World Transactions on Engineering and Technology Education
Vol.2, No.1, 2003

Earth Systems Engineering Management: a course for students from multiple disciplines

Michael E. Gorman†, Brad Allenby‡, Matthew M. Mehalik* & Kathleen Hall†

University of Virginia, Charlottesville, United States of America†
AT&T, United States of America‡
Coro Center for Civic Leadership, Pittsburgh, United States of America*

ABSTRACT: Earth Systems Engineering Management (ESEM) represents a new, interdisciplinary approach to working with complex environmental systems. This article describes an undergraduate seminar that places environmental science and engineering students on the cutting-edge of ESEM. The article gives some background to ESEM and its importance in promoting the concept that human beings must accept responsibility for the ways that Earth systems are being shaped. The article also presents the structure of the course with regard to students, skills development and activities. Students also worked in teams on warm-up projects to investigate current issues such as sustainable fisheries. They then chose to work on one of two final projects: improving aspects of a conservation area that stretches from Yellowstone to Yukon, or managing parts of the restoration of the Everglades. Student feedback to the course has been positive. Future plans call for the addition of a project that covers an urban system.

INTRODUCTION

With increasingly complex interactions with natural systems, humanity continuously creates challenges. How, for example, will we cope with the potential ramifications for environmental systems of nano-technology, biotechnology and information technology? How can we begin to redesign human relationships with complex ecosystems such as the Everglades, engineer and manage urban centres to be more sustainable, or design Internet products and services to reduce environmental impact while also increasing the quality of life? Our capacity to irrevocably change the planet is growing beyond our ability to adequately react to, let alone anticipate solutions to, these issues. The current base of scientific and technical knowledge, governance institutions and ethical approaches are inadequate to this challenge [1]. Entirely new approaches and tools are needed to intelligently and ethically redesign responsive relationships between human and natural systems and to accommodate bio-complexity in the environment.

Earth Systems Engineering and Management (ESEM) is a new interdisciplinary approach to comprehending and managing the interplay between human and natural systems. ESEM, in essence, is a *framework* for designing intelligent systems and policies premised on disciplinary ambidexterity.

A practitioner using an ESEM approach would have the ability to see how human and natural dimensions of complex systems are closely coupled and to create design options that protect environmental values while also providing the desired human functionality. In order to do so, an ESEM practitioner must be a new type of expert: a problem-solver unfettered by rigid disciplinary boundaries, a network-builder who can build linkages among multiple disciplinary methodologies (eg ecology, systems engineering, environmental science, social sciences) and a multidisciplinary thinker who can still bring intellectual rigour and methodology to complex Earth systems design and management challenges.

As a first step towards creating this kind of multidisciplinary practitioners, the authors offered the first-ever undergraduate ESEM course in the spring of 2002, and are now offering a second iteration of the course. During the first iteration of the course, students were drawn in equal numbers from engineering and environmental science. They heard lectures on such topics as complex system dynamics, adaptive management, systems engineering, ethics and the role of social networks in innovation. Students worked in interdisciplinary projects on topics concerning the future of sustainable fisheries, the prospects for carbon sequestration, the design of wildlife corridors in the Yellowstone to Yukon region and the management of the Everglades. Three students from the first class volunteered to continue conducting or investigating ESEM work and are helping to teach the second version.

More background on ESEM and course information are given in this article in hopes of inspiring others to similar efforts.

Background on ESEM

Planet Earth has become a human project – there are no more pristine places unaffected by *Homo sapiens*. The physics and chemistry of every cubic meter of air and water on the surface of this planet has been affected in some way by human activity. As a result, the by-products of human economic activity have critically altered atmospheric, oceanographic and hydrological systems. The biosphere, at levels from the genetic to the landscape, is increasingly a human product. At the genomic level, the human genome has been mapped, as has that of selected bacteria, yeast, plants and other mammals. At the organism level, species are being genetically engineered by humans to increase agricultural yields, reduce pesticide consumption, reduce the demand for agricultural land, enable plant growth under saline conditions and thereby conserve fresh water resources, produce new drugs, reduce disease, increase hardiness and support a healthier human diet. At a landscape level, islands and mainland regions are affected by agriculture, resource extraction, human settlement, pollution and invasive species transported by humans. Few biological communities can be found that do not reflect human predation, management or consumption. Moreover, too little of the discussion about the potential effects of advancements in cutting-edge fields, such as nano-technology, biotechnology and information technology, is focused on their global environmental impacts. The latter is impeded not just by a lack of data and foresight, but by lack of an intellectual framework within which such broad technological trends can be conceptualised.

