Some Basic Concepts of Sustainability

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Key Concepts

1) Sustainability: Definitions and concepts
2) Collapses in the past: Examples and causes
3) Club of Rome study
4) Growth models: Linear, exponential, logistic and collapse
5) Applications
6) Metrics: Maximum sustainable yield and ecological footprint
7) Sustainable development: Ponderables
8) Sustainable engineering
9) School of Sustainability at ASU

Definitions of Sustainability

Perhaps the most widely cited qualitative definition:

• Sustainable development is one which “meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, UN, 1987)

Sustainable development

• Those paths of social, economic, and political progress that meet the needs of the present without compromising the ability of future generations to meet their own needs (Steele, 1997)
Another view:

Sustainability represents one of the most challenging interface problems in science today. The design of a sustainable *interface* between the natural environment and the built or designed environment is as essential to our collective well-being as any intellectual pursuit of the age.

*Michael Crowe,*  
*President of ASU*

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**Sustainability as an interface issue that balances development/growth and long-term needs of all four systems**

- **Natural systems**: Atmosphere, Environment, Oceans, Lakes, Rivers, Flora, Fauna
- **Engineered systems**: Buildings, Transportation, Manufacturing, Highways, Bridges, Water distribution, Telecommunication
- **Social or collective systems**: Trade and Commerce, Banking, Healthcare, Education, Law, Government, Defense, International relations
- **Individual**: Prosperity, Sense of justice, Pursuit of happiness
Lack of sustainable energy resources could be major contributing factor to our society’s downfall!

Historic civilizations which collapsed!

THE WORLD IS MORE INTERCONNECTED NOW!

Take-aways from Prof. Diamond’s Book

- **Causes for collapses** of past societies can be grouped into:
  - Natural events beyond control
  - Invasions by external/outside armies
  - **SELF-INFLICTED**
    - some locations are more fragile and some practices unsuited to the environment of location- so instability occurs leading to collapse
- **Four key phases** in decision-making of a society heading towards collapse:
  - Failure to anticipate a problem
  - Failure to perceive a problem when it has arrived (denial)
  - Clash of interest (example: tragedy of the commons)
  - Problems are beyond available technology
Most Serious Environmental Problems
from “Collapse” by Jared Diamond

- Destruction of natural habitats
- Overfishing
- Loss of genetic diversity
- Farmland soil erosion
- Fossil fuel depletion
- Dwindling fresh water
- Environmental pollution
- Introduction of “alien” species
- Human population growth and impact
- ....

Sustainability includes, but goes far beyond environmental studies

Club of Rome (1970s)

- Premise: Civilization has become very complex- so much so that mankind does not understand the origin, significance and inter-relationships of its many parts
- A group of scientists developed a complex integrative mathematical model to study the interactions of:
  - Accelerated industrialization
  - Rapid population growth
  - Widespread malnutrition
  - Depletion of nonrenewable resources
  - Deteriorating environment
Their Conclusions:

- With present growth trends, the limits of growth will be reached within 100 years.
- The end will be precipitous (due to exponential behavior).
- It is possible to alter these growth trends and establish stability (or sustainability).
- The sooner mankind begins working on the second, the less disruptive the transition.

(and 40 years later we are still debating!)

Growth Models

Figure 4 THE GROWTH OF SAVINGS

Exponential Growth

If a miser hides $10 each year under his mattress, his savings will grow linearly, as shown by the lower curve. If, after 10 years, he invests his $100 at 7 percent interest, that $100 will grow exponentially, with a doubling time of 10 years.
Legend has it that chess was invented by a mathematician who worked for an ancient king. For a reward he asked the king to put one grain of what on the first chess square, two on the second, four on the fourth, etc.

Was this a reasonable request? Let's do the mathematics:

- There are 64 squares on a chess board
- On the last square we would have $2^{64}$ grains
- On the board, there would be $2^{64} - 1$ grains
- This amount of grain is approximately equal to 500 times the 1976 world harvest of wheat!

