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Introducing Complex Sociotechnical Systems to First-and Second-Year Students

Afreen Siddiqi
Research Scientist, Engineering Systems Division,
Massachusetts Institute of Technology, Cambridge, USA,
siddiqi@mit.edu

Regina Clewlow
PhD Candidate, Engineering Systems Division,
Massachusetts Institute of Technology, Cambridge, USA,
rclewlow@mit.edu

Joseph M. Sussman
JR East Professor of Civil and Environmental Engineering and Engineering Systems,
Massachusetts Institute of Technology, Cambridge, USA,
sussman@mit.edu

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[1]Afreen Siddiqi, [2]Regina Clewlow, [3]Joseph M. Sussman

Research Scientist, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, USA, siddiqi@mit.edu[1];

PhD Candidate, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, USA, rclewlow@mit.edu[2]

JR East Professor of Civil and Environmental Engineering and Engineering Systems, Massachusetts Institute of Technology, Cambridge, USA, sussman@mit.edu[3];

Abstract

Retention of undergraduate engineering students remains a key challenge faced across the globe; in particular, the first two years of the required curriculum is often cited as a significant hurdle. Many students are attracted to engineering in order to solve important real-world problems. However, in the first two years, the majority of students find themselves in classes focused on the fundamentals of math and science, with little or no apparent connection to the real-world issues they hope to solve. Furthermore, most students traditionally develop a deep understanding in a specific engineering discipline, with limited opportunity to consider or analyze complex, sociotechnical systems (e.g. energy systems, transportation networks, healthcare) – systems that are the focus of critical engineering challenges. Although the subject of large-scale, sociotechnical systems has been successfully integrated into the realm of graduate education, it has seen limited attention in undergraduate studies where it has the potential to inspire and retain the next generation of engineers.

This paper describes the development and implementation of a novel course, intended for freshmen and sophomores, that has been designed to address some of the needs of a new generation of students who are passionate and more engaged 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 of 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 projects that span the semester. Through this approach, we enable students to engage in and understand the issues related to an engineering challenge of their interest, appreciate the scope of the sociotechnical complexities in CCIs, and gain an introduction to analytical tools that can help address some of these challenges. This paper discusses the overall philosophy and motivation for establishing the course, the design of the curriculum, and the approach, execution, and integration of team-based projects.

1. Introduction

Many students are attracted to engineering in order to solve important real-world problems. However, during the first two years, the majority of students find themselves in classes 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 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, healthcare) – systems that are the focus of critical engineering challenges.

Many of our most interesting, complex engineering challenges no longer fit into the neat silos of academic disciplines – they are interdisciplinary and require *systems thinking*. The level of interactions and complexity in modern systems requires a new level of expertise and trans-disciplinary perspectives that perhaps was 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 ever more important for even young engineers (not just senior practitioners) to obtain such skills. Charles Vest, President of the National Academy of Engineering, notes, "Engineering education in the 21st century will need to be redefined and reinvented if it is to successfully meet the grand challenges of sustainability, health and security…" [1].

While the need for updating and improving engineering curriculum is increasingly recognized [4], change has been slow, in particular at the undergraduate level. 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 analyzing these challenges. The development of analytical skills for studying such problems has been largely developed in 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 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 on a pre-pilot basis by the Engineering Systems Division (ESD) at the Massachusetts Institute of Technology (MIT) in the spring semester of 2011 [5]. Intended for first and second year students, 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 of 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 sociotechnical 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, and plans regarding its future scalability and improvement.

2. Motivation

The motivation for developing and offering this course stems from a broader vision of ESD at MIT [6], in which it is recognized that future engineering leaders should not just possess knowledge and expertise of devices and artifacts 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 [2]. 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 inter-twined, complex engineered systems. 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, we have conducted these efforts mostly at the graduate level, and a strong student response and interest in our programs indicates a good measure of success (see Fig. 1).

