26th annual INCOSE international symposium
Edinburgh, UK
July 18 - 21, 2016

Quantifying Sustainability in System Design

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Outline

26th annual INCOSE international symposium
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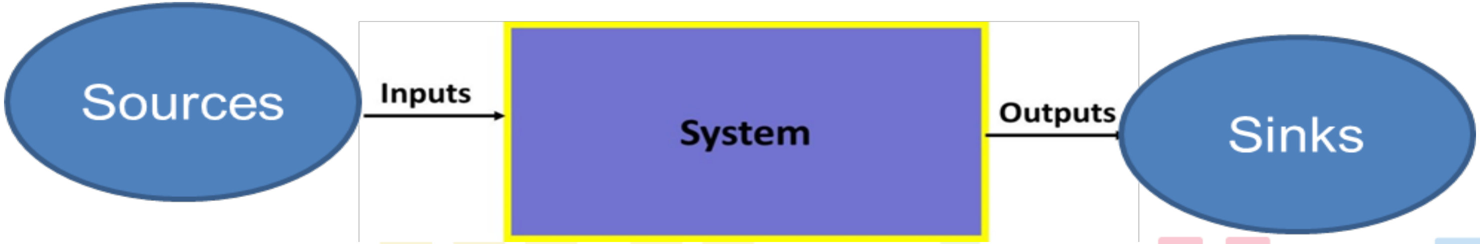
- Systems Engineering and System Design
- Sustainability and Appropriateness
- Mapping Syllabus to Course Description
- Quantifying Sustainability
- Quantifying Appropriateness
- System Design and Analysis using Measures
- Lessons Learned and Conclusions

Systems Engineering and Systems Design

- EGR4610: **Systems Design**: "Provides an analysis and design of engineered systems as they relate to their appropriate application and environmental, economic, and societal sustainability. Students will use a systematic approach, including life cycle assessment, and explore impacts on society, including public policy."

- "Systems Engineering" per IEEE* 1220 (2005): "An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability." See also ISO**/IEC/IEEE 15288:2015.



*Institute for Electrical and Electronics Engineers;
**International Standards Organization

Sustainability and Appropriateness

- "**Sustainable development** seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future." (Brundtland 1987)
  - Must define "needs and aspirations" and "compromising"
  - Should apply to the present as well ("instantaneous sustainability")

- **Appropriate Technology**: "Technology that is suitable to the social and economic conditions of the geographic area in which it is to be applied, is environmentally sound, and promotes self-sufficiency on the part of those using it."

UN Documents
Gathering a body of global agreements

Home | Sustainable Development | Education | Water | Culture of Peace | Human Rights | Keywords | Search

Report of the World Commission on Environment and Development: Our Common Future

Transmitted to the General Assembly as an Annex to *document A/42/427* - Development and International Co-operation: Environment

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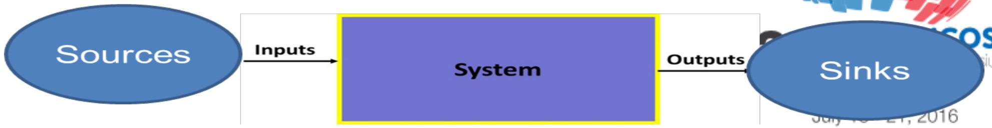
[Report of the World Commission on Environment and Development: Our Common Future]

