2.83 and 2.813

Energy, Materials and Manufacturing

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Department of Mechanical Engineering
Spring 2012
2.83/2.813 Addresses

- **Environmental issues**
  - energy, carbon, toxics, materials use, …

- **At large scales**
  - Global scale, sustainability…

- **Uses Engineering Tools**
  - Life Cycle Assessment (LCA), Energy and Exergy Analysis

- **Interacts with other Disciplines**
  - economics, chemistry, industrial ecology, paleontology, climatology, …
4 Major Themes

1. Life Cycle Assessment of goods and services
2. Resources accounting
3. Scale: Analysis boundaries
4. World Scale: possibilities and constraints
Life Cycle Assessment

- What can we assess? Goods and Services, renewable energy solutions...
- Phases of life: 1) Materials production, 2) mfg, 3) use, & 4) end-of-life including reuse, remanufacture, recycle
- Types of Assessment tools: Eco-Audit, Process LCA, EIO-LCA, hybrid LCA
Will electric vehicles reduce carbon emissions?
Resources accounting

• Counting things and comparing
• Energy, CO2, materials, toxics, land species, genuine investment,…
• Assigning responsibility
• Tracking progress
• Thermodynamics
If today is a typical day on planet Earth,

We will lose:
116 square miles of rainforest
72 square miles to encroaching deserts,
10 to 100 species.

We will add:
250,000 more people on this planet,
270,000 tons of nitrogen, and
18,000,000 tons of carbon to the atmosphere.

references: FAO UN, Orr, Meyer, Smil, DOE
The Royal Society's motto 'Nullius in verba' roughly translates as 'take nobody's word for it'. It is an expression of the determination of Fellows to withstand the domination of authority and to verify all statements by an appeal to facts determined by experiment.
**Baloney Detection Kit**

- How reliable are the sources of this claim? Is there reason to believe that they might have an agenda to pursue in this case?

- Have the claims been verified by other sources? What data are presented in support of this opinion?

- What position does the majority of the scientific community hold in this issue?

- How does this claim fit with what we know about how the world works? Is this a reasonable assertion or does it contradict established theories?

- Are the arguments balanced and logical? Have proponents of a particular position considered alternate points of view or only selected supportive evidence for their particular beliefs?

- What do you know about the sources of funding for a particular position? Are they financed by groups with partisan goals?

- Where was evidence for competing theories published? Has it undergone impartial peer review or is it only in proprietary publication?

after Carl Sagan
Scale: Analysis boundaries

• From products to global impacts
• Human behavior
• Space and time
• Sustainability
• Partitioning the problem
• Identity equations
Scales: From Process / Product to The Planet

- Scale of the Analysis
- Scale of our Use

Ex. CFC & Ozone Depletion
Sustainable Development

"...development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

UN 1983, “Brundtland Report”

Dr. Gro Harlem Brundtland
former PM of Norway,
chairwomen of UN commission,
“Our Common Future”
World Population

http://www.census.gov/ipc/www/popclockworld.html
Outline for Today

1. 2.83/2.813 Overview
2. Some Administrative Stuff
3. Manufacturing’s Profile
4. Identity eq’ns

TA: Sahil Sahni, sahil@MIT.EDU
Handouts for Today

• Schedule

• Readings

• Guide to Ashby’s book

• Card to fill out
Textbooks


See handout, webpage for the rest…
### Tentative Schedule

**Spring 2012**

**Mon. & Wed. 2:30 – 4 p.m.**

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<thead>
<tr>
<th>February</th>
<th>Monday</th>
<th>Wednesday</th>
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<tbody>
<tr>
<td></td>
<td>13. Resource Accounting</td>
<td>8. Introduction</td>
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<tr>
<td></td>
<td>27. LCA examples</td>
<td>22. Intro to LCA</td>
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<td>29. Guest speaker</td>
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<td>March</td>
<td>5. Energy and Exergy</td>
<td>7. Materials Production</td>
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<td></td>
<td>19. Discussion</td>
<td>21. Quiz 1</td>
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<td></td>
<td>26. (Spring Break)</td>
<td>28. (Spring Break)</td>
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<td></td>
<td>9. Use Phase</td>
<td>11. End of Life</td>
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<td>23. Guest speaker</td>
<td>25. Presentations</td>
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<td></td>
<td>30. Presentations</td>
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<tr>
<td>May</td>
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<td></td>
<td>7. Review</td>
<td>9. Quiz 2</td>
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* (Monday schedule on Tuesday)

Grading

1. Quiz I (March 21) (30%)
2. Quiz II (May 9) (30%)
3. Project (Report due May 16) (30%)
4. Class Participation (see discussions) (10%)

100%
Group Projects

• Undergrad Project
  • Application oriented
  • e.g. product or lifestyle analysis
  • Will provide list of topics
  • Group presentation and report

• Grad Project
  • Research oriented
  • “Journal standards”
  • Will provide a list of projects
  • Group presentation and report
Possible Project Topics