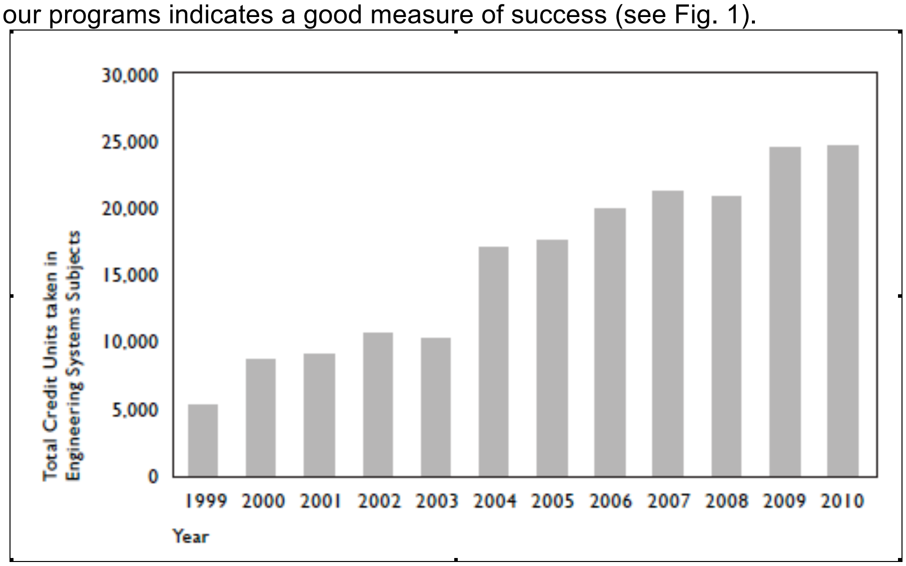

Figure 1: Student enrollment in ESD at MIT [3].

Building from our experience and success at the graduate level, we aim to extend this endeavor to undergraduate classes, as well as potential undergraduate experiences outside the classroom. In some ways it is perhaps more important at the undergraduate level since some 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 [7].

Traditionally, engineering education has focused on systems where the boundaries encompassed metal, 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 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 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.

3. Design of ESD.00

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 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.

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 [8-10]. A 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 [8]. 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.

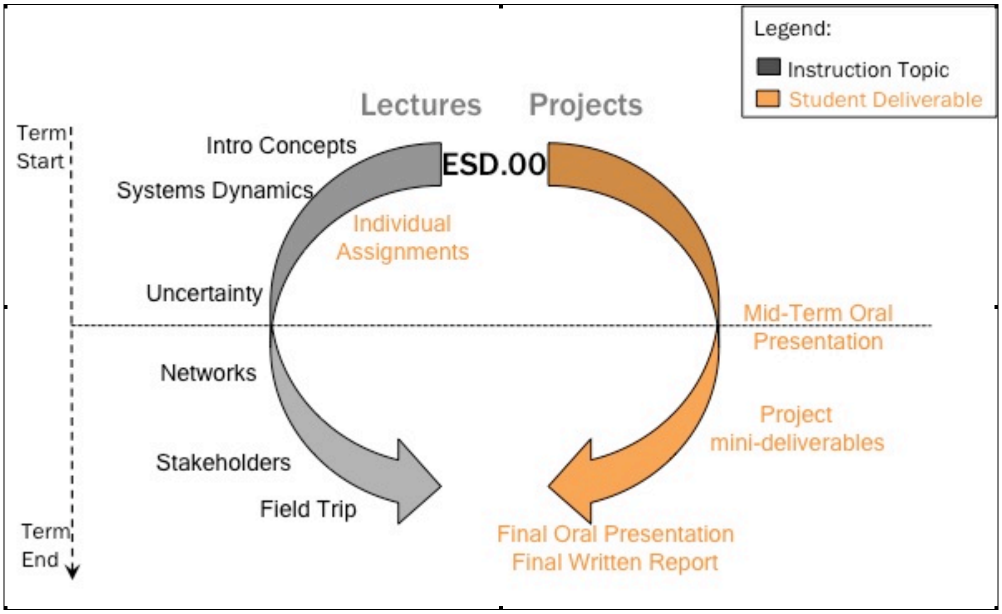

Fig. 2: Two-pronged approach for ESD.00 – theoretical instruction and practical application

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 (delivered at the beginning of the semester) and on stakeholders and evaluative complexity (delivered towards the end of the semester) [11]. 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.

A detailed description of the course and the syllabus can be accessed at [5]. The class materials will also become available through MIT's open course ware (OCW) website [12].

4. Pre-Pilot Offering of ESD.00

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, we think 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 senior graduate 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).

