Incorporating Earth Systems Engineering Concepts throughout the Civil Engineering Degree to create the Engineer of the 21st Century

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Abstract

We propose to integrate Earth Systems Engineering (ESE) into Civil Engineering (CVEN) curriculum at the University of Colorado at Boulder (CU) by including ESE concepts in existing courses. This will include every year of the B.S. degree and cross all of the sub-disciplines. The initiative emphasizes the role of civil, environmental and architectural engineering in society and the interaction between the built environment and natural and cultural systems. This paper describes the courses, modules, and assessment methods that will be used to evaluate the integration of ESE concepts into the Civil Engineering curriculum.

Background on Earth Systems Engineering

In response to the global nature of the problems that the Earth is facing today and is likely to face in the near future, we have started a new initiative called Earth Systems Engineering (ESE) in the Department of Civil, Environmental, and Architectural Engineering (CEAE) at the University of Colorado at Boulder. Further details about the initiative can be found on the web (http://ese.colorado.edu). In general, the initiative emphasizes the role of civil, environmental and architectural engineering in society and the interaction between the built environment and natural and cultural systems.

Allenby[1,2] introduced the concept of Earth Systems Engineering with reference to industrial ecology which is defined as "the multidisciplinary study of industrial systems and economic activities, and their links to fundamental natural systems." First proposed in Japan in 1970, industrial ecology received attention in the U.S. in the late 1980s and 1990s through several studies conducted by the National Academy of Engineering on the relationship between engineering and ecological systems. It was the subject of two Gordon Conferences in 1998 and 2000 at Colby-Sawyer College in New London, NH.

The success of industrial ecology motivated the U.S. National Academy of Engineering to organize a one-day meeting on Earth System Engineering on October 24, 2000. In that meeting and in the exploratory workshop that led to that meeting, the following working definition of Earth Systems Engineering was adopted[3]:

> "ESE is a multidisciplinary (engineering, science, social science, and governance) process of solution development that takes a holistic view of natural and human system interactions. The goal of ESE is to better understand complex, nonlinear systems of global importance and to develop the tools necessary to implement that understanding."

As a first step in our ESE initiative, an NSF-sponsored workshop on ESE was conducted at the University of Colorado at Boulder on October 4-6, 2001. The workshop was three days in length and brought together about 90 industry, government and university participants from engineering, physical sciences, biological sciences, and social sciences. The overall purpose of the workshop was three-fold: (1) provide an intellectual framework for interdisciplinary exchange, (2) provide recommendations on the future course of engineering education, research, and practice in the understanding of the interaction between natural and non-natural systems at multiple scales from local to regional and global, and (3) create an action plan to implement the recommendations. More specifically, the workshop addressed the interaction of natural systems with the built environment. Research, education and outreach were addressed throughout the workshop. The workshop participants unanimously proposed the following definition of the "engineer of the future":

> "The engineer of the future applies scientific analysis and holistic synthesis to develop sustainable solutions that integrate social, environmental, cultural, and economic systems."

The workshop participants also recommended that there is a dire need for a transformative model of engineering education and practice for the 21st century that:

- Unleashes the human mind and spirit for creativity and compassion;
- Expands engineers' professional and personal commitments to include both technical and non-technical disciplines;
- Inspires engineers to embrace the principles of sustainable development, renewable resources management, appropriate technology, and systems thinking; and
- Prepares engineers for social, economic and environmental stewardships.

A 2004 workshop at CU on "Integrating Appropriate-Sustainable Technology and Service-Learning in Engineering Education" further expanded on these ideas.

Earth Systems Engineering is a general concept that embraces the principles of sustainability, appropriate technology, industrial ecology, renewable resources, natural step and natural capitalism, biomimicry, and system thinking[4,5,6,7,8]. A few examples of ESE include: engineering for developing communities; sustainable infrastructure; green development and construction; sustainable city planning and design; and restoration of natural systems. One of the CU faculty in architectural engineering stated: "I should note that... the ESE phrase never enters my teaching and is not even on the radar screen for architectural engineering practice. It seems a much more CVEN oriented phrase. ...I mentally substituted 'sustainable design'...."

