AC 2010-1947: MODELING NATURE: GREEN ENGINEERING FOR A SUSTAINABLE WORLD

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Modeling Nature: Green Engineering for a Sustainable World

Abstract

A new course has been developed and offered which focuses upon sustainable engineering. The key elements of the course include introduction to the complex systems, systems engineering methods for complex systems, life cycle analysis, hard and soft system methodologies, failure analysis using rich pictures and reflection upon the impacts engineering has upon both society and the natural world through consideration of the writings of E.F. Schumacher. Cases included in the course focus on hydraulic fracturing and its possible use in Upstate New York and the oil spill associated with the Exxon Valdez.

Introduction

A new course has been introduced into the undergraduate engineering program which focuses on sustainable engineering from a complex systems perspective. Sustainable engineering, one facet in the broader discussion of sustainability, can be defined as environmentally conscious attitudes, values, and principles, combined with science, technology, and engineering practice, to develop products and processes directed toward enhancing the human experience while improving local and global environmental quality. It begins with our ability to model nature. Sustainable engineering encompasses all engineering disciplines, and is consistent and compatible with sound engineering design principles. It is, in part, focused on design with the objective of minimizing overall environmental impact (including energy utilization and waste production) throughout the life cycle of a product or process -from initial extraction of raw materials to ultimate disposal of materials that cannot be reused or recycled at the end of the product life. However, this approach may not be adequate to address the continued and accelerating deterioration of the Earth. Ultimately a new engineering design paradigm may be required – one that addresses the following question --rather than designing to reduce the negative impact, can we now design products and processes that have a positive impact on the Earth? By the end of the course, students understand the various aspects of sustainability and designing for a sustainable future. The specific course goals include the following expectations of the abilities of students:

- Understand sustainability, sustainable development, and sustainable engineering
- Model complex systems using control systems theory;
- Perform a Life Cycle Analysis;
- Use a Soft Systems Methodology approach;
- Perform a failure analysis using a Rich Picture approach
- Understand and reflect upon the impacts of engineering on society as well as the Earth.

The present work describes the systems approach taken in this course, including Life Cycle Analysis and Soft Systems methodology and applies those tools to the case of hydraulic fracturing which is presently being considered in Upstate New York. Failure analysis using Rich Pictures is applied to the case of the Exxon Valdez. Lastly to put the questions associated with sustainability in historical context, students are asked to read and reflect upon the essays and thoughts of E.F. Schumacher.

Course Approach

- Introduction to Systems Ideas

A systems approach is taken in the course: issues related to sustainability are considered with the emphasis placed on the relationship of the various components of any system not simply the individual elements. System properties which relate to the whole system rather than the parts are referred to as emergent properties as they emerge from the interaction of the different elements that make up the system. Sustainability typically brings into focus questions concerning the environment but in fact the linkage to social and developmental problems is equally as important. Solutions are required to a wide range of problems including global climate change, the destruction or rain forests, and damage to the ozone layer as well as extreme poverty, resource wars and inequitable economic development.

An overview of several of the main issues in sustainability and sustainable development is presented. Definitions of key concepts are provided as well as important documents such as the Earth Charter,[i] the Rio Declaration on Environment and Development[ii] and Agenda 21.[iii] Sustainability typically brings into focus questions concerning the environment but in fact the linkage to social and developmental problems is equally as important. The Precautionary Principle[iv] is introduced and discussed.

The mathematical and engineering background to systems, including the differences between linear and non-linear models, feedback and feed-forward control loops, open and closed systems is provided. Emphasis is placed upon single input/single output as well as multiple input/multiple output modeling, and the calculation of appropriate transfer functions using control theory and Laplace Transforms. Four important and distinct types of feedback loop systems are described and examples are explored including: Natural systems with natural feedback (e.g. Louisiana coastal wetlands and river flooding); Natural systems with human devised feedback (e.g. Reintroduction of wolves into Yellowstone); Human devised systems with natural feedback (e.g. Los Angeles highway system and smog); and Human devised systems with human devised feedback (e.g. Nuclear weapons and Nuclear Test Ban Treaty).