Course Design

Week / Topic	Mapping to Course Description	Topics
• Introduction to System Design	Design of systems. Quantify sustainability (depletion time).	Introduction to basic systems engineering concepts, including boundaries and context. Introduce sustainable and appropriate concepts. Quantify resource depletion time.
• Interactions of Engineering Disciplines	Review basic physics and engineering so that students from different disciplines are not lost.	Describe coupled effects of design solutions on engineering disciplines.
• Exergy	Quantify sustainability (exergy).	Calculate exergy changes in systems for energy and materials
• Design for the Life-cycle	Life cycle assessment.	Evaluate sustainability issues from concept through disposal
• Multi-criteria Decision-making	Systematic design approach; life-cycle impacts of designs.	Decision trees, Kepner-Tregoe, Analytic Hierarchy Process
• Managing Design Resources	Systematic design approach; life-cycle impacts of designs.	Budgets, allocations, tolerances.
• Topology and Boundaries	Systematic design approach.	System impacts on context. Boundaries, zones, penetrations.
• Design for Safety and Reliability:	Systematic design approach; understand impacts on society.	Failure rate, consequences, severity and criticality.
• Designing using Laws and Standards	Systematic design approach; understand impacts on public policy.	Sources of standards and laws, effects of diverse jurisdictions by life cycle phase.
• Designing for Humans: Human-systems Integration	Systematic design approach; understand impacts on people. Appropriate application.	Anthropometrics, cognition and decision-making, appropriateness.

Plus a group design & analysis project

Quantifying Sustainability – Depletion Time



- Resource depletion time
  - Applies to Sources and Sinks

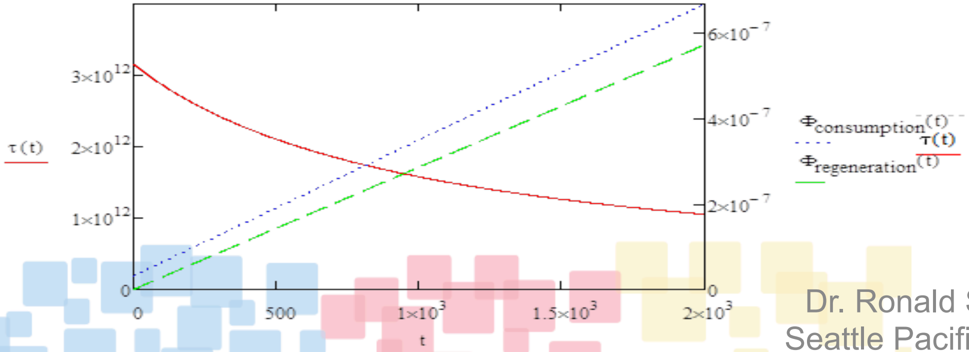
$$\tau(t) = \frac{M_{reserve}(t)}{(\Phi_{consumption}(t) - \Phi_{regeneration}(t))}$$

  - Time-dependencies are sensitive to technologies and costs (supply and demand)

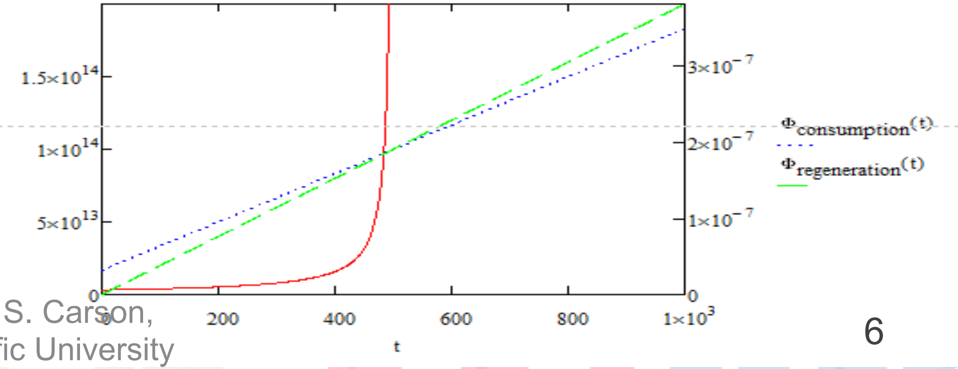
"Sustainable" requires $\tau = \infty$ or $\tau(t) \geq \tau_{initial}$

Lems, S., HJ van der Kooi, J de Swaan Arons, "The sustainability of resource utilization", *Green Chem 4:308-313* (2002)

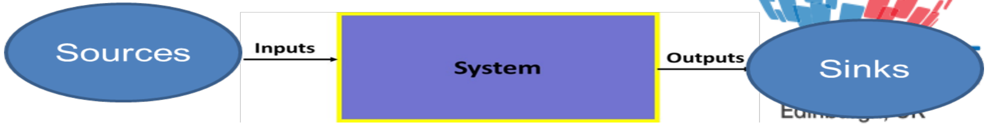
Depletion time falls when consumption increases and exceeds regeneration.