Human beings must accept responsibility for the ways in which we are shaping Earth systems. We must learn to understand and intelligently redesign relationships between human and natural systems that are responsive to change. However, the current base of scientific and technical knowledge, governance institutions and ethical approaches are inadequate to this challenge. Today, scientists and engineers are faced with complex system problems, from managing human activities around ecosystems such as the Everglades, to designing strategies and programmes for carbon emissions, to engineering and managing the nitrogen and hydrologic cycles. Dealing responsibly with the complex web of interconnections between human and natural systems will require experts skilled in entirely new approaches and frameworks.

A new kind of expertise is required to grasp the breadth, both of the issues faced and the required complex solutions. A new, more adept generation of Earth system engineers need to be educated. This capability will work among disciplines to rigorously integrate the different methodologies and approaches required to address the crosscutting challenges. The ESEM approach is a new framework for analysing complex problems and designing inclusive approaches to their solution. A practitioner using the ESEM approach would have an ingrained ability to see issues from multiple angles, an innate sense of the human and natural dimensions of complex systems, and design inclusive strategies to address these issues. It has been stated that:

> *Just as no single discipline can capture the complexities of the interactions between natural and social systems, neither can any single perspective provide a vision that is responsive and accountable to diverse stakeholders. The ESEM approach is to develop a repertoire of tools that can be applied as needed to move toward a vision. Both the approach and the vision will change over time. A solution to a problem, therefore, is the formulation and implementation of an integrative and iterative process, using a combination of social and technical approaches. A solution is not a static condition of complete control – such a condition is impossible* [2].

STRUCTURE OF THE COURSE

Students

Since ESEM is a multidisciplinary activity, a course had to be established that had no prerequisites, and cross-list it in engineering and environmental sciences. Students were mostly second, third and fourth years. Engineering students brought a multitude of internal technical disciplines, such as civil, chemical, mechanical, systems, computer science and applied mathematics. Students from a new interdisciplinary Environmental Thought and Practice major took the course, along with students from more traditional areas of environmental science. Eventually, it is envisaged that students from business, ethics, psychology and other majors will be recruited, but the environmental science and engineering spread served as a broad enough base for the initial efforts.

From the start, students in an ESEM course were on the cutting-edge that, for most of them, was a new experience. One of the course's goals was to produce students who could think more clearly and broadly about ESEM than those educated in more traditional ways. Therefore, fewer constraints were placed on their methods of problem solving and ideas for solutions.

Skills Development

The main goal of the class was to encourage students to think about global systems design. In order to reach that goal, a range of skills were taught including:

- Team building and communication, including learning how to research and write in a group context.
- Presentation skills: organisation (executive summary, clear analysis recommendations, as well as understanding the robustness of proposed solutions; maybe just stating *planning future actions*).
- Writing and professional report preparation.
- Data selection, analysis, representation, presentation and forming a basis for recommendations and actions.
- Geographic Information Systems (GIS) skills.
- Reflection: use of essays and discussion as a way to transform experiential research, analysis and presentation activities.

Activities

The design of the course consisted of nested, iterative, scaffolded, experiential learning activities that permitted students to explore, tune, integrate, transform and re-apply what they learned in terms of ESEM knowledge domain concepts and skills. The major activities of the course consisted of real-world case study analysis, an initial, shorter-termed ESEM project and a final, longer-termed, extensive ESEM project. These projects were arranged in sequence in order to provide an opportunity for students to iterate, integrate and tune their skills and knowledge from lectures and case experiences. The first, shorter, ESEM case served as an initial, but very challenging, practice run. After gaining experience in wrestling with the challenges and difficulties of merging knowledge and tools from multiple disciplines, students engaged with their final, major ESEM project. Case activities continued throughout the course of both projects so that new skills and knowledge were repeatedly being added to students' experiences.

At first, students reacted to this multi-layered, iterative design with some alarm – they were used to learning concepts in a linear sequence. Once they understood that the goal was to explore and transform knowledge, the course structure became less daunting and intimidating. Many students expressed the view that, even though the course involved a large amount of work, they learned more by performing the required activities.

Finally, students engaged in writing two essays that provided the opportunity to reflect upon and transform their experiences associated with the case analyses and projects.

Case Studies

A variety of case studies were used to teach students:

- How to work together in teams to analyse complex problems.
- How to approach problems in ways that provide structured insight into particular issues while maintaining flexibility in terms of access to multiple perspectives stemming from the case content and other group members' views.
- How to structure and present analyses in ways that provide a clear communication of recommendations and actions, as well as the uncertainties and strengths of particular action scenarios.

These cases provided short-term, experiential opportunities to learn various ESEM skills and knowledge essential for meaningful engagement with the longer, ESEM projects. Frequently, cases were linked together.

