Complex Socio-technical Problems for Engineers: Pedagogical Motivation and Experience at the Undergraduate Level

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Abstract. *Engineering courses, focused on complex, large-scale, sociotechnical systems, at the undergraduate level, have been rare. Traditionally, most students develop a deep technical understanding in a specific engineering discipline, but get little opportunity to analyze engineered complex systems, where both technical and social issues need to be well understood for devising long lasting solutions. The development of analytical skills for studying interdisciplinary problems has so far been largely limited at the graduate-level. In this paper we describe the motivation, design, and learning outcomes of an introductory course on Engineering Systems that has been developed and offered to primarily first and second year engineering students at the Massachusetts Institute of Technology. The course has been centered around the theme of critical contemporary issues (CCIs) including energy, mobility, sustainability etc. The aim of the course is to expose undergraduates to quantitative tools that are available for rigorously and methodically analyzing some of our most complex contemporary engineering challenges. The course consists of introductory lectures on system dynamics, networks and uncertainty, along with semester-long team-based projects. The projects focus on different topics related to CCIs and the students work in small teams on a project of their interest throughout the term. For the first pilot offering of the class (in Spring semester 2011), the students gave an average rating of 5.9/7.0 regarding how likely they were to recommend this class to others (with 7 being absolutely certain). There was also evidence (however based on limited and anecdotal data) of continued student interest (outside of class) in engaging with the complex socio-technical problems they worked on during the term.*

Keywords. *Socio-technical systems, project-based learning, undergraduate engineering curriculum*

1 Introduction

Many of our most interesting, complex engineering challenges do not fit into the neat silos of academic disciplines – they are interdisciplinary and require *systems thinking*. The level of complexity and interactions in modern systems requires a new level of expertise and trans-disciplinary perspectives that perhaps were not needed before. Systems thinking, and the skills to tackle complexity, need to be inculcated in engineering students sooner rather than later. It is becoming more important for young engineers (not just senior practitioners) to obtain such skills. To date, the development of analytical skills for studying such problems has been largely reserved for graduate-level engineering education. However, engineering students are increasingly interested in working on contemporary challenges earlier in their careers. Students entering engineering programs today are more aware and better equipped for conducting sophisticated analysis due to their access to information, knowledge and tools that previously were not available to prior generations. It is therefore important – both for retaining students in engineering and for harnessing their curiosity towards potentially finding new solutions – to offer *undergraduate* courses that allow them to engage with complex, contemporary problems.

This paper describes the development and implementation of a novel course, ESD.00- *Introduction to Engineering Systems,* offered by the Engineering Systems Division (ESD) at the Massachusetts Institute of Technology (MITnews, 2011). Primarily intended for first and second year engineering students (but open to all undergraduates), it has been designed to engage and challenge a new generation of students who are passionate and more involved than ever before in understanding and impacting contemporary problems.

The new course centers around the theme of Critical Contemporary Issues (CCI) – important and difficult problems pertinent to our present times on topics including sustainability, mobility, energy and the environment, healthcare, communication, the internet etc. In this course, we integrate introductory instruction in system dynamics, networks and uncertainty with team-based semester-long projects. Through this approach, we enable students to engage in and understand the issues related to a problem of their interest, appreciate the scope of the socio-technical complexities in CCIs, and gain an introduction to analytical tools that can help in addressing some of these issues. This paper discusses the overall philosophy and motivation for establishing the course, the design of the curriculum, the execution and integration of team-based projects, the teaching and learning experiences over two terms, and plans regarding its future evolution.

2 Motivation

Historically, engineers have largely acquired expertise and understanding of complex systems through practice in their profession. Little attention was paid to creating structured curricula, classes or degree programs focused on studying complex engineering *systems*. However, we are presently part of an era in which the inventions of the past two centuries for energy, transportation, and communication have coupled together to form highly interdependent, large-scale systems (deWeck, Roos and Magee, 2011). Thomas Edison's light bulb, James Watt's steam engine, and Alexander Graham Bell's telephone have not only transformed into more sophisticated devices today – but they also now form only a part of larger systems within which they function and without which they will not deliver value. The light bulb requires a functioning electric grid, the locomotive engines require transportation networks, and the modern phones are of use within the larger signal and communication networks. While we have, to a great degree, advanced our knowledge in the art and science of designing new products, we have yet to explore the domain of design, operation, and management of complex engineered systems with considerable nonlinearity and feedback.

Furthermore, engineering education has traditionally focused on systems where the boundaries encompassed materials, machines and constructed facilities. It is has now become important to expand those boundaries to include humans and institutions. Such an expansion essentially extends the focus from simply technical to *sociotechnical* systems, where technical as well as societal, economic, political, and regulatory factors weigh in prominently.