Depletion time increases when regeneration exceeds consumption.



Quantifying Sustainability – System Depletion Time



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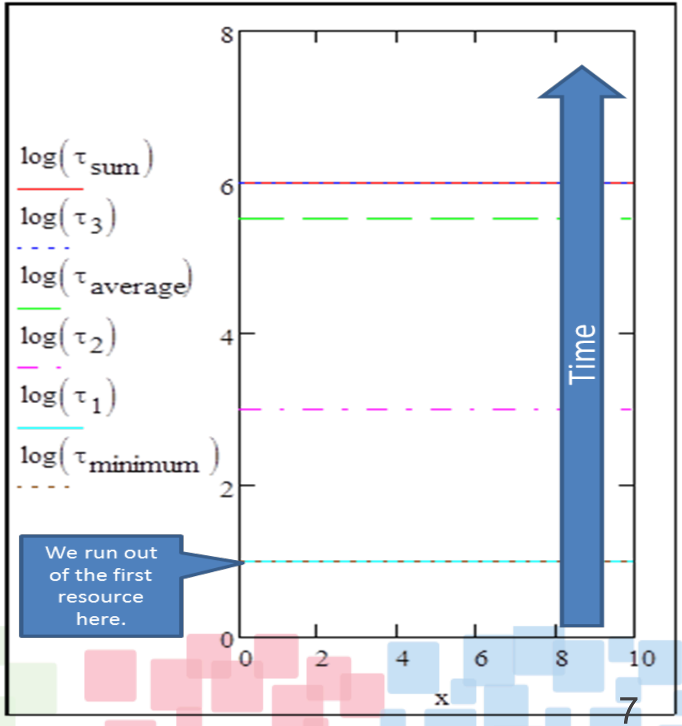
- *System* resource depletion time is the *minimum* time considering all required resources

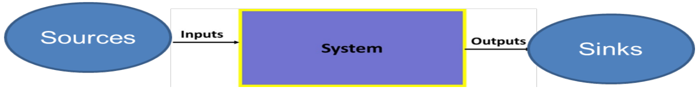
$$\tau_{system} = \min(\tau_1, \tau_2, \tau_3)$$