Unilever, a global multinational company that developed a triple-bottom-line, included environmental and social impacts in addition to financial profits and losses [3]. The goal was to show students how a middle manager with a technical background could sell an entire organisation on a policy that is consistent with the principles of ESEM.

Hindustan Lever, a subsidiary of Unilever, sold soap to India's middle and upper class when it was surprised by a competitor who had built a huge market selling to the poorest of the poor [4]. Hindustan Lever came up with an equally inexpensive soap that had environmental advantages. Students were asked to write a paper on whether Hindustan Lever's soap satisfied the triple bottom line.

Shorter Projects

Students worked on shorter projects early in the class to get them *warmed-up* for a major project later in the semester. Each project followed the broad outlines of systems engineering methodology, which is outlined in an unpublished manuscript by Jack Gibson and available from the Department of Systems and Information Engineering, University of Virginia, Charlottesville, USA. Students began by sketching a descriptive scenario, which required covering the current state of the problem. They then moved to a normative scenario that contained their vision for the future. Finally, they had to outline a transition scenario that would move them as far as possible from the descriptive scenario to the normative.

For example, consider their first major project on sustainable fisheries. Students were given initial information about the Unilever corporation's concern with ensuring an adequate supply of fish for the next century and also on the company's plans to implement a triple bottom line [3]. Students were told they would act in a consulting role for Unilever, describing the current state of the fishery problem, imagining what it ought to look like in the future, and what actions should be taken to move from the current problem state to a better future state. Student teams had to present their research findings and recommendations at each stage of the project, culminating in a final recommendation. They were encouraged to provide qualitative or quantitative data supporting their assertions. Each group from last year's class and the current class focused on different aspects of the fishing industry. As a result, one group's final solution incorporated the concept of establishing stronger fishing privatisation rights, especially for people along the ocean's edge of third world countries. A second group decided that incorporating fish farming would produce more fish to supply the ever-increasing world population. Another team decided that Unilever and the Marine Stewardship Council knew what problems needed to be fixed for the future and did not feel that change was in the best of interest for the world. The groups based their decisions on many long hours of research to produce solutions based on knowledge gained from only three previous lectures. Their willingness to be open-minded, creative and present their ideas in a professional manner exemplified the many goals previously stated for this class.

Design of a Conservation Area

After completing this project, students embarked on a more ambitious effort to either plan a major conservation area or redesign an existing one. The new conservation project was Yellowstone-to-Yukon (Y2Y) or the redesign was of the Everglades. Half of the students picked one, and half the other. Given ESEM's global focus, a project outside North America could easily have been picked, but it was felt that students were already stretched far enough. Both projects are still replete with cultural issues and divisions among major stakeholders.

Each student group chose to focus its primary attention on an aspect of the system, while keeping the whole clearly in mind. For example, one of the best groups in the first version of the class used GIS methodology to design a wildlife corridor for grizzly bears in the Y2Y region. A healthy grizzly population indicates that the full ecosystem necessary to support this *charismatic megafauna* is also healthy. Parks like Yellowstone and Glacier serve as *islands* where grizzlies are protected. But if the species is isolated on these islands, it cannot maintain sufficient genetic diversity. Therefore, these islands need to be connected by corridors through which wildlife can pass safely. One student group independently discovered a promising route that led through the Bozeman Pass in Montana. Subsidiary issues included how to build overpasses and underpasses that would allow wildlife to cross major highways and how to cluster development so that potential corridors are not broken up by scattered homes. Decisions about corridors needed to take into account the entire system, including the interests of miners, loggers, developers, ranchers, tourists and bears.

In the first iteration of the course, Everglades groups tended to focus on the overall restoration plan, a complex set of documents that could certainly profit from an ESEM analysis, but one that represented a difficult challenge for students – and also tended to funnel them down the current Everglades solution path. It was hoped that more focused cases would force students to consider the whole system. Consider, for example, the fate of the Tamiami canal, which runs alongside a levy separating the water management district in the north from the Everglades National Park in the south – an arbitrary manufactured barrier. To the north, the Everglades is a reservoir, to the south it is a wildlife sanctuary; however, both are part of the same slow-flowing river of grass. The Tamiami is broken by frequent dams, built by the Army Corps of Engineers and controlled by the South Florida Water

Management District. These dams can restore flow to the river of grass, but not in the form of great sheets of slow-moving water. One proposal was to eliminate the levy and replace the road along it with a series of bridges or overpasses [5]. ESEM calls for a continual dialogue with the human-natural system, which means that reversible technologies should be deployed whenever possible. In other words, ESEM would preserve the means to adjust the water flow and also to modify the corridors in the light of further data on their system-wide impact. The same problem, on a smaller scale, exists for expensive highway overpasses in Y2Y.