- Introduction to Life Cycle Analysis (LCA)

Students are introduced to Life Cycle Analysis.[v] A 'Life Cycle Analysis' (LCA) is the investigation and evaluation of the environmental impacts of a given product or service caused or necessitated by its existence.[6-8] The goal of LCA is to compare the full range of environmental and social damages assignable to products and services, to be able to choose the least burdensome one. At present it is a way to account for the effects of the cascade of technologies responsible for goods and services. It is limited to that, though, because the similar cascade of impacts from the commerce responsible for goods and services is unaccountable because what people do with money is unrecorded. As a consequence LCA succeeds in accurately measuring the impacts of the technology used for delivering products, but not the whole impact of making the economic choice of using it.

The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence. The sum of all those steps or phases - is the life cycle of the product. The concept also can be used to optimize the environmental performance of a single product (ecodesign) or to optimize the environmental performance of a company. Common categories of assessed damages are global warming (greenhouse gases), acidification, smog, ozone layer depletion, eutrophication, eco-toxicological and human-toxicological pollutants, habitat destruction, desertification, land use as well as depletion of minerals and fossil fuels.

Students were asked to select a product or a process which they had a great interest in or felt passionate about and perform a detailed LCA analysis. The diversity of the items selected were amazing…enlightening? The items ranged from a Rubik's cube to a skateboard to a computer gaming box to a Buddhist monk's robe.

- Introduction to Soft System Methodologies (SSM)

Primarily Checkland and Wilson developed Soft Systems Methodology from earlier systems engineering approaches.[9,10] The primary use of SSM is in the analysis of complex situations where there are divergent views about the definition of the problem — "soft problems" (e.g. How to improve health services delivery; How to manage disaster planning; When should mentally disordered offenders be diverted from custody? What to do about homelessness amongst young people?). [vi]

In such situations even the actual problem to be addressed may not be easy to agree upon. To intervene in such situations the soft systems approach uses the notion of a "system" as an interrogative device that will enable debate amongst concerned parties. The SSM methodology consists of seven steps, with initial assessment of the problem situation leading to the modeling of several human activity systems that might be thought relevant to the problem situation. By discussions and exploration of these, the decision makers will arrive at accommodations (or, exceptionally, at consensus) over what kind of changes may be systemically desirable and feasible in the situation.

The seven stage representation of SSM can be stated as follows:

- Enter the situation considered problematical
- Express the problem situation
- Formulate root definitions of relevant systems of purposeful activity
- Build conceptual models of the systems named in the root definitions
- Compare models with real world situations
- Define possible changes which are both possible and feasible
- Take action to improve the problem situation

In 1975, Smyth further elaborated on the elements needed in formulating the root definitions of different purposeful activities. These elements, remembered by the mnemonic CATWOE, identified the people, processes and environment that contribute to a situation, issue, or problem to be analyzed.[11] CATWOE is used to prompt thinking about what is actually being sought. There are six elements of CATWOE which include:

- Customers - Who are the beneficiaries of the highest level business process and how does the issue affect them?
- Actors - Who is involved in the situation, who will be involved in implementing solutions and what will impact their success?
- Transformation Process - What processes or systems are affected by the issue?
- World View - What is the big picture and what are the wider impacts of the issue?
- Owner - Who owns the process or situation being investigated and what role will they play in the solution?
- Environmental Constraints - What are the constraints and limitations that will impact the solution and its success?

Case Study: Gas Well Drilling in the Marcellus Shale

Students are challenged to use SSM to develop their response to one of the most contentious environmental issues in Upstate New York State today –gas drilling using hydraulic fracturing.[12] The Marcellus Shale is a black shale formation extending deep underground from Ohio and West Virginia northeast into Pennsylvania and southern New York. Although the Marcellus Shale is exposed at the ground surface in some locations in the northern Finger Lakes area, it is as deep as 7,000 feet or more below the ground surface along the Pennsylvania border in the Delaware River valley. Drilling activity is expected to focus on areas where the Marcellus shale is deeper than 2,000 feet.

Geologists estimate that the entire Marcellus Shale formation contains between 168 trillion to 516 trillion cubic feet of natural gas throughout its entire extent. Although geologists have long known about the natural gas resources of the Marcellus Shale formation, the depth and tightness of the shale made gas exploration and extraction very difficult and expensive. Interest has increased significantly of late due to: recent enhancements to gas well development technology, specifically horizontal drilling and hydraulic fracturing, the proximity of high natural gas demand markets in New York, New Jersey and New England and the construction of the Millennium Pipeline through the Southern Tier.