- We must examine *all* system resources

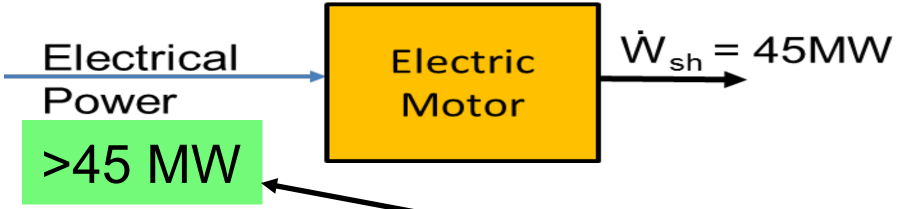


Even if an energy *resource* is infinite, the conversion *technology* is not

Quantifying Sustainability – Exergy



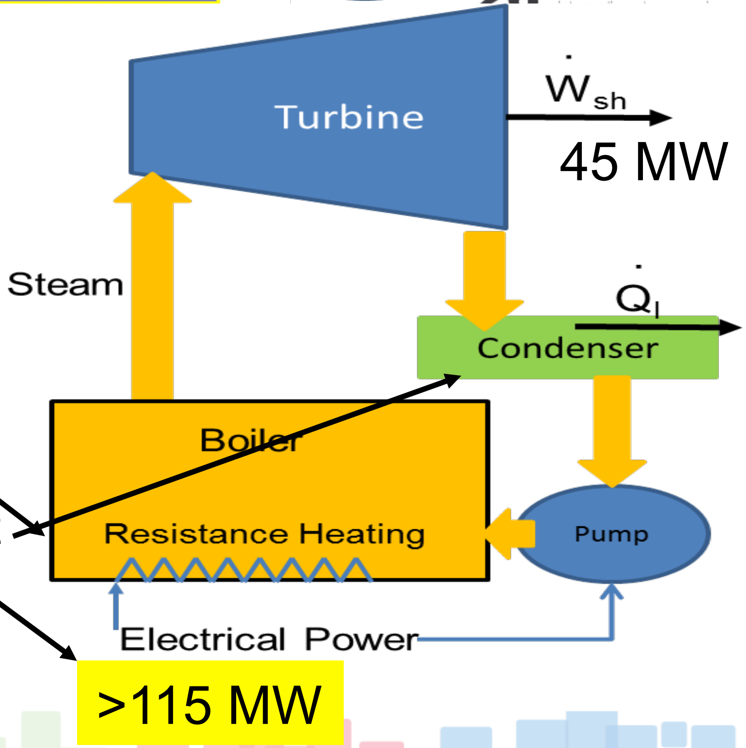
- Exergy, X ("available work")
  - Why is one system better than another?



  - Input exergy X_{in} is different
  - Exergy is destroyed by irreversibility

$$X_{destroyed} = T_0 S_{gen}$$

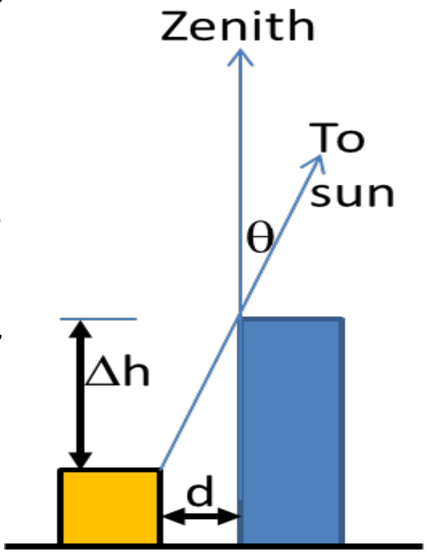
  - Available heat out may be irreversibly lost and unrecoverable (more $X_{destroyed}$)



$X_{destroyed}$ is the *depleted* resource

Instantaneous Sustainability

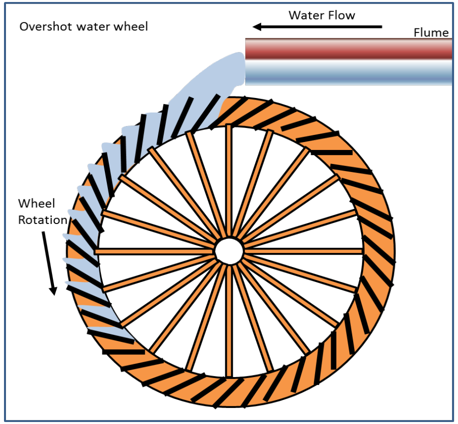
- Flowing power resources are subject to *instantaneous* sustainability considerations if one use compromises another
- Affects solar, wind, water power
- Solar shadowing can compromise some users

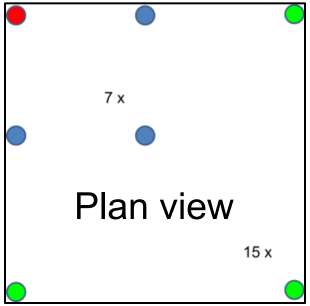


"Up" House, 1438 NW 46th St., Seattle, USA
Seattle Times, Pacific NW Magazine, 8 October 2015 (Alan Berner)
http://www.seattletimes.com/pacific-nw-magazine/searching-for-edith-macefield/

