AC 2012-4058: INTRODUCING ENGINEERING SYSTEMS TO FIRST-AND SECOND-YEAR STUDENTS THROUGH PROJECT-BASED LEARNING

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Introducing Engineering Systems to First- and Second-Year Students through Project-Based Learning

Abstract

The importance of systems thinking has arisen as a key issue in engineering education. Indeed, in order to address current and future global challenges, the next generation of engineers will likely need a different set of skills than previously required by society. Over the past few decades, systems thinking, modeling, and analysis have successfully been integrated into graduate levels of engineering education and research. However, these concepts have seen limited treatment at the undergraduate level. This paper describes the development of a novel course that introduces "engineering systems" to first- and second-year students through project-based learning.

"Introduction to Engineering Systems" focuses on the theme of critical global challenges, while teaching students concepts and modeling techniques useful for analyzing large-scale complex systems. Through the lectures, students are introduced to quantitative and qualitative methods, including stakeholder analysis, system dynamics, network analysis, and uncertainty analysis. Interwoven throughout the semester, system concepts such as complexity, flexibility, and sustainability are also presented in course lectures and individual assignments. Through a semester-long project, students work in teams to analyze a complex, sociotechnical system. During the first offering of the course in spring 2011, projects focused on challenges associated with transportation and energy, telecommunications, and healthcare. Course projects enabled students to further apply analytical and modeling methods that were introduced during the course lectures and class-wide assignments.

This paper provides an overview of the introductory "engineering systems" undergraduate course, the motivation for initiating the course, and key lessons learned. We describe the modeling and analytical methods core to the course curriculum, as well as a detailed overview of semester-long projects. Finally, we present an analysis of student expectations and learning outcomes for the pilot version of this course. By integrating systems thinking and critical, contemporary issues into first- and second-year curricula, this course aims to improve the retention of the next generation of engineers, while developing a broader set of skills that will enable them to address the complex problems faced by society.

1. Introduction

Many students are attracted to engineering in order to solve important real-world problems. However, during the first two years of engineering education, the majority of students find themselves in courses focused on the fundamentals of math and science, with little or no apparent connection to the real-world issues they care deeply about. Through their undergraduate experience, most engineering students develop a deep understanding in a specific engineering discipline. However, they often have very limited opportunity to learn about and analyze complex sociotechnical systems (e.g. energy systems, transportation networks, etc.) – engineered systems that are the focus of many critical global challenges.

The most interesting and important engineering challenges no longer fit into the neat silos of academic disciplines – they are interdisciplinary and require *systems thinking*. In the Journal of

Engineering Education, National Academy of Engineering President Charles Vest recently argued that the engineering workforce of tomorrow will need to address challenges in the twenty-first century that will be very different from those in the twentieth.[1] The complexity of modern systems requires new levels of expertise and trans-disciplinary perspectives that perhaps were not required of previous generations of engineering professionals. Systems thinking, and the ability to place engineering problems in a broader contextual framework, need to be inculcated in engineering students sooner rather than later; some argue that teaching this material to freshmen and sophomores (rather than waiting until the junior and senior year) so that students not be "captured" by the reductionist mode of thinking inherent in the introductory science and math subjects as well as introductory engineering subjects. It is becoming ever more important for young engineers (not just senior practitioners) to cultivate such skills.

While the need for modernizing and improving engineering curriculum is increasingly recognized[2], change has been slow, in particular at the undergraduate level[3]. Students who are interested in addressing current real-world problems that are interdisciplinary in nature typically have limited exposure, at an early undergraduate level, to tools and methods that are available for rigorously and systematically examining these challenges. The development of analytical skills for addressing such problems has been primarily offered in graduation education. However, undergraduate 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 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, *Introduction to Engineering Systems,* offered on a pre-pilot basis by the Engineering Systems Division (ESD) at the Massachusetts Institute of Technology (MIT) during the spring semester of 2011. Intended for first and second year students, the course has been designed to engage and challenge a new generation of students who are passionate and more involved than ever before in understanding and solving current, large-scale, real-world problems.