As historically disparate technical systems become inter-twined and humans and societal factors become non-negligible variables in design decisions, engineers of tomorrow will need to deal with requirements that are not just physical, but also increasingly social, political, economic in nature. At some level, this has always been the case. However, such considerations were not needed to be as integrated in the design, management and operation of engineering systems as they are increasingly required now. This new, increased level of integration requires a rethinking and redesigning of how we go about training our future engineers who will, for instance, have to deal with global manufacturing and supply chains, create and maintain new interdependent infrastructures, design systems for accessible and affordable healthcare and so on.

This course is an initial step, at the undergraduate level, towards inculcating broad, holistic thinking in our next generation of engineers. While learning the technologies central to these systems is essential, our students need to learn how social sciences and management ideas are integrated into our study of CCIs, creating that holistic individual. It is necessary to teach methods related to analysis of natural phenomenon and material or component behavior (such as Finite Element Analysis, Computational Fluid Dynamics *etc.*) to engineering students. It is now also important to offer the students an exposure to sophisticated methods for understanding system interdependencies (using tools of networks and graph theory), understanding uncertainty (based on probability theory) and tools for decision-making (such as decision analysis, multi-attribute utility theory) etc.

The Engineering Systems Division at MIT is driven by this vision of research and education in large-scale engineering systems and is focused on complex, socio-technical problems. The division was established in 1998, and since its inception there has been strong and increasing student interest in terms of enrollment and class registrations (see Fig. 1).

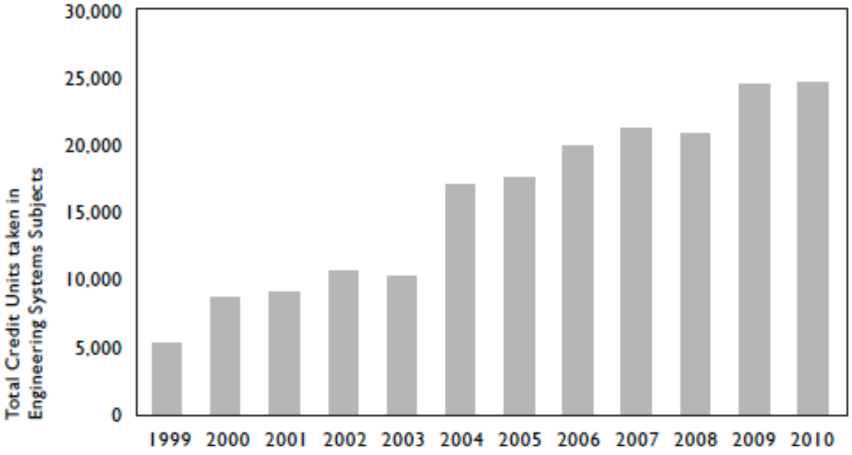


Figure 1: Student enrolment in ESD classes at MIT (de Weck, Roos and Magee, 2011)

However, to date the educational efforts of the division have been primarily targeted towards graduate students. Fig. 2 shows the total graduate-level course offerings (across all semesters) by departments in School of Engineering at MIT. This data counts joint-listed courses (i.e. same classes listed with different numbers in multiple departments) only once. Joint-listed classes were associated with a department that is designated as ‘Master’ department for the class in the registrar’s office. Furthermore, course numbers for thesis work and directed/individual student research classes were not counted. It can be seen, in Fig. 2, that while the number of graduate courses offered by ESD are significant, the undergraduate courses are the smallest in number within the school.

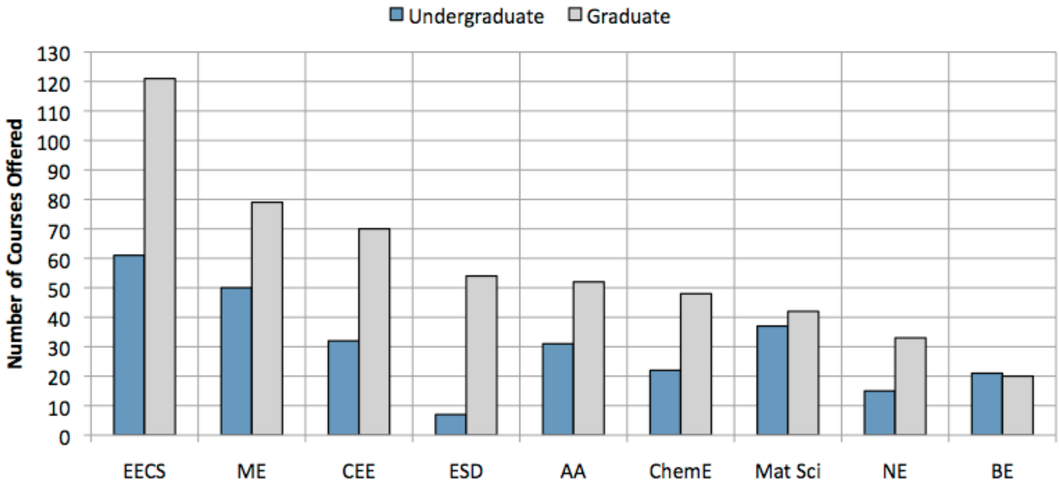


Figure 2: Number of classes currently offered (across all semesters) in School of Engineering. *Abbreviations: EECS: Electrical Engineering & Computer Science; ME: Mechanical Engineering; CEE: Civil & Environmental Engineering; ESD: Engineering Systems Division; AA: Aeronautics and Astronautics; Chem E: Chemical Engineering; Mat Sci: Materials Science and Engineering; NE: Nuclear Engineering; BE: Biological Engineering.*

