
*U.S. Renewable Energy*
*U.S. Material Use*
Other Resources:

Annual Energy Review (suspended)  
[http://www.eia.gov/totalenergy/data/annual/index.cfm](http://www.eia.gov/totalenergy/data/annual/index.cfm)

Air Quality and Emissions Trends:  
[http://www.epa.gov/air/airtrends/sixpoll.html](http://www.epa.gov/air/airtrends/sixpoll.html)

Toxic Release Inventory  
[http://www2.epa.gov/toxics-release-inventory-tri-program](http://www2.epa.gov/toxics-release-inventory-tri-program)


Climate Indicators Analysis Tool – World Resources Institute:  [http://cait.wri.org/](http://cait.wri.org/)


Progress on Drinking-Water and Sanitation 2014 Update, World Health Organization and UNICEF.  

Jan. 20  **Industrial Ecology the Metaphor**

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

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

Reading:  

Other Resources:  
Nature Conservancy Biomimicry slideshow:  [http://www.nature.org/newsfeatures/specialfeatures/biomimicry-in-nature-slideshow.xml](http://www.nature.org/newsfeatures/specialfeatures/biomimicry-in-nature-slideshow.xml)

Fact Sheets from the Ecological Society of America:  [http://www.esa.org/esa/?page_id=1674](http://www.esa.org/esa/?page_id=1674)

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.  
Frosch, Robert A., and Nicholas E. Gallopoulos. “Strategies for Manufacturing.” *Scientific American*, (September 1989): 144-152.  

Jan. 22  **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

Other Resources:
Metals_Recycling_Rates_UNEP 110412-1
USGS Material Flow Resources http://minerals.usgs.gov/minerals/mflow/

II. Life Cycle Assessment

Jan. 27  
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

Comparative Energy and Environmental Impacts for Soft Drink Delivery Systems, National Association of Plastic Container Recovery

Other Resources:
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 US EPA Life Cycle Assessment Resources:
http://www.epa.gov/nrmrl/std/lca/resources.html
LCA 101: http://www.epa.gov/nrmrl/std/lca/lca.html

Jan. 29  
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.


Other Resources:
Global Guidance Principles for Life Cycle Assessment Databases: A Basis for Greener Processes and Products UNEP/SETAC 2011
“Input Output Models for LCA” Chapter 7 in Environmental Life Cycle Assessment 2014

Feb. 3

**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


Other Resources:
- Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model – Argonne National Laboratory
  http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
- Transportation Energy Data Book Oak Ridge National Laboratory; http://cta.ornl.gov/data/index.shtml

Feb. 5

**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


Other Resources:
- International Aluminum Institute: http://www.world-aluminium.org/
- International Iron and Steel Institute: http://www.worldsteel.org/
- Aluminum Association Inc.: http://www.aluminum.org
- American Iron and Steel Institute: http://www.steel.org
Feb. 10  **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.


Other Resources:
- “DuPont Tate & Lyle Bio Products Begin Bio-PDO™ Production in Tennessee” (press release)

Feb. 12  **Manufacturing Phase**

Manufacturing Processes (e.g., stamping, extrusion, molding)

Co-Product Allocation Rules

Cases: Steelcase office furniture, Steel vs HDPE Fuel Tanks


Other Resources:

Feb. 17  **Use Phase**

Processes
- Operation (use)
- Service (maintenance, repair)

Cases: Cups – Paper, Plastic or Ceramic?

Lightweighting Cars

Wireless technologies


Other Resources:

Feb. 19  **End-of-Life Management Phase**

Options
- Remanufacturing
Recycling  
Waste to Energy  
Landfill Disposal  
Recycling Allocation  

Examples: Packaging, Cars, Tires, Grocery Bags  


Other Resources:  

Mid-term Exam Period (3 day take home) start taking your exam between Feb. 24 – Feb. 27  
Feb. 24  
Life Cycle Impact Assessment I: Introduction, GWP and ODP  
Methodology  
Classification  
Characterization  
Valuation  
Impact Potentials – GWP and ODP  
Greenhouse Gases: CO2, CH4, N2O, CF4, C2F6, SF6, CFC substitutes  
Case example: aluminum  


Other Resources:  
Carbon Footprint Calculators: e.g., http://coolclimate.berkeley.edu/  
Ozone Depletion site at EPA: http://www.epa.gov/spdpublc/index.html  

Feb. 26  
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  


Other Resources:  
Environmental Defense Scorecard http://www.scorecard.org/  
Feb. 28 – Mar. 8  Winter Break

Mar. 10  **Life Cycle Impact Assessment III: Water, Land Use and Social LCA**
Water Footprint and Water Stress Index
Land Use
Social LCA

*Guidelines for Social Life Cycle Assessment of Products* UNEP/SETAC 2009

Mar. 12  **Life Cycle Impact Assessment IV: Resource Depletion and Materials Criticality**
Resource Depletion Impact
Material Criticality Issues: scarcity, substitutability, supply risk
Conflict Minerals
Rare Earth Elements, Lithium, Cobalt
Enough Li for Electrified Vehicles?