2. Motivation and Background

The motivation for developing and offering this course stems from a broader vision of the Engineering Systems Division at MIT, in which it is recognized that future engineering leaders should not just possess knowledge and expertise of devices, artifacts and processes but also be experts in dealing with complex, large-scale sociotechnical systems. Historically, engineers have largely acquired expertise and understanding of complex systems through practice in their profession. Little attention was paid towards 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.[4] Thomas Edison's light bulb, James Watt's steam engine, and Alexander Graham Bell's telephone have transformed into ever more sophisticated and impressive devices today – but they form only a part of larger systems, that in turn are parts of even larger system-of-systems. 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 socio-technical systems subject to intense feedback. As a result of this increase in demand for multi-disciplinary systems experts, graduate engineering education has started to focus on offering courses, concentrations and degrees in engineering systems. MIT's ESD program is a concerted effort in this direction.

ESD's vision is to advance research in these areas and to also simultaneously impart knowledge of established methods and approaches to our students for tackling such problems. To date, these efforts have primarily been conducted at the graduate level, where a strong student response and interest in our programs indicates a good measure of success (see Fig. 1). More broadly, outside of MIT, many engineering systems educational initiatives are focused at the graduate level.[5] Similarly, there are numerous examples of junior or senior-level design courses that draw on systems-based approaches, often focused on designing a large engineered product such as a satellite or vehicle.[6] More recently, the need to integrated systems analysis into undergraduate engineering curricula has been recognized.[7] However, there are few examples of integrating engineering systems methods into undergraduate curricula, particularly during the first or second year of study.

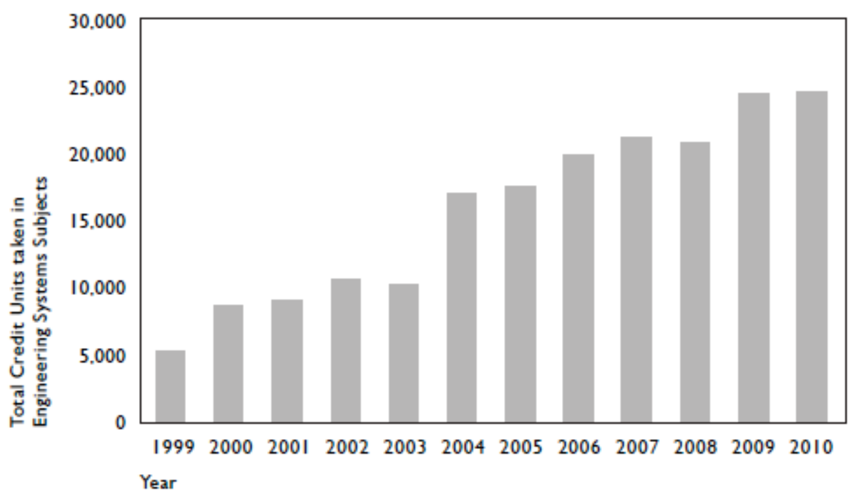

Figure 1. Student enrollment in Engineering Systems Division at MIT.

Building from our division's experience and success at the graduate level, we aim to expand our focus to undergraduate curricula, as well as potential undergraduate experiences outside the classroom. In some ways, it is perhaps more critical to transform undergraduate education, during a time when the basic needs of the engineering profession, education and practice are changing in significant ways. The US National Academy of Engineering recognizes that in today's landscape of a continually changing society, engineering education must adapt to remain relevant.[8]

Traditionally, engineering education has 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 and 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 today. 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 infrastructures and design systems for accessible and affordable healthcare. This course is an initial step, at the undergraduate level, towards inculcating broad, holistic thinking in the next generation of engineers.

Finally, an important design element of the class was the decision to integrate team-based projects into the course offering. There is significant evidence that project-based learning (PBL) can be a useful and effective method of instruction, particularly in undergraduate engineering education.[9,10] Project-based learning approaches to undergraduate education have been promoted as a key component for shaping engineering education in order to satisfy several stakeholders, including students, industry and education accreditors.[10] Through ESD.00, we attempt to both teach novel systems analysis methods in an introductory course, as well as fully engage students through team-based projects.

3. Design of "Introduction to Engineering Systems"

The basic objective of the course was to expose first and second year students to concepts and methods that can be used for tackling critical, contemporary issues associated with sociotechnical systems such as that of energy, mobility, communication, healthcare, etc. We designed this course 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 an engineering systems Ph.D. 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. This two-pronged approach is illustrated in Fig. 2.