A more in-depth analysis of the course offerings was done to determine how many classes were focused on 'systems' (in any domain or context). As a crude proxy of this measure, class titles that had the keyword 'system' were tallied for each department. The results are shown in Fig. 3. The reader should note that from the viewpoint of full-time equivalent (FTE) faculty, ESD is the smallest unit in the School of Engineering with 13 FTEs. EECS has about eight times that so the numbers when normalized tell a different story.

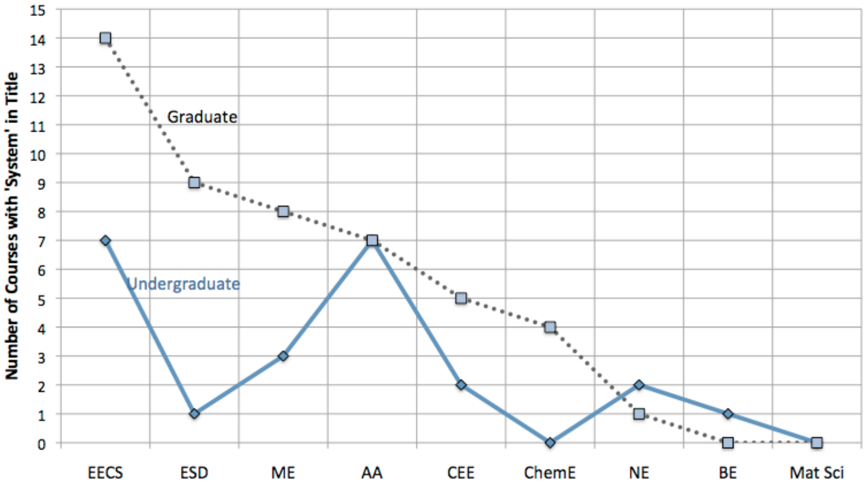


Figure 3: Number of courses with keyword 'system' in course title.

A review of the undergraduate classes currently offered by ESD shows, that apart from ESD.00, there are 6 listings. These include courses related to engineering leadership offered through the Gordon-MIT Engineering Leadership program (GEL, 2012), statistics and data analysis, technology and public policy etc. There had been no undergraduate class, offered by ESD, which focused on concepts and methodologies for analysis of complex large-scale, engineering systems from a domain neutral perspective. The new course, ESD.00, was thus developed to close this gap and create new learning opportunities for undergraduates. The one undergraduate 'systems' class shown in Fig. 3 for ESD is due to the recent inclusion of ESD.00 in the listing.

3 Introducing Socio-technical Problems to Engineers

3.1 Objectives

The basic objective of the course was to expose undergraduate students to concepts and methods that can be used for tackling critical, contemporary issues associated with socio-technical systems such as that of energy, mobility, communication, healthcare etc. A key feature was emphasis on project-based learning (Blumenfeld et al. 1991), and the goal was to have student teams work on specific projects as part of this class. There were seven goals that were outlined for the course (Sussman, 2010):

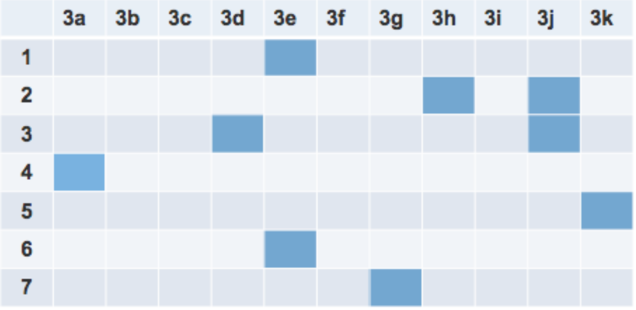
1. To introduce concepts and methods of engineering systems at a level that can be understood and applied by undergraduate students in real-world projects.
2. To enable students to gain conceptual understanding of the complex interplay among technical, social political, and cultural aspects of socio-technical systems.
3. To motivate and energize students via project work with student teams and faculty mentors on complex global issues.
4. To develop students' problem solving and critical thinking abilities in deciding how to model and analyze a complex socio-technical system as part of their project work.
5. To enable students to draw directly on their math, science, and social studies background in conceptual understanding and practical application of engineering systems concepts and methods.
6. To introduce and provide practice in use of mathematical methods and computer simulation tools used in modeling, analysis and design of engineering systems.
7. To develop students' abilities in teamwork, oral communication and written communication as part of completion of team projects.