The ESE initiative of the CEAE department has been selected as one of five major initiatives in the College of Engineering at the University of Colorado at Boulder. The ESE initiative involves all components of engineering education, research and development, outreach and practice. It encompasses activities such as the *Consortium on Advanced Life Cycle Engineering for Sustainable Civil Environments* (COALESCE), the *Engineering for Developing Communities* (EDC) program, the *Center for Advanced Decision Support in Water and Environmental Systems* (CADSWES), the *Center for Drinking Water Optimization* (CDWO), and the 2002 "Solar Decathlon" which CU won by designing and building an "off-the-grid" solar house.

The Civil Engineering program at the University of Colorado at Boulder has selected several educational objectives (as required for ABET 2000) that embrace the ESE concept: (http://bechtel.colorado.edu/Abet/ce_objectives.html). For instance, *BS graduates in the Civil Engineering Program will be able to:*

3. Understand how non-technical concerns such as cost, public safety and health influence Civil Engineering projects.
4. Uphold ethical relationships with both clients and the public at large.
5. Understand broad social and cultural issues so they can participate fully in a democratic society.

We are still in the process of broadly implementing ESE across the curriculum.

Survey of Existing Curriculum

A written survey was distributed to all 38 faculty and senior instructors in the Department of Civil, Environmental, & Architectural Engineering (CEAE) at CU Boulder. The survey solicited faculty feedback on 7 questions, and was used to identify courses where ESE concepts are already being emphasized. Table 1 summarizes faculty feedback, where faculty filled in: 1 disagree, 2 somewhat disagree, 3 neutral, 4 somewhat agree, and 5 strongly agree. As of February 28, 2005, 29 surveys were returned representing faculty who primarily teach in the sub-areas of architectural/ building systems (7), environmental (6), construction (4), geotechnical (3), structures (5), and water resources (4). Note that some respondents did not answer every question, thus the total responses for each statement in Table 1 will not always sum to 29.

Table 1. Summary of Faculty Responses to Written ESE Survey

	# of faculty responses in each category				
Statement	Disagree 1	2	Agree 3	4	Strongly Agree 5
Q1. I believe that it is important for all CEAE undergraduate students to have an appreciation for ESE	1		2	7	19
Q2. I believe that ESE concepts should be incorporated into undergraduate courses across all the sub-discipline areas of CEAE	3	3	8	5	10
Q3. I believe that ESE concepts should be incorporated into a few required undergraduate CEAE courses	1	1	3	8	16
Q4. I believe that ESE concepts should be taught in elective CEAE courses	1	1	3	9	15
Q5. I teach some ESE concepts in my courses to undergraduate students	9	1	6	2	11
Q6. I teach some ESE concepts in my courses for graduate students	6	2	3	5	11
Q7. I would be interested in adding content related to ESE into my courses	4	2	3	2	15

There is a broad distribution of opinions evident. However, most of the faculty who responded to the survey agree or strongly agree with the importance of ESE concepts. The widest disparity in responses relates to question 5, currently teaching ESE concepts in undergraduate courses. The results may be somewhat biased, if those that agreed more strongly took the time to respond to the survey.

As shown in Figure 1, these opinions aren't clearly differentiated between faculty members who specialize in different sub-discipline areas. Only selected sub-disciplines with 4 or more responses are shown. Environmental faculty had a statistically higher than the total group average response on questions 1, 2, and 7 (t-test at 95% confidence). The structures faculty had a statistically lower than total group response for questions 2 and 5. The water resources faculty had a statistically higher than total faculty average response on question 1. The survey indicates that there is a broad basis for support of ESE across the CEAE department, and a strong potential to expand ESE into all sub-discipline areas. This commonality is important given the broad and sometimes fragmented nature of civil engineering education.