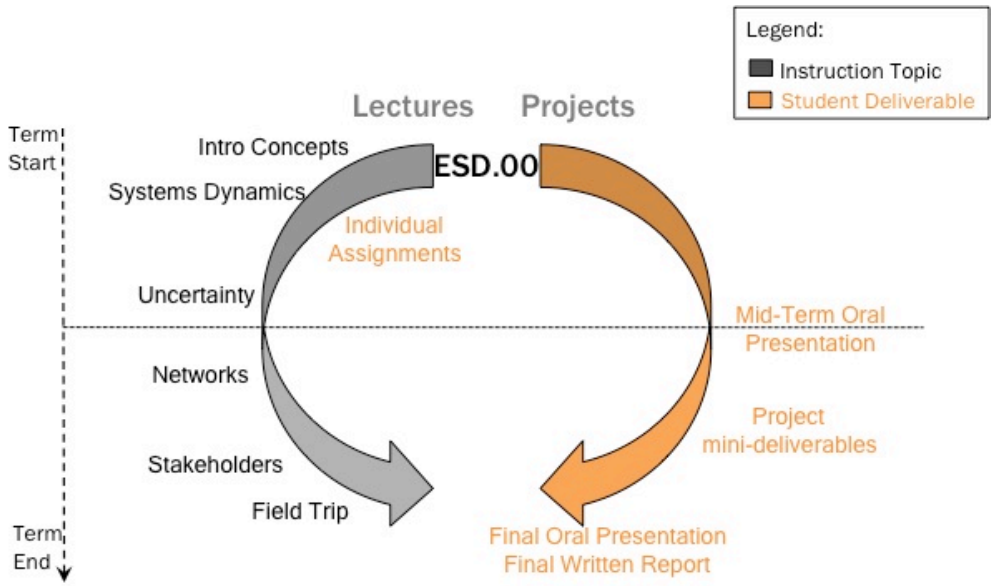

Figure 2. Two-pronged approach to course design: theoretical instruction and practical application

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, sociotechnical 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. Furthermore, there is a rich body of literature and a fair level of maturity that exists for these topics.[11,12,13] Substantive and well-grounded material, suitable for undergraduate instruction, could therefore 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.[4] 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.

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 (delivered at the beginning of the semester) and on stakeholders and evaluative complexity (delivered towards the end of the semester).[14] Near the end of the semester, one lecture session was reserved for a local field-trip to a facility relevant to the student projects.

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 real-world applications.

4. Pre-Pilot Offering of "Introduction to Engineering Systems"

In our pre-pilot offering of the course in the spring semester of 2011 at MIT, seven students completed the course, out of initially nine students who started off at the beginning of the semester. This drop rate is in the range of what we observe in other elective classes. Since this was the first time the class was offered, we wanted a small group and advertised that enrollment was limited to 12 students. In retrospect, this may have suppressed interest. The students worked on three projects on healthcare, transportation, and communication that were broadly designed and supervised by ESD faculty and engineering systems Ph.D. students. Each project touched upon a different critical contemporary issue. A brief description of each project is presented below.

4.1 Stroke Care Chain

The objective of the project (see Fig. 3a) 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, executable systems dynamics model in Vensim^{TM} (originally prepared by a team of MIT and Harvard graduate students that had conducted exploratory work on the topic).

The students focused their analysis on the state of North Carolina (Fig. 3b), 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.