These objectives were largely driven by motivation to expand course offering for undergraduate students on topics of engineering systems (as discussed above in Section 2.0) as well as to use projects to enrich their learning experience. In retrospective analysis, we evaluated the goals using program-level outcomes defined by the Accreditation Board of Engineering and Technology as a basis of assessment (ABET, 2012). The outcomes (commonly referred to as Outcomes 3a-3k and described in Table 1) are used to evaluate engineering programs.

Table 1: Program-level Outcomes 3a-3k as defined by ABET (Felder, 2003)

3a	An ability to apply knowledge of mathematics, science, and engineering
3b	An ability to design and conduct experiments, as well as analyze and interpret data
3c	An ability to design a system, component, or process to meet desired needs
3d	An ability to function on multidisciplinary teams
3e	An ability to identify, formulate and solve engineering problems
3f	An understanding of professional and ethical responsibility
3g	An ability to communicate effectively
3h	The broad education necessary to understand the impact of engineering solutions in a global and societal context
3i	A recognition of the need for and an ability to engage in lifelong learning
3j	A knowledge of contemporary issues
3k	An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

The expectation is that the core set of classes in a program will collectively produce the outcomes at the required levels (Felder and Brent, 2003). While the outcomes are for program-level evaluations, they provide a basis for assessing specific courses as well. In general, a single course cannot fully cover the full spectrum (from 3a-3k). A comparison of how the goals (from 1-7) for the course connected with the outcomes 3a-3k is shown in Fig. 4. A dark blue box in the matrix indicates that the goal in its corresponding row is linked with the outcome in its corresponding column. Note that in this figure only links are marked, but the level of connection (i.e. *how strongly* a goal links to an outcome) is not assessed at this stage.



	3a	3b	3c	3d	3e	3f	3g	3h	3i	3j	3k
1					🟦						
2								🟦		🟦	
3				🟦						🟦	
4	🟦										
5											🟦
6					🟦						
7							🟦				

Figure 4: Comparison Matrix of class objectives with ABET's program-level outcomes.

3.2 Structure and Content

In terms of class structure, we designed it to be principally a project-based class, grounded with weekly lectures and a few supplemental tutorials. The lecture component provided the means for introducing the concepts and methods relevant for the class as well as a forum for in-class discussions. The projects were supervised by a graduate student or faculty member, and were conducted in small teams over the course of the entire semester. The projects served to engage the students' interest and provided real-world examples for applying the concepts and methods introduced in the lectures. Fig. 5 provides a schematic representation of how the class was structured.

The lecture topics were selected carefully to reflect the introductory level of the course, but also to enable the students to acquire understanding of important concepts related to complex engineering systems. We selected three key topics: systems dynamics, uncertainty and networks. These topics collectively provide means for studying non-linearity, feedback, interconnections, and ambiguity that characterize most real-world problems and are often not adequately covered in classical engineering courses at the undergraduate level. Given the rich body of literature and a fair level of maturity that exists for these topics, a substantive and well-grounded material, suitable for undergraduate instruction, could be presented. Additionally, the *application* of these methods towards studying sociotechincal systems is well developed and recognized not just in a theoretical sense, but also in actual practice and real-world applications (Sterman, 2000; Newman, 2003; Bertsekas and Tsitsiklis, 2008). The application of these methods and approaches towards modeling and analyzing systems with both technical *and* social aspects was emphasized and demonstrated. Usually, these topics are covered in various engineering courses (especially uncertainty and to some extent systems dynamics through differential equations); however the examples and applications are typically focused on technical and physical modeling only. The key difference in this class was how these topics were introduced and explained, and the kinds of examples used so that the students could understand how these methods apply to analysis of sociotechnical systems.

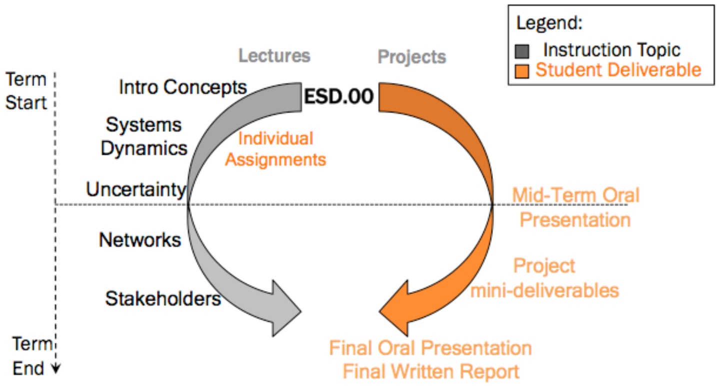


Figure 5: Two-pronged approach for ESD.00 - theoretical instruction and practical application.