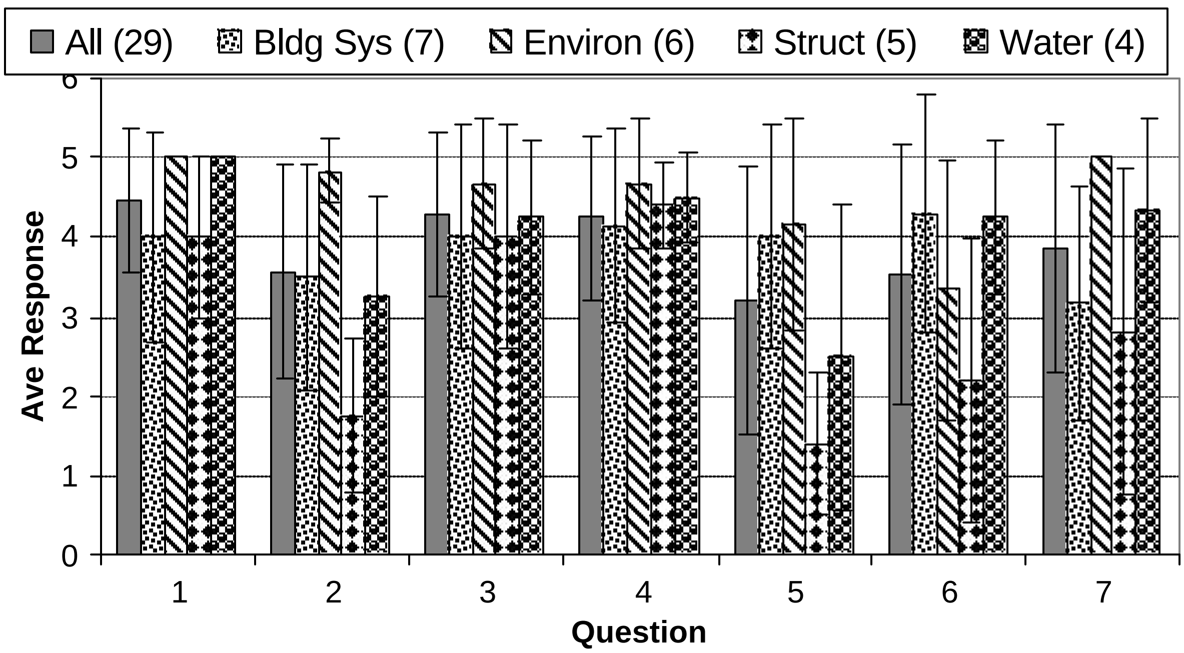

Figure 1. Summary of faculty responses on a scale of 1 (strongly disagree) to 5 (strongly agree), with differences by sub-discipline shown.

Existing Curriculum Related to ESE

Modules to teach ESE concepts are currently being taught in a variety of required courses. As can be seen in the block diagram in Table 2 showing the required CVEN curriculum, existing course content incorporating ESE spans a minimum of 1 course per academic year. However, the content does not yet rigorously span all sub-discipline areas. Note that CVEN students at CU can also self-select into a Water Resources/Environmental emphasis; this encompasses about 13-17% of the total graduating CVEN students over the past 3 years. This emphasis changes some of the required courses in the junior and senior year, and replaces most technical electives with specific courses. In this option, an additional 4 required courses contain significant ESE-related content. Overall, the faculty survey illustrated the strongest support for ESE among environment and water faculty (as illustrated by 100% consensus of "strongly agree" that all CEAE students should have an appreciation for ESE on question 1 of the faculty survey). Examples of ESE related content in various courses in the CVEN curriculum are discussed below.

Table 2. Block Diagram of Civil Engineering B.S. Curriculum

Sem	Cr						
1	15	Calculus I	Chemistry for Engrs	Chem Lab for Engrs	Engrg Drawing	* Intro to Civ & Env Engrg	SS&H elective
2	17	Calculus II	Physics I		+ Plane Surveying	+ Engrg Geology	SS&H elective
3	18	Calculus III	Physics II + Lab	Statics		* Thermo-dynamics	SS&H elective
4	16	Intr Lin Algebra & Diff Eqns	Fluid Mechanics	Mechanics Materials I	Dynamics	Engineering Computing	
5	15	* Intro to Construction	Hydraulic Engrg	Structural Analysis	Geotechnical Engrg I	* Envir Eng Fundamentals	
6	15	* Probability and Statistics	Mechanics Materials II	Structural Design	+ Geotech Engrg II		Writing on Sci & Soc
7	15	Construction Equipment & Methods		Transportation Systems	*<u>* Capstone Design</u>*	Electrical Circuits	SS&H elective
8	16	+ Senior Seminar	*Technical elective*	Lg Dsn Tech Elect	Technical Elective	Technical Elective	SS&H elective

* currently contains ESE-related content; + future addition of ESE content
SS&H = social science and humanities

Freshman year:
<u>Introduction to Civil Engineering</u> (CVEN 1317; 1 credit) Professor Bielefeldt has taught this course since 1997. For the past 2 years the course includes a 3-week “module” on the Three Gorges Dam. A holistic analysis of the benefits and drawbacks of the Three Gorges Dam is conducted, including air and water pollution impacts, social impacts of relocation, impacts on endangered species and archaeological sites. This includes 2 of 7 written assignments submitted by the students. (www.colorado.edu/engineering/civil/CVEN1317/assignments.html)