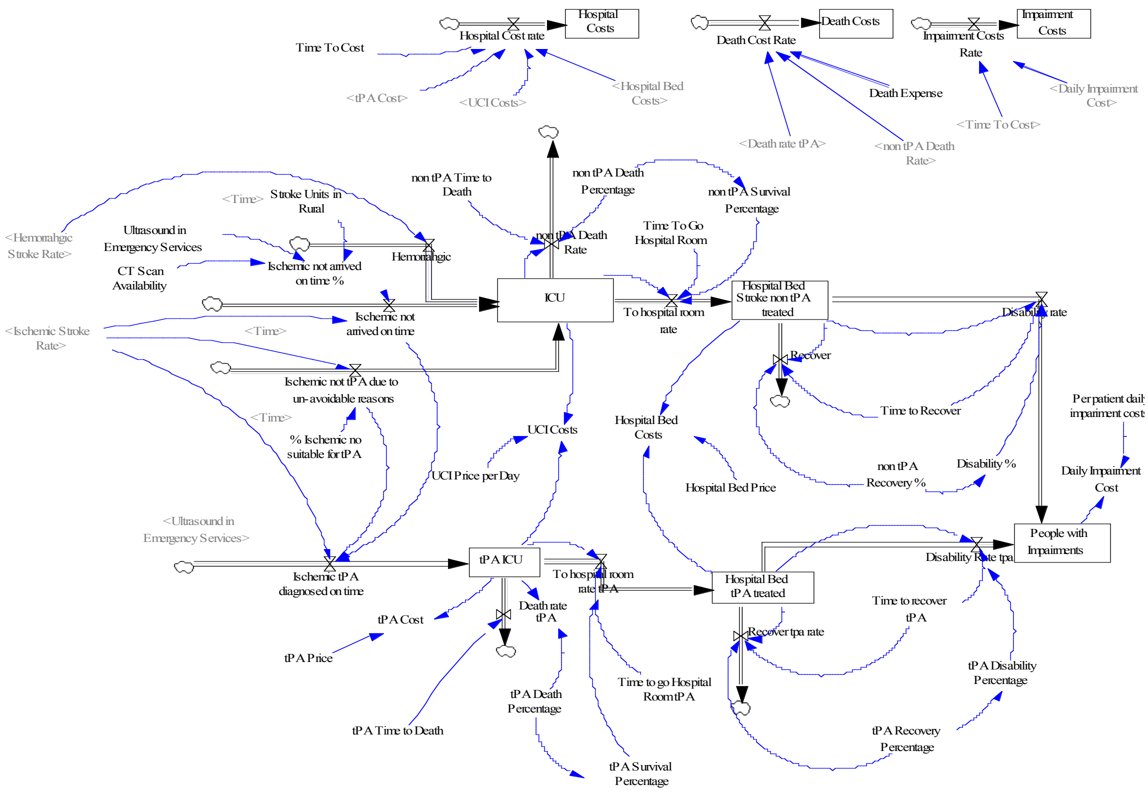

Figure 3-a. Systems Dynamics model for Stoke Care Pathway.

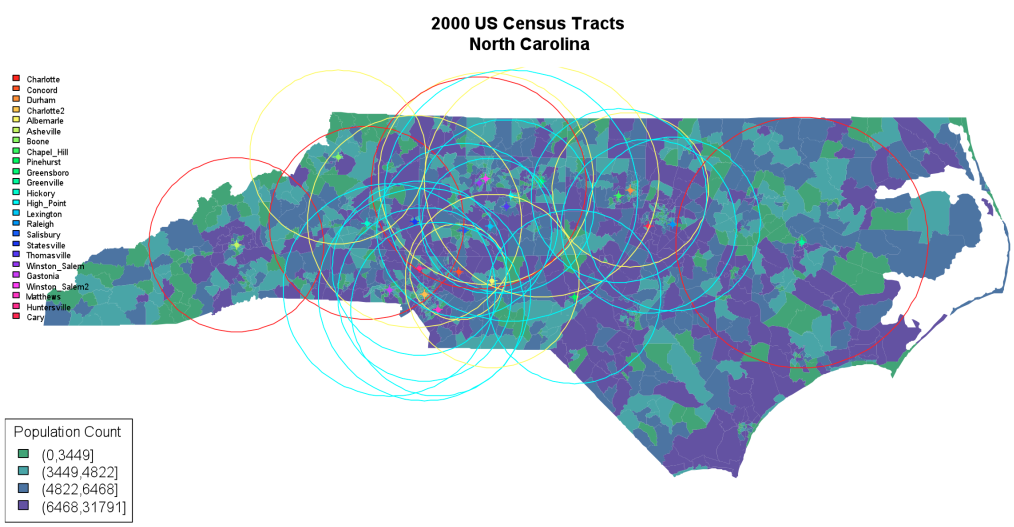

Figure 3-b. Population density in NC with overlaid stroke care center locations and 1-hour driving distance radii showing accessibility of population to urgent stroke care.

4.2 Life-cycle Assessment of High-Speed Rail (HSR) 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 CO_2 emissions of the Acela Express as compared with short-haul flights in the Northeast Corridor. (Fig 4a).