In addition to the key topics that were treated in depth (with multiple lectures devoted to each), we included lectures on basic systems concepts and definitions, stakeholders and evaluative complexity (Sussman, 2011), and other lectures on related topics.

We took special care to integrate the two segments, the lecture and the projects, of the course. The integration was done through assigning mini-project deliverables to each team, in which the methods and concepts discussed in lectures were applied to the projects. For instance, each team was asked to create causal loop diagrams (as taught in systems dynamics approach), identify key uncertainties, and create network models for their respective systems. This integration of lecture material with projects was expressly designed to ensure cohesion between the two threads of the course as well as to allow students to apply the concepts to actual applications.

A detailed description of the course and the syllabus can be accessed at (ESD00, 2012). The class materials (as offered in Spring 2011) are also available through MIT's open courseware website (OCW, 2012).

3.3 Term Projects

As discussed earlier, this class was fundamentally designed around term projects. The idea was to have students grapple with open ended problems with no canned methods to apply or 'right' answers to compute. The students were equipped with instruction on multiple methodologies, and were given freedom to choose appropriate methods and tools that would be applicable in their judgment to the questions under investigation.

In the first offering of the course (in the spring semester of 2011), the students worked on three projects on healthcare, transportation, and communication that were broadly designed and supervised by ESD faculty and engineering systems PhD students students. In the second offering (currently on-going at the time of submission of this article), the student teams have projects on using electricity from renewable energy sources, decision modeling for flu vaccination, and site selection for nuclear waste disposal in the US. It is noted that the projects touch upon different critical contemporary issues, and are in fact well aligned with a number of grand challenges of engineering that have been outlined by the National Academy of Engineering (NAE 2008). Fig. 6 shows how the fourteen grand challenges, as described in (NAE, 2008), connect to more general categories into which the ESD.00 projects (that have been offered to date) can be classified.

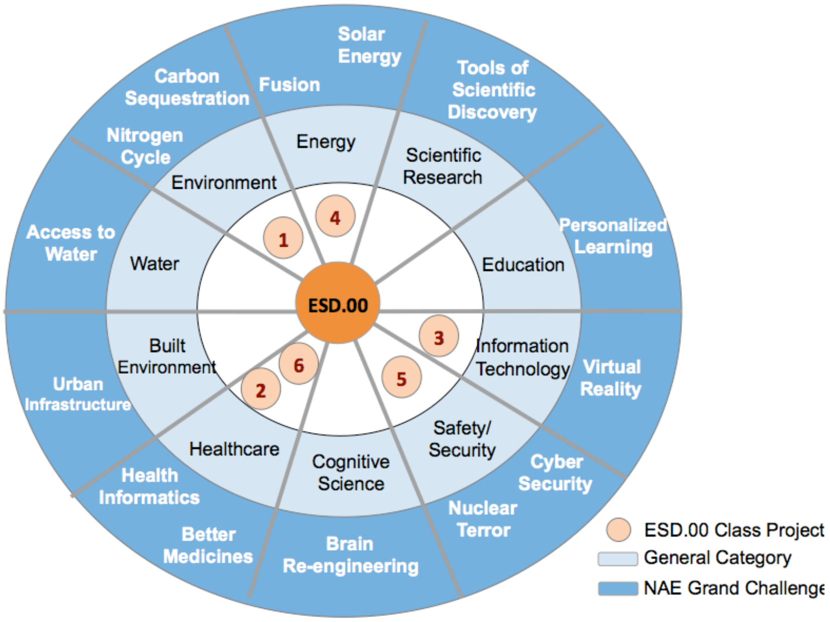


Figure 6: Mapping grand challenges in engineering to projects offered in ESD.00.

The project numbers in Fig. 6 (in the small inner most circles) correspond to projects 1- 6 discussed as follows:

3.3.1 Life-Cycle Assessment of High-Speed Rail and Aviation

This project focused on a life-cycle assessment of high-speed rail and air transportation in the U.S. Northeast Corridor. The primary objective was to compare energy use and CO2 emissions of the Acela Express as compared with short-haul flights in the Northeast Corridor (Fig. 7).

Figure 7:Proposed High-Speed Rail Corridors.

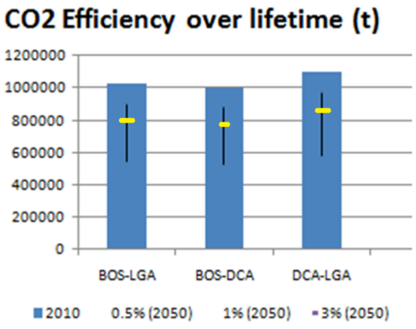


Figure 8: Sample Analysis Results of emissions.

The team examined future projections of demand for both modes of transportation between three corridors: Boston to New York, New York to Washington, D.C., and Boston to Washington, D.C. (see Fig.8) The life-cycle energy consumption and CO2 emissions associated with these corridors were assessed utilizing a combination of the Economic Input-Output Life Cycle Assessment (EIO-LCA) method for transportation infrastructure and "well-to-wheel" approach for vehicle emissions.