Instantaneous Sustainability – Water and Wind

- Water and wind resources are similarly subject to *instantaneous* sustainability considerations – one user can immediately affect other users
  - Recharge rate for the gravitational potential energy limits density of power extraction along rivers (W/m)
  - Recharge rate for wind limits density of wind turbines (W/m^2)





https://www.mitchelltech.edu/media/library/Videos/48/cover/honda-windfarm.jpg

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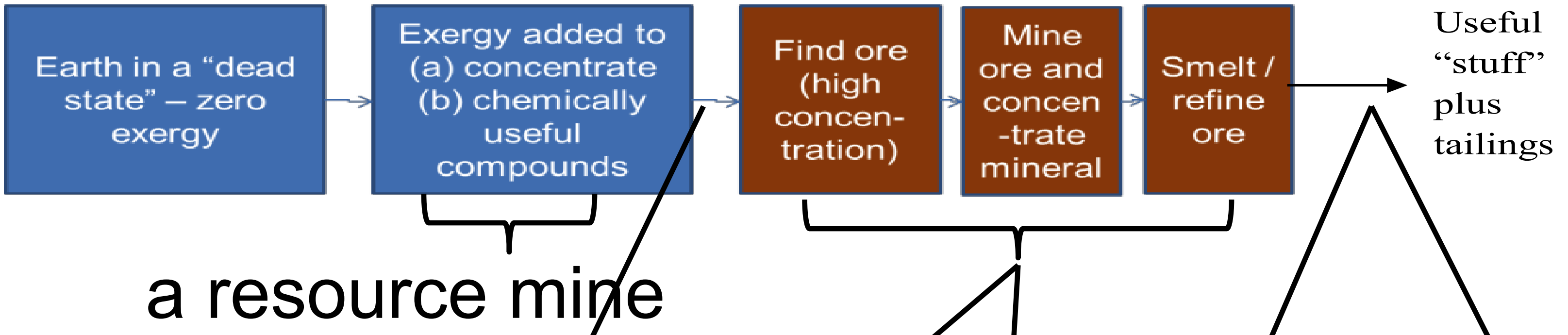
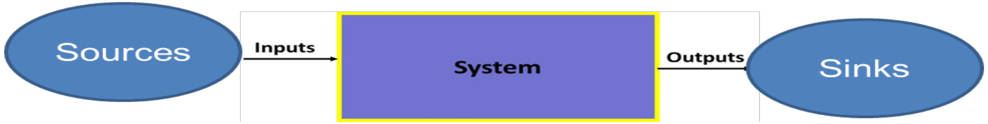
Exergy of Materials



$$X_{InOre} + \underbrace{(W_{in} + Q_{in})}_{[X_{Process}]} - X_{Destroyed} = X_{OutMaterial} + X_{Tails}$$

- Exergy balance
- **Inputs** are the exergy of the ore and processing
- **Outputs** are the desired product and unusable materials (tails)
- Some exergy is **destroyed** because of irreversible processes

Reducing Exergy Loss to Improve Efficiency



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- The *overall* efficiency is measured as

$$\eta = Desired\ output/Inputs = X_{OutMaterial}/X_{\ldots}$$

- A sustainability goal is to reduce the exergy of tails and exergy destroyed

0 0 $\eta \cong 1$

$$X_{InOre} + X_{Process} - X_{Destroyed} = X_{OutMaterial} + X_{\ldots}$$

$$X_{InOre} + X_{Process} \cong X_{OutMaterial}$$

- Process exergy should include restoration and remediation of the resource and sink

Example – Uranium Fuel Cycle (LWR)*

- Desired output is electricity (1 TWh)
- *Reactor* exergy input vs. output is > 40x
- Little exergy is *destroyed*, but most is unavailable without recycling the uranium
- Overall efficiency is

$$\eta = 0.0036x10\uparrow 6 \ / 1.56x10\uparrow 6 \ = 0.23\%$$

Process Step (Uranium State)	Exergy Output (10^6 TJ)
In situ (Uranium Ore)	1.56
Mining and Milling (U_3O_8)	1.482
Uranium Conversion (UF_6)	1.475
Enriched Fuel (UF_6)	0.147
Enrichment Tailings (UF_6)	1.32
Fuel Fabrication (UO_2)	0.146
Nuclear Reactor Electricity generation	0.0036 (1 TWh)
Waste disposal	0.13