Exponential Growth

One of the major problems of the energy crisis is the failure to grasp the significance of exponential growth

$$Q_0 = \text{energy use in some base year}$$
$$r = \text{growth rate per year (proportionality constant)}$$
$$t = \text{time (in years)}$$

$$\frac{dQ}{dt} = Q$$
$$\text{or } \int \frac{dQ}{Q} = \int r dt$$
$$\ln Q = rt + c$$
$$\ln Q_0 = c$$
$$\ln \frac{Q}{Q_0} = rt$$
$$Q = Q_0 e^{rt}$$
World primary energy use has increased exponentially as did population but at a higher rate (due to higher per capita energy use)

From Boyle et al., 2003
Q(t) = Q_0 e^{rt}

If Q(t) = 2Q_0

\[ e^{rt} = 2 \]

Q_0 = energy use in some base year
r = growth rate per year
t = time (in years)

How long does it take for energy use to double:

Doubling time \( t_d = \ln(2) / r \)

or \( t_d = 0.7 / r \)

Overall growth rate in US = 1.07%
China = 9.5%
World = 2.4%

<table>
<thead>
<tr>
<th>Growth Rate (%/yr)</th>
<th>Doubling Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

Doubling Time

There is a certain number of days, or months, or years (it depends on the species) in which the population doubles.

An example is a pond with a lily pad whose doubling time is one week.
You may not even notice its growth until the pond is half covered.
The next week, the pond has disappeared under lilies!

CHOKE!

From Gonick and Outwater, 1996
Exponential models also apply to other situations:

- *Levelized fuel inflation rate*:

Cost of gasoline was $0.90/gallon about 25 years back. In 2010 it is $2.70/gallon. What is the levelized rate?

\[ Q(t) = Q_0 e^{rt} \] or \[ r = \frac{1}{t} \ln \left( \frac{Q}{Q_0} \right) = \frac{1}{25} \ln \left( \frac{2.7}{0.9} \right) = 0.044 \text{ or } 4.4\% \]

Compared to US inflation rate around 2%!

*In August 2011, gasoline cost was around $3.40/gallon. What is the levelized rate? 5.1%*

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Steady Growth in a Finite Environment

- Bacteria grow by division
  - 1 => 2 => 4 => etc.
- Let’s say we have a bottle with a single bacteria
  - Bacteria only needs air for sustenance
  - Bacteria reproduce every minute  \text{Doubling rate is 1 minute}
  - We put bacteria in at 11 a.m. and leave
  - At noon, we return and the bottle is full

**Let’s Ask Some Questions**

1. **At what time was the bottle half full?**  \text{Answer: 11:59}
2. If you were an average bacteria in the bottle, at what time would you first realize you were running out of space?

At 11:55 a.m., 5 minutes before noon, the bottle is only 3% full and 97% empty. Does anyone know there is a problem?

Now, suppose some farsighted bacteria sent out a crew to explore offshore the continental shelf, the Arctic, and some of the western lands. They find 3 new empty bottles. The discoveries quadruple the total space reserves. Surely the bacteria can now be "SELF SUFFICIENT".

3. How long can steady growth continue as a result of this magnificent discovery?

ANSWER: [Blank]

Two more minutes!
WHAT CONCLUSIONS CAN WE DRAW FROM THESE EXAMPLES?

* CONSUMPTION OF CONVENTIONAL RESOURCES CANNOT CONTINUE TO GROW

* SIGNIFICANT DISCOVERIES OF NEW OIL/GAS/COAL CAN ONLY DELAY A MAJOR CRISIS.

* ENERGY CONSERVATION OFFERS ONE MEANS OF STRETCHING OUR CURRENT ENERGY RESOURCES BY REDUCING OUR GROWTH RATE.

* ALTERNATIVE ENERGY SOURCES MUST BE DEVELOPED

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Lifetime of a Reserve under Exponential Growth

Total consumption $C$:

$$ C = \int_{0}^{T} Q_0 e^{rt} \, dt $$

$$ = \frac{Q_0}{r} (e^{rt} - 1) $$

$$ e^{rt} = \left( \frac{C}{Q_0} \right)^{\frac{1}{r}} $$

$$ \frac{T}{r} = \ln \left[ \frac{C}{Q_0} \right] $$

LOOK AT ONE OF OUR RESOURCES:

PROVEN WORLD OIL RESERVES: $C = 10,000$ Quads

CURRENT CONSUMPTION: $r Q_0 = 140$ Quads/yr

- @ 1% GROWTH RATE: $T = 54$ years
- @ 3% GROWTH RATE: $T = 38$ years
- @ 5% GROWTH RATE: $T = 30$ years
Logistic Growth

Growth proportional to existing or available resources → limits growth

\[ \frac{dQ}{dt} = r \cdot Q \left( 1 - \frac{Q}{K} \right) \]

where \( K \) = carrying capacity

or \( \lim_{t \to \infty} Q(t) = K \)