- LCA for Energy storage systems, round trip efficiency
- Recycling of flat panel displays
- Algae for fuels
- PV pump for African village
- Baseball teams
- Rebound effect…
PV water pumping in Africa
Baseball Stadiums
Homeworks

• Posted on the Web
• Answers Appear One Week later
• Not graded, but…
• Office Hours are posted for discussion
  – TG Rm 35-234: Tu 2-3, W 4-5
  – SS Rm 35-009: Tu 4-5, Th 4-5
Course Webpage

http://web.mit.edu/2.813/www/
Please fill out card

• Name
• email
• year (e.g. G2 or U4)
• course / program
• Have you taken economics, and/or physical or chemical thermodynamics?
• How would you describe yourself in terms of environmental awareness? Interests?
Manufacturing

• Value Adding
  – Jobs, Value Creation, Standard of Living

• Long Reach
  – Design Decisions control material and energy flows, Supply Chain, Services

• Shadow Side
  – Environmental Footprint
  – “Excess” Consumption
Manufacturing’s Shadow Side

- Energy
- Carbon
- Toxic Materials
- Waste
- Mixing and Diluting
- Regulations
World Energy and Carbon

IEA 2010
2004 Total Primary Energy = 468.7 EJ
CO₂ from coal, gas, oil = 10.6 + 5.3 + 10.2 = 26.1 Gt/yr

Electricity & CHP = 60.9 / 182.9
η = 1/3

Industry
4.2 EJ
21.4
7.1
20.9
23.6
23.6
27.9
105.1 EJ
+ TPE
For elect & CHP =
+ 51.2, or
156.3 EJ
and 10 Gt
of CO₂
Net Primary Resource Consumption ~103 Exajoules

Electrical imports* 0.08
Nuclear 8.6
Hydro 2.7 2.7
Biomass/other** 3.4 0.9 0.04 1.8
Natural gas 20.6 6.0
Net imports 3.8
Coal 23.8 21.1 0.4
Imports

Bal. no. 0.3

Bal. no. 0.1

Bal. no. 0.7

Bal. no. 1.1

Export 2.2

U.S. petroleum and NGPL 15.7 2.4
Imports 25.6

Bal. no. 0.9

Export 1.1

0.2

Bal. no. 0.3

0.1

1.0

0.1

0.7

0.7

2.3

8.2

27.8

27.0

27.9

20.1

16.1

15.5

Useful energy 37.1

Industrial 20.7

Residential/commercial 59.3

Lost energy 5.2 4.0 22.4

5.6

Nonfuel 6.3

Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2002.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore National Laboratory
http://ieed.illnl.gov/flow
U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO₂**

Renewables 3***

Natural Gas
1,203

299

1,875

Electricity power sector
2,249

1,603

Residential/commercial
2,206

Coal
2,070

433

179

10

35

3

643

Industrial
1,674

Coal coke imports 6

72

157

413

Petroleum
2,453

1,811

Transportation
1,850

*Includes adjustments of 42.8 million metric tons of carbon dioxide from U.S. territories, less 90.2 MtCO₂ from international and military bunker fuels.
**Previous versions of this chart showed emissions in metric tons of carbon, not of CO₂.
***Municipal solid waste and geothermal energy.
Note: Numbers may not equal sum of components because of independent rounding.

Lawrence Livermore National Laboratory, May 2004
http://eed.llnl.gov/flow/
Total Toxic Releases by Sector

- Off-site/Underground Injection
- Land
- Underground Injection
- Water
- Air

Lbs

Mfg. | Metal Mining | Coal Mining | Elec. Utilities | Chem. Wholesale | Petrol Bulk Term | RCRA Solvent Recovery

EPA, TRI 1998
Major Waste Types by Weight in the United States

2005 EPA data:
Ind. ~7 G t
MSW~ 0.23 G t

Note: A large fraction of the total weight in the industrial categories is water. Dry weight of industrial wastes can be as low as 10% of the total.
Mixing & Dilution

Manufacturing
Environmental Regulations

Figure 3.1-1  Cumulative growth in federal environmental laws and amendments.

ref Allen & Shonnard
Engineering Strategies

source

recirculation

sink
Engineering Strategies

1. Reduction at Sink
   • pollution prevention
2. Reduction at Source
   • substitution
   • efficiency
3. Recirculation
   • reuse, remfg, recycle
### Environmental Concerns