3.3.1 Stroke Care Chain

The objective of the project was to analyze and then suggest improvements to the process of how patients are provided medical care after they suffer a stroke. The students were provided with an elementary systems dynamics model executable in Vensim^{TM} (originally prepared by a team of MIT and Harvard graduate students that had conducted exploratory work on the topic).

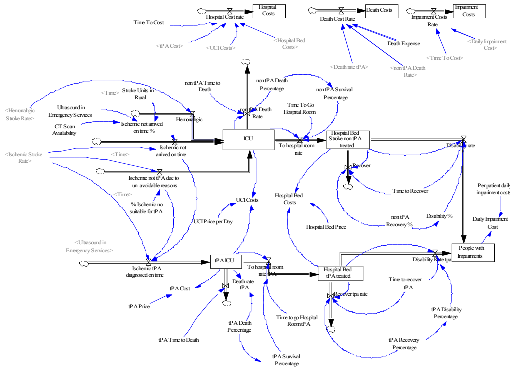


Figure 10: Systems dynamics model for stroke

The students focused their analysis on the state of North Carolina, a state that has a 10% higher death rate from strokes as compared to the US national average. The students used the model to first determine key variables that impact the stroke care process and can lead to tangible improvements, and then explored various policy options based on costs and benefits. The policy options included deployment of in-field ultrasound technology, increasing staffing of stroke care personnel at medical facilities, and increasing awareness through public out-reach and education.

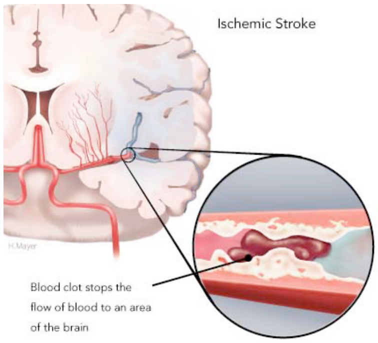


Figure 9: Ischemic stroke due to blood clot in the brain.

3.3.3 The Digital Divide

Broadband has increased from 8 million in 2000 to 200 million in 2009 in the US, but there are still 100 million Americans that do not have broadband. The focus of this project was to understand the barriers to broadband adoption in the US, and to identify solutions that may help in increasing broadband accessibility. The team analyzed recently released (February 2011) data from a large Federal Communications Commissions (FCC) survey (see Fig. 11).

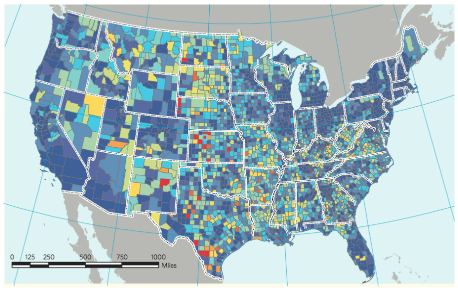


Figure 7: Broadband access by county.

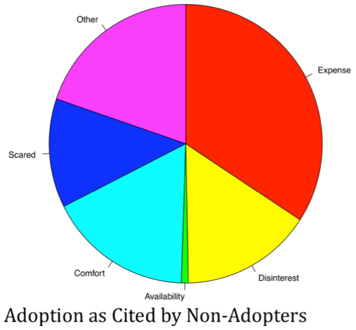


Figure 8: Sample results of top barriers to broadband adoption

The students used R, a statistical package, to compile and visualize the data in order to formulate a broadband adoption model. The key task was to explore the social, economic and technical factors that contribute to broadband and internet access trends in the US. Fig. 12 shows sample results.

3.3.4 Electricity Power: Combining Renewables, Capacity Expansion, and Demand Response

This project explores the challenges in using electricity generated from renewable sources.
Production of electricity with renewables will reduce carbon emissions but will increase the cost of electricity and require the electric power system to adapt in order to absorb the characteristic intermittency of wind and solar generation. Motivated by the need for low emissions, low cost and security of supply, a number of questions regarding optimal technology choices to balance competing objectives, and role of demand response were investigated.

3.3.5 Finding a Nuclear Waste Repository Site in the US

A multi-attribute approach to evaluating nuclear waste sites was designed in the late 1980's. Using expert elicitation to determine rank orderings and estimates for repository impacts, the methodology was applied to five potential waste repository sites, including Yucca Mountain. This project aimed to update that methodology for the new political and public resistance in 2011 in which the Yucca Mountain site has been ruled out. The team project consists of establishing a value tree (considering a wide range of metrics that should be used in selecting a site for a waste repository in the U.S); a network analysis on five candidate waste sites to determine which are optimal from a transportation-minimization perspective; a multi-attribute analysis of two possible project sites, and then inclusion of uncertainties using a decision-analytic approach.