\( r \) = unrestricted growth rate

\[ \frac{dQ}{dt} \left( \frac{Q}{K} \right) = r \cdot Q \left( 1 - \frac{Q}{K} \right) \]

Let \( \alpha = \frac{Q}{K} \)

\[ \frac{d\alpha}{dt} = r \cdot \alpha (1-\alpha) \]

\[ Q(t) = \frac{Q_0 \cdot K}{Q_0 + (K - Q_0) \cdot e^{-rt}} \]

\[ = \frac{Q_0}{\frac{Q_0}{K} + (1 - \frac{Q_0}{K}) \cdot e^{-rt}} \]

Solved Examples

\[ Q(t) = \frac{Q_0}{(Q_0/K) + [1 - (Q_0/K)]e^{rt}} \]

- Exponential growth: calculate doubling time
  - world population growth in 2008: 1.188\% \hspace{1cm} 58 yrs
  - in U.S: \hspace{1cm} 0.883\% \hspace{1cm} 78 yrs
  - in India: \hspace{1cm} 1.58\% \hspace{1cm} 44 yrs
  - Energy growth in US in 2008: \hspace{1cm} 1.07\% \hspace{1cm} 65 yrs
  - in India/China: \hspace{1cm} 9.5\% \hspace{1cm} 7.3 yrs
  - in world \hspace{1cm} 2.4\% \hspace{1cm} 29 yrs

- Logistic growth: If \( k=20 \text{ TW}, Q_0=14 \text{ TW} \) (in 2008) and \( r=2.4\% \), what would be energy use in 2036 (28 years later)

Answer: 16.4 TW compared to 27.4 TW for exponential growth
Because of exponential behavior—statistics changes rapidly

### TABLE 1.2
Percentage Shares of World Population, World GDP, and World Commercial Energy Consumption for Selected Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>% of World Population 2001</th>
<th>% of World GDP 2002</th>
<th>% of World Energy Consumption 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>1.6</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>Japan</td>
<td>2.0</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>France</td>
<td>0.9</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Germany</td>
<td>1.4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1.0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>China</td>
<td>20</td>
<td>4</td>
<td>11</td>
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</table>


In 2009 China became the largest energy consumer: China: 2,252 Mtoe versus USA 2,169 Mtoe

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### Practical Implications

- How we view energy use and growth affects the decisions we will be making (or not making) in the near future. Some people view the state of affairs as fine and do not question the idea of exponential energy growth. Some say we cannot continue using energy and expanding our use this way.
- To predict energy use, we can use models, such as the exponential growth model and the logistic growth model.
- In the past, both population and energy use have been spoken of in exponential terms.
- Now because of finite resources, better to talk in terms of logistic growth
This is what happened in the Easter Islands

From Gonick and Outwater, 1996

“Is the World Running Out of Oil”, Video clip by Australian Govt
http://www.youtube.com/watch?v=87FJliOHcl
Depletion of nonrenewable Minerals

Depletion time- time taken to use up a certain portion (~ 80%) of the reserves

*Figure 14-23 Natural capital depletion: depletion curves for a nonrenewable resource (such as aluminum or copper) using three sets of assumptions. Dashed vertical lines represent times when 80% depletion occurs.*

Miller and Spoolman, 2009

Maximum Sustainable Yield

This corresponds to the maximum removal rate which can sustain the existing population, and would occur at the inflection point:

\[
\frac{d}{dt} \left( \frac{dQ}{dt} \right) = Q
\]

or at \( Q = k/2 \).

Thus, if the fish population in a certain pond follows the logistic growth curve when there is no fish harvesting, then the maximum sustainable rate of fishing would be achieved when the actual fish population is maintained at half its carrying capacity.
Sustainability in terms of ecology-centric view

• Sustainability is maintaining/improving the quality of human life while living within the carrying capacity of supporting eco-systems—presumes concept of finite limits

Another related concept—self healing period of ecosystems

Concept of Ecological Footprint
Amount of biologically productive land and water needed to supply the people in a particular country or area with resources and to absorb and recycle the wastes and pollution produced by such resource use

One measure of unsustainability-
The degree to which we are living unsustainably by depleting and degrading some of earth’s irreplaceable natural capital and renewable resources
World Wildlife Fund (WWF) estimated that in 2003, humanity’s global ecological Footprint exceeded the earth’s biological capacity by 25%.