<u>Freshman Projects</u> (GEEN 1400; recommended for undeclared engineering majors; optional as a technical elective for CVEN students). Currently, 72 of the 190 active CVEN undergraduate students have taken GEEN 1400. The course is hands-on and team oriented. Professor Amadei has taught sections in fall 2002 and 2003 that emphasize appropriate technology and the use of such technology in solving water, sanitation, energy, and health problems in developing communities. The course sections give students a thorough understanding of some of the most common and important technologies being introduced in small-scale community developments. Students are asked to create, design and construct appropriate technological systems, processes and devices for a variety of settings associated with the developing world. Sections have also been previously taught by Prof. Silverstein and Ryan with an environmental focus. Enrollment in this course has been shown to help increase retention of under-represented groups in engineering[9,10]. Also, the course has shown that ESE ideas seem to be particularly attractive to women and minority students.

Sophomore year:
<u>Thermodynamics</u> (AREN 2110) Prof. Silverstein discusses energy conservation and the application of thermodynamic principles to renewable energy in this course. About 5 lecture hours and 20% of the assignment content relates to ESE.

Junior year:
Environmental Engineering Fundamentals (CVEN 3414) This course covers hazardous materials, air pollution generation and the resulting global impacts, and water pollution. About 10 out of 48 lecture hours and 2 of 12 assignments directly relate to ESE.

Introduction to Construction (CVEN 3246) Prof. Hy Brown includes lectures on the LEED (Leadership in Energy and Environmental Design) Green Building Rating System® developed by the U.S. Green Building Council. LEED is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. About 1 week is devoted to this topic.

Senior year:
Environmental Engineering Design (CVEN 4434; optional capstone for all CVEN students; required for Water Resources/Environmental option) Prof. Bielefeldt has included 1 or more EDC projects in the course for the past three years. These projects are real needs in various communities, thus integrating a service learning (SL) component into the curriculum. Examples of recent projects include: upgrade over-loaded evaporative wastewater treatment lagoons for Jemez Pueblo, New Mexico (Fall 2003); replace existing individual cesspools and septic systems in the community of Guadalupe, CO (Fall 2002); provide reliable water and sanitation for a primary school in Jalapa, Nicaragua (Fall 2002); provide treatment to achieve safe potable water for San Pablo, Belize (Fall 2001). Prof. Bielefeldt received a grant from the CU Service Learning Program in 2004 to expand SL in this course. Of particular importance is having the students reflect on their experiences[11,12]. Future plans include expanding the multi-disciplinary nature of the course, such as including students majoring in Environmental Studies and Business. Currently, the students in the course are undergraduate civil (CVEN) and environmental engineers (EVEN; a cross-departmental degree), and recently added (for the first time in Fall 2003) CVEN graduate students.

Other capstone courses such as CVEN 4423 Water Resources Design and CVEN4728 Foundation Engineering also include some ESE related content, based on instructor feedback.

Proposed Required Curriculum Related to ESE
New course content related to ESE is proposed for an additional four courses. These modules will build on the work of colleagues throughout the world, in addition to creating new modules at CU. Some examples of courses where content that can be added or enhanced to emphasize ESE include:

Surveying (CVEN 2121) Modifications to this course to expand from traditional plane surveying to include GIS and GPS. Course title subsequently changed to Fundamentals of Geomatics.

Engineering Geology (CVEN 3698) A lecture on earthquakes, sinkholes, and other natural phenomenon that impact civil engineering structures can be added.

Geotechnical Engineering 1 and/or 2 (CVEN 3708/3718) The variability and complexity of natural geological materials has a significant impact on engineered structures and excavations for construction. ESE concepts could be discussed within this framework.

Senior Seminar (CVEN 4039, 1 credit) In the past this course has included lectures on ethics and professional practice. Lectures or exercises can be created that discuss systems thinking and sustainability concepts.

Engineering Economy and System Design (CVEN 4147; required for Water Resources/ Environmental option; in the future may be required for all CVEN) Homework assignments and lectures can be used to discuss issues of importance to natural resource economics.

Capstone course for Civil Engineering (proposed) The CEAE Department is currently evaluating the potential to create a true capstone design course for general civil students that would incorporate all of the various CE disciplines into a single semester project. This would be a change from the current list of capstone options of reinforced concrete design, steel design, and foundation design. If such a course were created, ESE ideas could be emphasized.