Figure 9: Sample Decision Tree

Figure 10: Nuclear waste generation sites.

3.3.6 Multi-Criteria Decision Models and Influenza Vaccination

This project is based on modeling decision making for vaccination and evaluating effectiveness of vaccination policies. Every year, a new influenza vaccine is available for the general public during the influenza season (October-March) and there is a brief period to monitor the outcomes of this vaccine – both its safety (adverse events) and its effectiveness (avoidance of influenza-related illnesses). Of course, **the effectiveness of the vaccination policy depends on the public's perception of the benefits and risks of influenza v. getting vaccinated against influenza**. These are dynamic measures that only become fully known after an influenza season is over. Federal regulators have a difficult job communicating these changing/developing benefits and risks for a myriad of reasons and continually cope with significant scientific misinformation surrounding vaccination and vaccines. The project uses Systems Dynamics modeling to investigate the problem.

4 Assessment

The course was reviewed by both students (through end-of-term evaluations) and by the faculty to gauge learning outcomes (largely based on final project presentations). At the time of submission of this article, data regarding assessment and evaluation of the first offering (of Spring 2011) was available. The second offering (of Spring 2012) is on-going, therefore its evaluation data was not available.

4.1 Student Assessment of Learning

Student feedback for the course was elicited through a focus group at the end of the semester and through an online course evaluation form. The course evaluation was specially customized for the class and was not simply the generic evaluation used for all classes at the Institute. The response rate was 100%, and the overall feedback was very positive. Many students gave the highest 'strongly agree' rating to the question of whether they would recommend this class to others. Across all responses, the average rating for this question was 5.9 on a 7-point scale.

Table 2 summarizes students' expectations of their learning outcomes, and the extent to which the course met their expectations. These results are based on responses the students provided in the customized, end-of-term course evaluation. The responses were on a 7-point scale defined as follows: 1 = Not at all, 4 = Somewhat, 7 = To a Very Great Extent.

Table 2: Summary of Student Evaluations

	What were your expectations of the class?	**Mean Score**	**Responses**	**St. Dev.**
Student Expectations	Expected to learn about engineering systems and how they connect with some critical contemporary issues.	6.0	7	1.0
	Expected to work on a complex, engineering systems project.	6.6	7	0.79
	Expected to gain knowledge about tools used to analyze engineering systems.	5.7	7	0.95
	Expected to learn to apply tools used to analyze engineering systems.	5.6	7	1.27
Effectiveness Meeting Expectations	**How effectively did the class meet expectations?**	**Mean Score**	**Responses**	**St. Dev.**
	Learned about engineering systems and how they connect with some critical contemporary issues.	6.4	7	1.13
	Learned to work on a complex, engineering systems project.	6.7	7	0.49
	Gained knowledge about tools used to analyze engineering systems.	6.0	7	0.82
	Learned to apply tools used to analyze engineering systems.	6.1	7	0.9

In general, the effectiveness of the course in meeting their expectations was ranked highly, with the highest mean score (6.7) associated with the project-related expectation. The students also agreed that they had “gained knowledge” about tools used to analyze engineering systems, as well as learned to “apply” those tools analyze engineering systems. The students’ strong self-assessment of their ability to “apply” tools for engineering systems analysis is a useful initial evaluation that could be strengthened with further outcomes-based assessment of the course.

4.2 Faculty Assessment of Learning

In terms of faculty assessment, the evaluations for student learning were made through a combination of individual homework assignments (given in first half of the class), quality of class discussions, mid-term oral presentations and final project oral presentations and a written report. As a sample of the evaluation that was conducted, Table 2 shows the rubric used for evaluating the oral presentations of the final projects. A total of 10 evaluators (faculty and research staff with four who were not affiliated with the ESD.00) attended the presentations and orally quizzed the students on their work. A scale of 1 to 7 was used which was defined as follows: 1 = poor, 4 = satisfactory, 7 = superior. The results are summarized in Table 3 and also shown in a radar plot in Fig. 15.

Table 3: Final Project Assessment

Category	**Project 1**		**Project 2**		**Project 3**	
	Mean Score	Std. Dev	Mean Score	Std. Dev	Mean Score	Std. Dev
1. Understanding of Engineering Systems Concepts (nonlinearity, feedback etc.)	5.6	1.2	5.7	1.1	5.8	1.1
2. Conceptual understanding of interplay of social, technical, political factors	5.3	1.5	4.9	1.4	6.1	0.9

3. Understanding of different stakeholder perspectives	5.2	0.9	5.1	1.3	6.3	0.6
4. Application of quantitative modeling methods	5.9	0.8	6.0	1.1	5.4	1.2
5. Analysis of results and understanding implications, limitations	5.3	1.1	5.4	1.6	5.4	0.7
6. Teamwork	5.4	1.2	5.9	1.1	6.0	1.0
7. Oral communication	5.8	0.9	5.5	0.8	5.6	0.6