**Sustainability Metrics**

Ayres (1996) suggested six criteria for “perfect sustainability: which requires stabilization, i.e., no further net increase in:

(a) atmospheric greenhouse gas concentrations
(b) acidity in rainfall
(c) accumulation of ... long-lived halogenated chemicals in soils or sediments
(d) withdrawals for non-replenishing aquifers in arid regions
(e) loss of topsoil (i.e. erosion or desertification)
(f) loss of such biological resources as wetlands or old-growth forests
Sustainability Metrics

Shane and Graedel (2000): Ten categories for urban metrics evaluated as: low, medium or high according to some determined level of environmental efficiency:

- air quality
- water
- solids waste
- transportation
- energy
- resource use
- population (and land use)
- urban ecology
- livability
- general environmental management

Sustainability Metrics - Engineer’s View

- **Material Intensity**
  
  \[
  \frac{\text{Mass of Raw Materials} - \text{Mass of Products}}{\text{Output}}
  \]

- **Energy Intensity**
  
  \[
  \frac{\text{Net Fuel Energy Consumed}}{\text{Output}}
  \]

- **Water Intensity**
  
  \[
  \frac{\text{Volume of Fresh Water Consumed}}{\text{Output}}
  \]

- **Land Use Intensity**

- **Pollutant Effects**
  
  Or toxic effects
  
  \[
  \frac{\text{Measure of Pollutant Effect}}{\text{Output}}
  \]

- **Greenhouse gases**: 
Flow Diagram for Natural Resources

**Sources**
- Total Resource Available
  - RESERVES: Est. Known Discoveries
  - Replenishment Of Natural Resources

**Use**
- Products being Used by Humans
  - Extraction & Conversion
  - Exhaust & Disposal

**Sinks**
- Wastes Produced And Stored or Emitted into the Environment
  - Environmental Assimilation of Wastes

Energy Trends And Depleting Supplies!

Global Warming and other Pollution Effects

The Deficiency of Sustainability Metrics

- Is sustainability a set of quantifiable objectives, or is it a contemporary myth?
  - Developed to explain complexities we can’t yet approach descriptively (evolution of the anthropogenic Earth)
  - Developed for us to “feel good” about ourselves and as a “marketing” tool
  - Translation of vague sustainability issues into design objectives and constraints is biggest gap

(slide from Allenby, 2010)
Ambiguity in the term “Sustainability”

• The concept of “sustainability” is relative rather than absolute
• What is sustained?
  The earth? Biodiversity? Human life? Living standards?
• What is meant by “future” 25 years, 50 years, 100 years, 500 years…. 1 million years?
• To what geographic scale is it best applied to: entity (building, industry), community, city/metro, state, region, country, global

The definition of sustainability has become increasingly ambiguous as different definitions emerge depending on specific circumstances

(slide from Allenby, 2010)

Sustainable Development- Shortcomings

“On the one hand, [sustainable development] represents much more than simply an analytical approach to environmental auditing or improving business accountability. It also encompasses and represents a way of acknowledging our values and beliefs, and ascribing meaning to our activities...... it must also be acknowledged that sustainable development is both ideological and immature. As such, it has neither the breadth nor the profundity of the traditions that, to an extent, it supersedes.”


(slide from Allenby, 2010)
Sustainable Development- Myth?

“There have always been, and will always be myths because it is through the metaphorical language of myth that a culture articulates its deepest concerns. Sustainable development can be seen as our modern myth, emerging from a culture of science, technology and reason.”


Sustainable Engineering

• “Sustainable Engineering” is in large part simply good engineering but with a more exhaustive set of considerations
• Sustainability has not yet been well enough understood to provide robust guidance to engineers (or anyone else)- lacks robust framework
• Sustainability in current usage is a highly subjective concept, and may represent only one of the worldviews that engineers must integrate into their designs- use existing “heuristics”
• Engineering must become better at integrating social and environmental context
• Engineering must become better at understanding systems context, especially role of products and innovation in creating service ad social change
• “sustainability can(not) be understood, studied, or indeed even conceptualized without understanding technology”

Allenby (2009)

Therefore, two parallel efforts are required:
- In the short term, specific activities intended to modernize engineering education and practice are necessary
- In the longer term, “sustainable engineering” must be built into all engineering disciplines

From Allenby (2008)
Advancing sustainability science: report on the International Conference on Sustainability Science (CS) 2009 by Joanne Kauffman

Sustainability Science (2009) 4:233-242

Universities should:
- Bridge scientific knowledge with societal needs and cultural norms
- Be centers of scholarship that contribute to sum total of human wisdom
- Create network of networks
- Work with industry
- Share knowledge with developing countries
- Be proactive in taking “effective” action