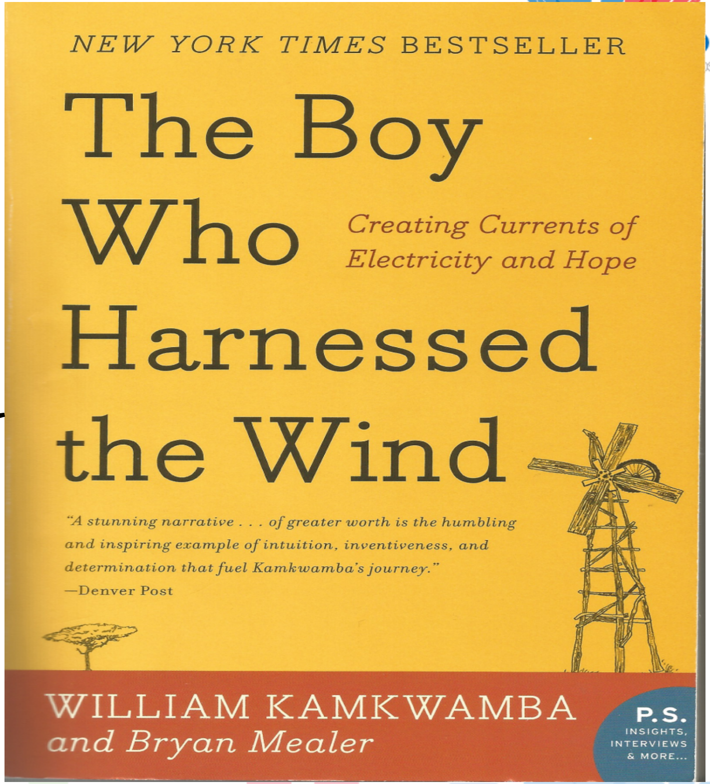
- *Tani, Filippo et al., "Exergy-based Comparison of the Nuclear Fuel Cycles of Light Water and Generation IV Reactors", *Proceedings of 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy* (Lausanne, Switzerland) [ECOS 2010]

Quantifying Appropriateness

- Qualitative scale based on the **degree of match(t)** between the technology throughout its life cycle and
  - Local resources
  - Local environment
  - Individual (or social group) knowledge and skill

- *Appropriate* for the individual

- But *not Sustainable*
  - This is an example of finite system depletion time because of *limited* windmill resources (materials, knowledge and skill)



System Design & Analysis Using Measures

Teaching Topic	Measures
• **Design for the Life-cycle**	System resource depletion time Exergy management (input, tailings, destruction) vs. life cycle phase
• **Multi-criteria Decision-making**	System design optimization based on resource depletion and exergy management
• **Managing Design Resources**	Overall efficiency; resource allocations
• **Topology and Boundaries**	Inputs, outputs, susceptibility and protection for natural and induced environments
• **Design for Safety and Reliability**	Failure rates, consequences and mitigation
• **Designing using Laws and Standards**	Degree of conformance, effects of different jurisdictions throughout the life cycle
• **Designing for Humans: Human-systems Integration**	Human factors measures for ergonomics, cognition, bio-engineering; person-centered design

Lessons Learned and Conclusions

- Student course evaluations: overall score 4.2/5 (Spring 2015)
  - "Most helpful" topics
    - System life cycle from conception through disposal
    - Multi-criteria decision-making
    - Topology and boundaries in system design
- Positive effect on Senior Design projects
  - Multi-disciplinary considerations benefited students
  - 3/3 Seniors agreed or strongly agreed that course was helpful or very helpful
- Engineering faculty very supportive of continuing this new course
- Quantitative sustainability measures provide analytical tools for assessing the impacts of systems on their environment and contexts
- Quantitative sustainability measures guide system design through alternatives with different contextual impacts