Conflict Minerals Initiative: Raise Hope for Congo (browse site) [http://www.raiselifehopeforcongo.org/content/initiatives/conflict-minerals](http://www.raiselifehopeforcongo.org/content/initiatives/conflict-minerals)

Other Resources:

**III. Life Cycle Design and Management**

Mar. 17  **Life Cycle Design Framework and Design Requirements**
Life Cycle Management
Multistakeholders
Internal Elements: Environmental Management Systems
External Factors: Consumer preferences, Government regulations
Life Cycle Design Process
Needs Analysis
Specification of Requirements
Selection and Synthesis of Design Strategies
Design Evaluation


Other Resources:
Mar. 19

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


Other Resources:

Mar. 24

**Life-Cycle Costing**
Purchase, ownership, disposition
Private and social costs

Cases: Compact Fluorescent Light Bulbs, Appliances, Cars


Other Resources:

Mar. 26

**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.


Other resources:

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)

Pelton, R.E.O., Smith, T.M. Hotspot Scenario Analysis: Comparative Streamlined LCA Approaches for Green Supply Chain and Procurement Decision Making, *Journal of Industrial Ecology* (accepted: in press);


Mar. 31

**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


**Other Resources:**

“LCA Based Product Claims” Chapter 19 in *Environmental Life Cycle Assessment* 2014

“Communicating LCA Results” Chapter 18 in *Environmental Life Cycle Assessment* 2014


**IV. Sustainable Systems (Production and Consumption)**

Apr. 2

**Sustainable Mobility**

Trends, Technology, Environmental Impacts, Economics, Policy

Plug-In Hybrid Electric Vehicles (PHEV) LCA

**Reading:**


*Mobility 2030: Meeting the challenges to sustainability;* World Business Council for Sustainable Development (browse)

CSS Factsheet: Personal Transportation [http://css.snre.umich.edu/css_doc/CSS01-07.pdf](http://css.snre.umich.edu/css_doc/CSS01-07.pdf)

**Other Resources:**


Apr. 6

**Sustainable Buildings**

Trends, Technology, Environmental Impacts, Economics, Policy
House LCA

CSS Factsheet: Residential Buildings http://css.snre.umich.edu/css_doc/CSS01-08.pdf

Other Resources:
BEES 4.0 Building Products Database NIST http://www.bfrl.nist.gov/oae/software/bees/
LEED (Leadership in Energy and Environmental Design) http://www.usgbc.org/

Apr. 9 Sustainable Food Systems
Sustainability Indicators for the US Food System
   Environmental, Economic, and Social
Material Flows
Life Cycle Energy Consumption
Aurora Organic Dairy: Life Cycle Greenhouse Gas Emissions

CSS Factsheet: US Food System http://css.snre.umich.edu/css_doc/CSS01-06.pdf

Other Resources:

Apr. 14 Industrial Ecology Symposium: Term Project Presentations
Apr. 16 Industrial Ecology Symposium: Term Project Presentations
Apr. 21 Term Project Papers Due and Peer Evaluation Forms Due
Course Review and Evaluations
April 29 Final Exam (1:30 – 3:30 pm)

COURSE REQUIREMENTS AND EVALUATION

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Class participation*</td>
<td>10%</td>
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<tr>
<td>Assignments</td>
<td>20%</td>
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<tr>
<td>Term Project</td>
<td>20%</td>
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<tr>
<td>Mid-Term Exam</td>
<td>25%</td>
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<tr>
<td>Final Exam</td>
<td>25%</td>
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* 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. 23 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  Take home exam.  3 days to complete starting anytime between February 24 and 27. Exams will be 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 time. For example, if you start the exam at 3pm on Tuesday, February 24 you must seal it up in the envelope before 3pm on Friday, February 27. Last possible day to submit is 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 29, 1:30 –3:30 pm