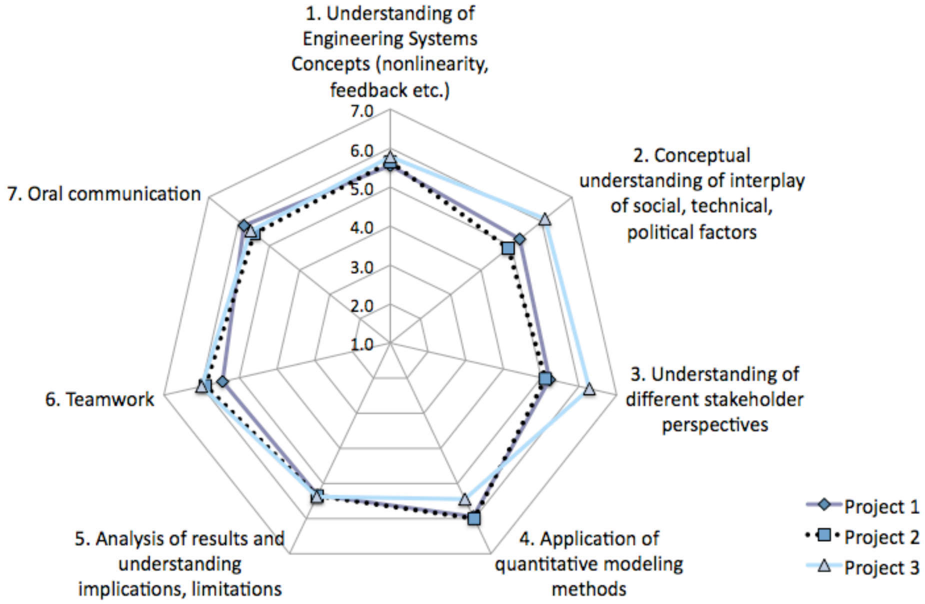


Figure 11: Project Evaluations.

5 Summary

The Engineering Systems Division at MIT, in building up from its advances in graduate-level teaching and research, is now making efforts towards unique additions to the undergraduate engineering curricula. ESD.00 represents an initial attempt into defining and establishing a new set of topics that have largely been absent at the undergraduate level.

5.1 Lessons Learnt

Based on student reviews of the first completed class (of 2011) and the instructors' experiences, this effort has taken off on a strong footing. The overall experience has been encouraging. Perhaps a key indicator of success was the fact that some students were drawn into the problems they worked on in class to the extent that a few expressed desire in continuing work on their project after the conclusion of the course. They were interested in subsequent undergraduate research experience and wanted to pursue actual implementation. Since a main motivation in creating this course was to enable undergraduates to engage with real, complex socio-technical problems, this outcome of continued student interest was greatly encouraging. A related factor regarding the student enthusiasm was the reality and relevance of the problems. Ranging from nuclear waste disposal (where the project leader is engaged with actual policy makers and shapers on the issue), to the stroke care chain project (where the researchers are working with practitioners on the issue and so on, the projects connect the students to actual, on-going problems.

The students show great motivation and excitement to work on such projects (rather than on hypothetical scenarios and issues).

At a structural and organizational level, a mix of different class-years in the student teams (e.g. a mix of freshmen and sophomores) worked well. It allowed and enriched a collaborative learning experience for the students. Furthermore, the varied background of the students (with majors spanning mechanical engineering, biological engineering, civil and environmental engineering, chemical engineering, mathematics and biology) provided a unique opportunity to students to participate in a multi-disciplinary forum – something that is not typically available to undergraduates within engineering classes.

A key issue, pertinent to replicating this class model, is its scalability. A large degree of success at MIT has been dependent on active participation of engineering systems PhD students and multiple faculty members who are engaged in research on contemporary problems. At institutions where a large research base may not exist, this model will be difficult to replicate. Even within ESD at MIT, there can be challenges towards sustaining this model for large class sizes. Another issue – which we hope to resolve over time – is to expand the supplementary reading material that touches upon topics and concepts of engineering systems, systems architecture, performance, evaluation, modeling methodologies etc. While a rich body of literature (books and teaching notes) exist – the majority cater to graduate-level studies. A long-term goal is to create suitable instruction and reading material for engineering students at the undergraduate level.

5.2 Future Directions

In the future, our vision is to offer a suite of courses that collectively offer undergraduates the opportunity to learn – and to a modest degree specialize – in the methodologies that allow for analyzing and designing complex, large-scale, engineering systems. For a new generation of engineers, that needs to address the *grand challenges* (NAE, 2008) of its times, augmenting the skill-set knowledge with tools for modeling complexity, interdependency, emergent behavior, and trading off technical as well as environmental, social and regulatory constraints will be greatly beneficial. Our hope is that this course, and others motivated by this broader vision, will serve to provide this opportunity to our future engineers.

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