ESE Content in Technical Electives

A variety of technical elective courses contain substantial content related to ESE. Many of these courses are either cross-listed with graduate courses or are graduate courses (5000 level). A few of the courses with significant content related to ESE are listed in Table 3, along with total enrollment and number of CVEN undergraduates in the class.

Table 3. CVEN Undergraduate Enrollment in Technical Electives with Significant ESE Content

	Ave total enroll-ment	# of CVEN Undergraduates			
Course		2002	2003	2004	2005
CVEN 4333 Engineering Hydrology * *large scale climate, GIS modeling, non-linearity, scale issues*	32	12	11	8	*13*
CVEN 4700 Sustainability & the Built Environment * *introduces fundamentals of sustainability and sustainable development: understanding natural systems, the interaction of the built environment (infrastructure) with natural systems, the role of technical/non-technical issues in shaping engrg decisions*	31	7	4	7	*6*
AREN 4830 Energy Technology & Policy *renewable energy, environmental impacts of energy technologies and energy use*	27	7	4	*3*	--
CVEN 5565 Life Cycle Engineering *Lifetime cost analysis, green energy systems, community sustainability and hazard analysis*	19	NO	NO	11	*5*
CVEN 5830 Sustainability in Building and Design *Buildings can be designed to produce less greenhouse gases while being more comfortable, healthy and economical through the application of sustainable design principles; emphasizes both fundamentals and practical applications .*	23	NO	5	2	--
CVEN 5256 Strategic Issues in Construction Mgmt *4 weeks on LEED*	17	2	0	1	*3*

NO = not offered; ND = not determined; * cross-listed graduate/undergraduate course, so total enrollment includes graduate and undergraduate students; *numbers in italics are estimates from pre-semester enrollments as of Jan. 3, 2005*

Note that the total CVEN graduates in 2002 and 2003 were 35 and 52, respectively. This indicates that a significant percentage of CVEN undergraduates are likely exposed to additional ESE content via their technical elective choices.

Evaluation Tools

In order to evaluate the success of implementing ESE throughout the CVEN curriculum, a variety of methods can be used. First, at the course level and end of course survey has been used for the past 4 years to evaluate coverage of ABET A-K criteria[13] in CEAE courses. Some of the questions in this survey are already relevant to ESE, particularly[13]:

(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

Students rate whether these topics were large, medium, or small components of the course that they took. For example, in the Spring 2002 surveys students ranked CVEN 3414 as the highest for course content pertaining to ABET criterion (h) of the 10 CEAE courses surveyed. In Spring 2003, of the 13 courses surveyed, students rated 4 courses as having a large component pertaining to ABET criterion (h), including two courses required for all CVEN students: Environmental Engineering Fundamentals (CVEN 3414) and Geotechnical Engineering II (CVEN 3718). Additional questions or more specific sub-questions could be added to this survey to receive feedback particular to ESE such as:

- the impacts of sustainability considerations on design
- the impacts of engineering solutions in a global context
- the impacts of engineering solutions in a societal context
- the effects of real world complexity and non-linearity on engineering solutions

A second tool that can be used to evaluate ESE through the curriculum is the exit survey given to students at the end of the required 1-credit Senior Seminar course. This survey has students reflect upon their entire undergraduate experience. This would be an ideal place to determine if ESE concepts were adequately covered and emphasized in all sub-discipline areas.

The ESE program goals and outcomes will also be evaluated using tools in place for Department level review. These include the Joint Evaluation Committee process where the curricula in sub-discipline areas are reviewed by practitioners, alumni, and student panels on a rotating basis. Surveys to employers and alumni can also be used to determine the importance and sufficiency of ESE coverage in the CU curriculum.

Conclusions

It is important for all engineering students to have an appreciation for the interaction of natural and manmade systems. The broader impacts of engineering decisions on social, environmental, and global systems should be understood by all civil engineers. To better educate engineers to ensure a sustainable future, the CEAE Department at the University of Colorado is implementing Earth Systems Engineering concepts throughout our undergraduate CVEN curriculum. As this vision is more fully realized in the coming years, evaluation tools will be in place to determine the success of these efforts. These concepts are appropriate to all Civil Engineering courses, and it is our hope that in the future ideas and modules on these topics can be developed and shared among teachers worldwide.

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