Questions have been raised about possible environmental and community impacts.[13] Most concerns are related to water use and management and the composition of the fluids used for fracturing the shale. Horizontal drilling and hydraulic fracturing are legal and common in New York. The majority of wells in the Marcellus Shale will be hydraulically fractured. Horizontal drilling has been used in New York since the 1980s. A "horizontal well" is first drilled down vertically to a depth above the target gas-bearing rock formation. Special tools are then used to curve the well so that the hole is drilled horizontally within the gas-bearing rock for up to several thousand feet.

Hydraulic fracturing consists of pumping a fluid and a propping material such as sand down the well under high pressure to create fractures in the gas-bearing rock. The propping material (usually referred to as a "proppant") holds the fractures open, allowing more gas to flow into the well than would naturally. No blast or explosion is created by the hydraulic fracturing process, which has been used in New York since at least the 1950s. Hydraulic fracturing technology is especially helpful for "tight" rocks like shale.

Hydraulic fracturing of the Marcellus Shale will require large volumes of water to fracture the rocks and produce the desired amount of gas. Each well may use more than one million gallons of water. The hydraulic fracturing fluid typically contains compounds added to the water to make the hydraulic fracturing process more effective. These may include a friction reducer, a biocide to prevent the growth of bacteria that would damage the well piping or clog the fractures, a gel to carry the proppant into the fractures, and various other agents to make sure the proppant stays in the fractures and to prevent corrosion of the pipes in the well.

Students recommended a course of action on the proposed drilling using the formal SSM and CATWOE methodology. Of particular note is the fact that 13 out of 13 students recommended against drilling at this time though each felt that it was inevitable given the developed world's insatiable need for more energy even if the search and acquisition of energy sources may result in serious environmental damages.

- Rich Picture and Failure Analysis

Rich pictures were particularly developed as part of Soft Systems Methodology for gathering formation about a complex situation.[14] The idea of using drawings or pictures to think about issues is common to several problem solving or creative thinking methods because our intuitive consciousness communicates more easily in impressions and symbols than in words.

Rich pictures may be drawn at any stage of SSM though they have proven to be most useful at the pre-analysis stage.[15] Rich pictures are also extremely useful in exploring failures of complex systems. It is in this context—in understanding the failure of complex systems- that rich pictures were introduced into the course

Rich pictures are used to depict complicated situations. They are an attempt to encapsulate the real situation through a frank, straightforward, cartoon representation of all the ideas including layout, connections, relationships, influences, and cause-and-effect. As well as these objective notions, rich pictures depict subjective elements such as character and characteristics, points of view and prejudices, spirit and human nature. Elements of rich pictures typically include pictorial symbols, keywords, cartoons, sketches, symbols, and a title.

Students are challenged to use 'rich pictures' analyze the Exxon Valdez oil spill[16] which occurred in the Prince William Sound, Alaska, on March 24, 1989. It is considered one of the most devastating human-caused environmental disasters ever to occur at sea.[17] As significant as the Valdez spill was, it ranks well down on the list of the world's largest oil spills in terms of volume released. However, Prince William Sound's remote location (accessible only by helicopter and boat) made government and industry response efforts difficult and severely taxed existing plans for response.[18] Beginning three days after the vessel grounded, a storm pushed large quantities of fresh oil onto the rocky shores of many of the beaches in the Knight Island chain. According to official reports, the ship was carrying 54.1 million U.S. gallons (about 200 million liters) of oil, of which 10.9 million U.S. gallon were spilled into the Prince William Sound. This figure has become the consensus estimate of the spill's volume, as it has been accepted by the State of Alaska's Exxon Valdez Oil Spill Trustee Council, the National Oceanic and Atmospheric Administration, and environmental groups such as Greenpeace and the Sierra Club.