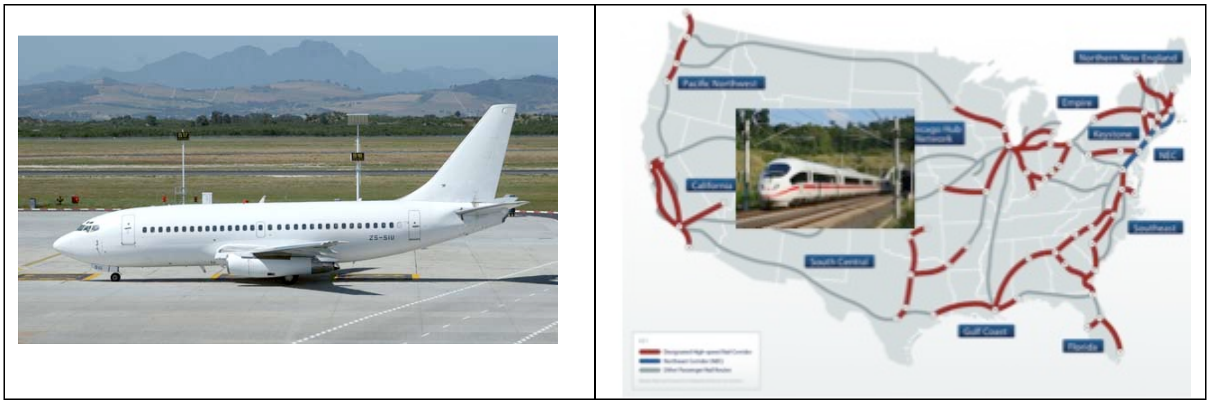

Figure 4a. Left: Boeing -737, representative aircraft for short haul flights. Right: Proposed High-Speed Rail Corridors in the US.

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. The life-cycle energy consumption and CO_2 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.

4.2 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 5a).

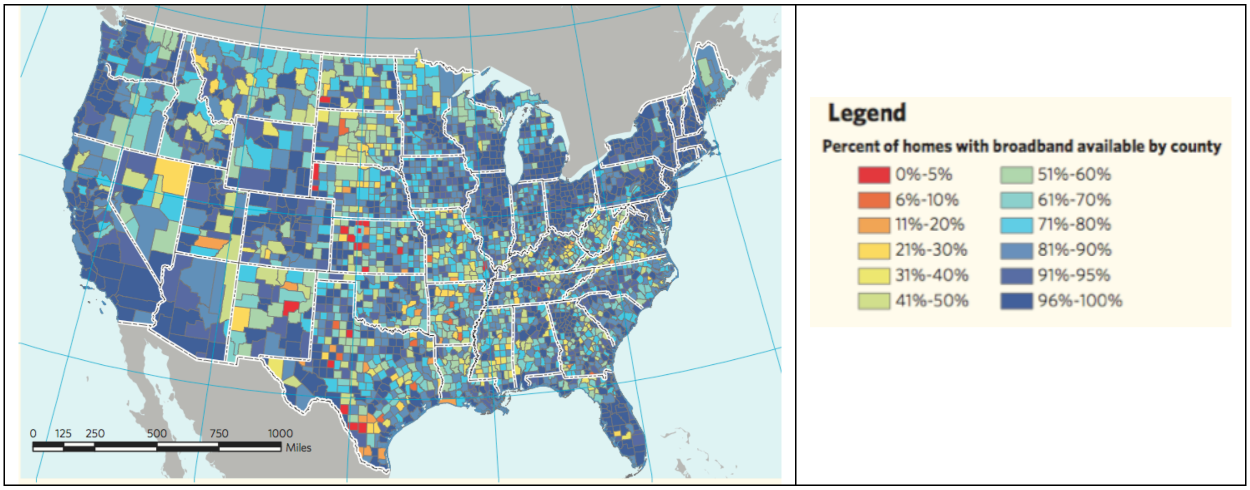

Figure 5a. Sample Analysis results for CO_2 efficiency of rail and air transport options [15]

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 5b shows sample results and causal-loop diagrams (CLDs) that were built to explain the trends.