Project groups were put in touch with experts working in appropriate areas of either Y2Y or the Everglades; several of these experts also gave guest lectures in the class.

Grading

The grading system was structured to complement the emphasis on the iterative learning opportunities that the course's activities supported. Sixty percent of a student's overall grade was based on that student's contributions to team activities, such as case analysis presentations and ESEM project documents and presentations. The remaining portion of the grade was based on individual assignments, such as reflection essays and individual assignments associated with the cases. For the final project presentation, each student was required to speak, with an individual grade given for that performance.

WHAT STUDENTS FELT THEY LEARNED

The Accreditation Board of Engineering and Technology (ABET) recommends that every engineering programme achieve certain outcomes [6]. One of these is to encourage life-long learning. In this ESEM class, it was hoped to make students aware of, and get them interested in, innovative work with environmental systems. The best indicator of success was that eight of the students, about one-third of the class, volunteered to continue work on ESEM in a variety of ways. Those who were graduating asked about a graduate degree in ESEM. Those who were undergraduates asked about helping with the course; eventually, three were hired as assistants.

Students also filled out an anonymous evaluation form at the end of semester that included an opportunity for them to comment on the course. Regarding life-long learning, one student noted that

> *This class was my favorite class this semester. I learned about things I never even knew existed and they were interesting. Because of the projects (Y2Y and fisheries), I have decided to minor in biology. I hope you continue to offer this class.*

Another noted that *With the tools I learned, I believe I can solve problems that require a lot of thinking*.

Regarding specific changes in thinking, others responded:

- *It* [the course] *has made me think more globally and look at the whole system, rather than parts of a big picture.*
- *It taught me to look outside the box and to look at problems from various perspectives.*
- *I never would have known how to take into perspective the viewpoints of all the various stakeholders had I not taken this course.*

In the class, it was attempted to teach the students to exercise moral imagination, which Mark Johnson defined as the ability to *go out toward people to inhabit their worlds, not just by rational calculations, but also in imagination, feeling, and expression* [7]. One student commented that *The course shows you things that are out there but people never really notice. It's all about the long-term effects and people in the world only notice the short term.*

Not all the lessons were ones that the instructors wanted students to learn. Consider the following statement:

> *I think it* [the course] *has given me a better feel for how difficult it is to come up with a solution to any of these problems. Basically the reality is that there are no solutions, only ways to minimise the damage.*

It was hoped that students would be more optimistic about the prospects for managing global environmental systems, but at least students saw the complexity of the problem and the need for working with multiple stakeholders at a systems level. One student recognised that his/her generation had a particularly important role to play and said:

> *I have learned that everything is more complex than it appears and that it is almost impossible to solve a problem while pleasing every stakeholder. However, I have learned that the impossible can be overcome…*

It is planned to continue to offer this course and evaluate its benefits for students. In its next iteration, the addition of a project on sustainable cities is conceived, including input from Beatley and additional resources [8-10]. ESEM is a difficult and demanding course, because students are asked to try to make progress on complex problems that no one has been able to solve yet. But it is these kinds of open-ended, ill-structured problems that represent the greatest challenge – and opportunity – for our species.

REFERENCES

1. Allenby, B., Earth systems engineering and management. *IEEE Technology and Society Magazine*, 19, **4**, 10-21 (2001).
2. National Academy of Engineering, *Engineering and Environmental Challenges: a Technical Symposium on Earth Systems Engineering*. Washington, DC: National Academy Press (2000).
3. Gorman, M.E., Mehalik, M.M. and Werhane, P.H., *Ethical and Environmental Challenges to Engineering*. Englewood Cliffs: Prentice-Hall (2000).
4. Balu, R., Hindustan Lever. *Fast Company,* 120-136, June (2001).
5. http://www.saj.usace.army.mil/dp/tamiami.htm
6. Gorman, M.E., Turning students into professionals: types of knowledge and ABET engineering criteria. *J. of Engng. Educ.*, 91, **3**, 339-344 (2002).
7. Johnson, M., *Moral Imagination*. Chicago: University of Chicago Press (1993).
8. Beatley, T., *Green urbanism: learning from European cities*. Washington, DC: Island Press (2000).
9. Sustainable Cities Programme, University of Southern California (2003), http://www.usc.edu/dept/geography/ESPE/
10. Arizona State University's Integrative Graduate Education and Research Training (IGERT) in Urban Ecology (2002), http://www.asu.edu/ces/igert.htm