<table>
<thead>
<tr>
<th>Environmental Concerns</th>
<th>Linkage to Manufacturing Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Global climate change</td>
<td>Greenhouse gas (GHG) emissions from direct and indirect energy use, land fill gases, etc.</td>
</tr>
<tr>
<td>2. Human organism damage</td>
<td>Emission of toxins, carcinogens, etc. including use of heavy metals, acids, solvents, coal burning...</td>
</tr>
<tr>
<td>3. Water availability and quality</td>
<td>Water usage and discharges e.g. cooling and cleaning use in particular</td>
</tr>
<tr>
<td>4. Depletion of fossil fuel resources</td>
<td>Electricity and direct fossil fuel usage e.g. power and heating requirements, reducing agents</td>
</tr>
<tr>
<td>5. Loss of biodiversity</td>
<td>Land use, water usage, acid deposition, thermal pollution</td>
</tr>
<tr>
<td>6. Stratospheric ozone depletion</td>
<td>Emissions of CFCs, HCFCs, halons, nitrous oxides e.g. cooling requirements, refrigerants, cleaning methods, use of fluorine compounds</td>
</tr>
<tr>
<td>7. Land use patterns</td>
<td>Land appropriated for mining, growing of bio-materials, manufacturing, waste disposal</td>
</tr>
<tr>
<td>8. Depletion of non-fossil fuel resources</td>
<td>Materials usage and waste</td>
</tr>
<tr>
<td>9. Acid disposition</td>
<td>Sulfur and NO\textsubscript{x} emissions from smelting and fossil fuels, acid leaching and cleaning</td>
</tr>
</tbody>
</table>

from Graedel and Allenby 2005
Identity Equations

Disaggregating the Problem

- IPAT eq’n - Ehrlich, Holdren, Commoner, 1972
- Master eq’n - Graedel and Allenby, 1995
- Kaya Identity - Yamaji, 1991
- ImPACT - Waggoner & Ausubel, 2002
Whatever you call it…

\[ \text{Impact} = \text{Impact} \]

\[ \text{Impact} = \text{Population} \times \frac{\text{Goods & Services}}{\text{Person}} \times \frac{\text{Impact}}{\text{Goods & Services}} \]

\[ I = P \times A \times T \]
for infinitesimals

\[ \frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T} \]

Population Growth
Affluence = GWP per captia
Technology
Second Order Terms

\[ \Delta C/C = \Delta A/A + \Delta B/B + \Delta A \Delta B/AB \]
Examples:

\[
\text{Impact} = \text{Pop} \times \frac{\text{GDP}}{\text{Person}} \times \frac{\text{Quantity}}{\text{GDP}} \times \frac{\text{Impact}}{\text{Quantity}}
\]

1. World CO\textsubscript{2} emissions
2. Carbon from Automobiles
3. Materials
4. Interactions between terms
Data Sources

• Population: U.S Census
• GDP: Bureau of Economic Affairs
• Energy: DOE
• Materials: USGS
• Impacts: EPA, DOE
Population Dynamics

\[ \frac{dP}{dt} = \Delta R \cdot P \quad \frac{dP}{P} = \Delta R \cdot dt \quad P = P_0 e^{\Delta R \cdot t} \]

in the discrete form…

\[ P = P_0 (1 + i)^n \]

Currently for World \( i \approx 1.2\% \)
We are adding 70-80 M people/yr

Add one Germany or 2X Canada each year
Affluence

\[
\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T}
\]

Affluence = GWP per captia
Affluence and GDP, GWP

• GDP = Gross Domestic Product

• GWP = Gross World Product

• GWP = market value of all goods and services produced for a year
GWP, $i \approx 3\%$ last 30 years

Figure 1. World GDP. Real 2000 GDP ($billions$)

Data from USDA
The International Macroeconomic Data Set
http://www.ernet.usda.gov/Data/Macroeconomics/
Carbon emissions

\[
\text{Carbon} = \text{Population} \times \frac{\text{GWP}}{\text{Pop}} \times \frac{\text{Energy}}{\text{GWP}} \times \frac{\text{Carbon}}{\text{Energy}}
\]

\[
\frac{\Delta \text{Carbon}}{\text{Carbon}} = +1\% + 2\% - 1.25\% - 0.25\% = +1.5\%
\]

These are *rough* averages over the last 3 decades, data taken or calculated from Pacala & Socolow, Science 2004
$Im = P A C T$

Impact = Pop $\times \frac{GDP}{Person} \times \frac{Quantity}{GDP} \times \frac{Impact}{Quantity}$

In general, these equations do not show causation because the terms on the right hand side may be (often are) related. However, they do show correlations.
See Homework Reading by Waggoner and Ausubel
Fertility and Affluence

Figure 1: Fertility and Economic Development

Note: X axis is on a logarithmic scale.
Source: Calculated using data from World Bank (2004).

\[ Im = P A C T \]
Affluence and Energy are correlated

Figure 2.1
A high correlation between TPES and GDP, with both values expressed as per capita averages for the year 2000. Values calculated from data in BP (2001) and UNDP (2001).
The Big Issues

• Sustainability
• Energy and Climate change
• Scale of the problem
• How to partition the problem?
• How to know a strategy will work?
• This is not business as usual
Goals for this Course

• Understanding
  – the pieces (engineering)
  – the big picture (more than engineering)

• Tools
  – Life Cycle Analysis, Exergy Analysis,
    Materials Flow Analysis, Economics…..
For Next Time:

• Please Do Your Ecological Footprint
  http://www.footprintcalculator.org/
• Reading on IPAT, Ashby Ch 11 & Waggoner…
• Find Readings, homeworks at:
  • http://web.mit.edu/2.813/www/
Oh yes, back to the
…….World Population

http://www.census.gov/ipc/www/popclockworld.html
“So this is the famous environment everyone’s so hyped up about?”