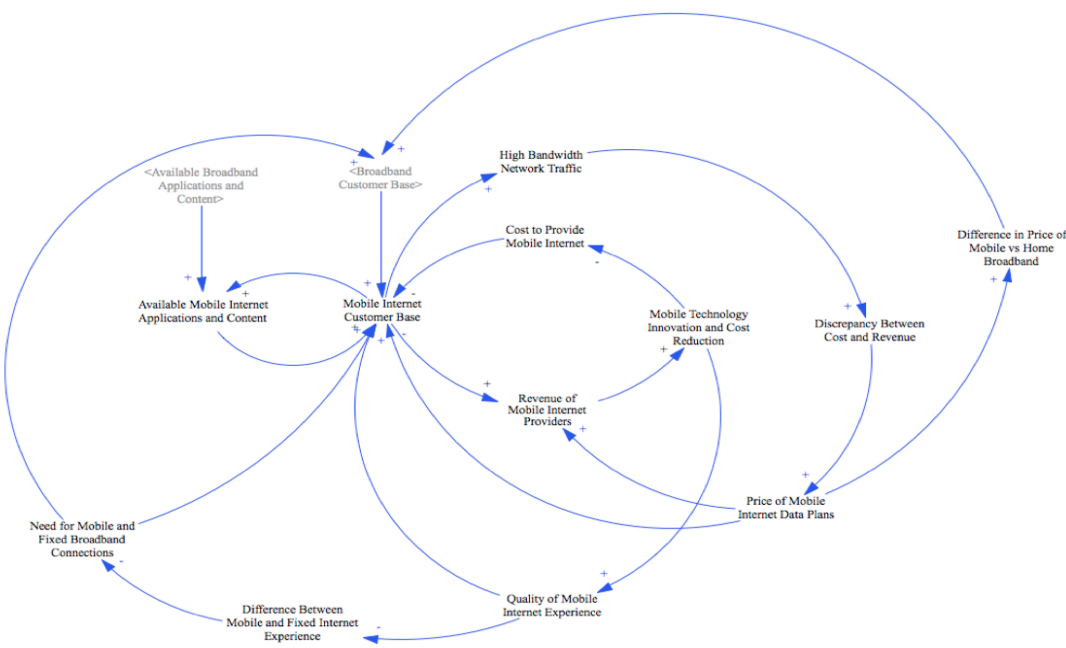

Figure 5b. Causal Loop Diagram to explain mobile vs. home broadband adoption.

5. Student Expectations and Learning Outcomes

Evaluation of the course was conducted both through a focus group at the end of the class, as well as online course evaluations (100% response rate). General feedback on the course was certainly positive, with the majority of students indicating they "strongly agreed" that they would recommend the class of other freshmen and sophomores (an average rating of 5.9 on a 7-point scale). A particularly interesting outcome of the class was several students' desire in continuing to work on their projects. Two of the seven students approached the faculty and graduate students leading class projects in order to set up subsequent undergraduate research experiences focused on the same project topics explored in the course.

Table 1 summarizes students' expectations of their learning outcomes, and the extent to which the course met their expectations. In general, students strongly agreed that they had expected to gain the experiences outlined by the instructional staff in the post-class survey (see Table 1). The effectiveness of the course in meeting their expectations was ranked even more highly, with the highest average score (6.7) associated with the project-related expectation. Perhaps more importantly, students both 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.[15]

Table 1. Student Expectations of the Course

	What were your expectations of the class?	**Average**	**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?**	**Average**	**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

6. Summary and Future Directions

The establishment of MIT's Engineering Systems Division in 1998 was motivated by the vision that future solutions for difficult problems will require inter-disciplinary approaches. Over the past 13 years, the research and education activities of the division have brought together approaches from engineering, management and social sciences to address large-scale, complex challenges in new and innovative ways. Building up from its advances in graduate-level teaching and research, ESD has increased its efforts towards making substantive and unique additions to the undergraduate engineering curricula.

Through "Introduction to Engineering Systems", we have made an initial foray into defining and establishing a new set of topics and focus that have largely been absent in engineering undergraduate curricula. In the future, we hope to establish this course as an annually offered class by ESD that is also cross-listed with other departments at MIT. Future iterations of the syllabus may add further depth to the topics that are introduced. We will also explore the possibility of enhancing the real-world awareness experience of the students through week-long domestic or possibly international trips.

A key issue that will need to be resolved in future offerings will be its scalability. For larger class size, we will revisit the current architecture (of project topics and teams) to ensure it is viable and sustainable. In the pre-pilot version, the small class size was easily served by different projects, supervised by different staff and graduate students. For larger class size (and varying level of staff resources available to the class), we will evaluate the best options for future project setups.

"Introduction to Engineering Systems" is part of a broader plan to develop over time, a larger suite of undergraduate Engineering Systems courses offered by ESD. As additional courses are developed, we expect to revise and coordinate the curriculum for ESD.00 in order to provide a well integrated learning experience to our students.

Our long-term goal is to make valuable and essential additions to an engineering curriculum, including the possibility of a minor in engineering systems, for undergraduate students of a new generation – a generation that becomes well prepared for successfully meeting the *grand challenges* of its times.

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