- **Engineering if People and the Earth Matter**

Searching for away to put the questions associated with sustainability and the environment in a broader, historical context, students were asked to read E.F. Schumacher's essays in ***Small Is Beautiful.***[19] Recalling this work, Schumacher comments on the state of economics and the functioning of the economy and is critical of both. In his opinion, economists are too tied to the notion that profits should be a determining factor in economic affairs; thus, they are blinded to many of the economy's negative features. The features on which Schumacher focuses his attention are related to the form of modern technology, which employs the techniques of mass production.

Students are the challenged to reflect upon their reading in light of the following set of questions.

- It has been over 35 years since Schumacher posited the central tenet of his work—that infinite economic growth is impossible within a finite system. Do you believe he has been vindicated?
- Just how relevant are Schumacher's ideas today? Some argue Schumacher was a visionary—that his ideas are as important today as when he wrote them; others say his views are outdated and no longer apply to 21st-century conditions. Where do you stand and on which ideas in particular?
- Most economists and politicians believe that our consumption-based society has created unprecedented wealth in the West and, therefore, justifies a degree of inequality. How does Schumacher view consumption-based economies? What kind of alternative system or reforms does he propose?
- Some of the book's insights are aimed at the scientific community, with Schumacher asserting that scientists are incapable of ethical decision-making regarding the direction of their research. Consider his arguments in light of recent advances in stem cell research, cloning, and bio-engineered agricultural products. Do you agree with Schumacher...or are scientists as capable as anyone else, perhaps even more so, to explore the consequences of their work?
- Schumacher asks a simple but penetrating question: what is progress? How does he answer that question...and how do you? Do you agree or disagree with Schumacher?
- What are Schumacher's views on assisting developing countries? Do you agree or disagree with Schumacher?

Student Feedback

Student opinion of the course was genuinely positive. Information was obtained from standardized computer scored feedback questionnaires, open-ended written responses and group feedback sessions. Particularly gratifying for me personally were the comments made by a majority of the students who stated that they really had no interest in sustainability or green engineering prior to the course but now were motivated to continue their study in this field and hopefully someday be able to make some difference. The assignments that seemed to generate the most interest were those corresponding to the gas drilling in Upstate New York and the tragedy of the Exxon Valdez oil spill.

Binghamton University uses a standard student evaluation mechanism. Perhaps what was most interesting in the feedback was the value the students placed on in-class discussions and the seeming increase in interest in sustainability and sustainable engineering. At least the course did no harm.

1. My interest in subject before course	13	3	23.1 %	Low
		4	30.8 %	Medium
		6	46.2 %	High
2. My interest in subject after course	13	0	0.0 %	Low
		5	38.5 %	Medium
		8	61.5 %	High
3. Difficulty (relative to other courses)	13	2	15.4 %	Low
		10	76.9 %	Medium
		1	7.7 %	High
4. Workload (relative to other courses)	13	2	15.4 %	Low
		10	76.9 %	Medium
		1	7.7 %	High
5. Usefulness of reading materials	13	1	7.7 %	Low
		10	76.9 %	Medium
		2	15.4 %	High
6. Usefulness of homework assignments	13	4	30.8 %	Not Applicable
		0	0.0 %	Low
		6	46.2 %	Medium
		3	23.1 %	High
7. Usefulness of class discussions	13	2	15.4 %	Not Applicable
		0	0.0 %	Low
		3	23.1 %	Medium
		8	61.5 %	High
8. Usefulness of examinations	13	0	0.0 %	Not Applicable
		0	0.0 %	Low
		10	76.9 %	Medium
		3	23.1 %	High

Table 1 Standardized Student Feedback (Total enrollment = 13)

Final Thoughts

The course was a technical elective so certainly the students were self-selected and the generalizability of the course to a wider audience is unclear. My sense was however that the general sentiment though favorably inclined to see issues related to the environment in as important I would not characterize the class as being filled with environmental activists. The enthusiasm for the subject at the beginning of the course was certainly in doubt from my personal observations.

As has been the case at other universities, there is a growing interest among the students enrolled in Binghamton University in the area of sustainability, sustainable engineering and green design. Here, we have chosen to consider it from a complex systems point of view and thus its location within the bioengineering department makes most sense for us. The present course, its first offering, has been developed to try to meet that growing need. In fact, I can happily report that soon the engineering school will have a sustainable engineering minor program to complement its major engineering disciplines. Perhaps one day the proposed minor may even become a possible major area of specialization.

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