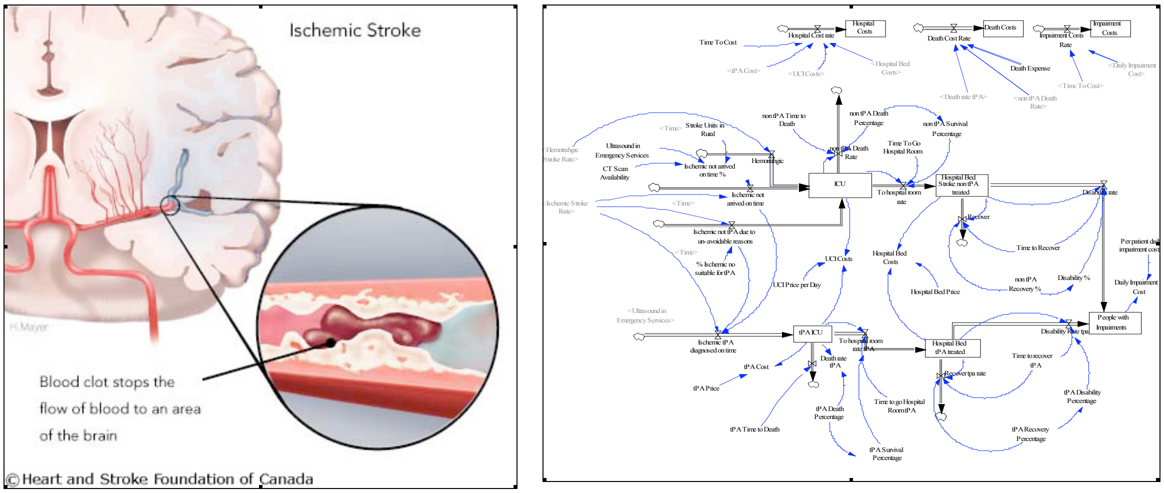

Figure 3-a: Left – Ischemic Stroke in the Brain, Right – Systems Dynamics model for Stoke Care Pathway [5]

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.

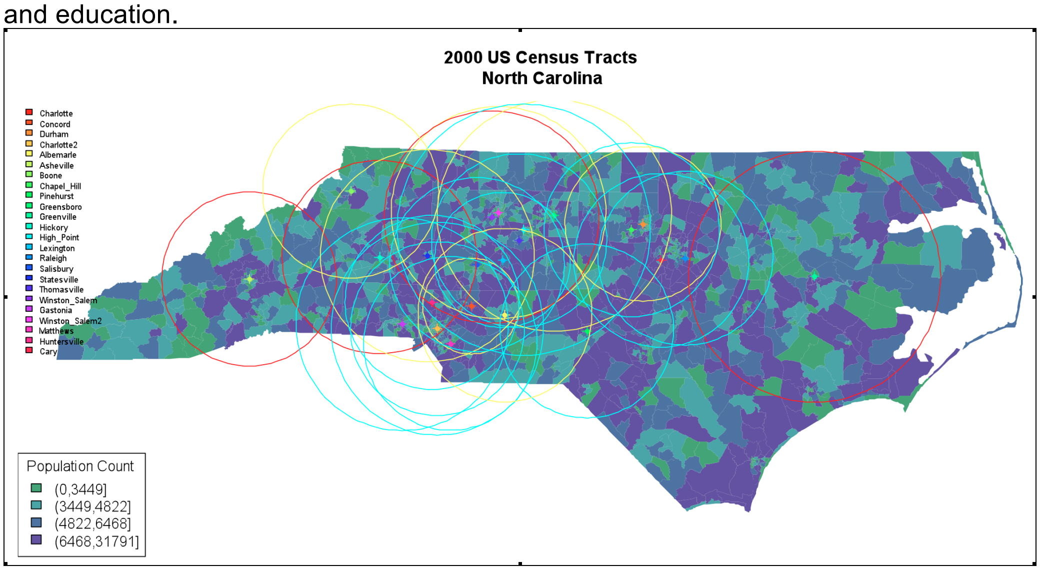

Figure 3-b: Population density in NC with overlaid stroke care center locations and 1-hour driving distance radii (incorporating urban and rural traffic conditions) showing accessibility of population to urgent stroke care [13]

4.2 High-Speed Rail (HSR) and Air Transport Systems Comparison

This project focused on examining environmental impact tradeoffs between high-speed rail and air transportation in the US Northeast Corridor. The primary question that was investigated was whether high-speed rail (traveling greater than 125 miles per hour) is a more energy and carbon efficient alternative (as compared to air transport) in the Northeast Corridor (Fig 4a).

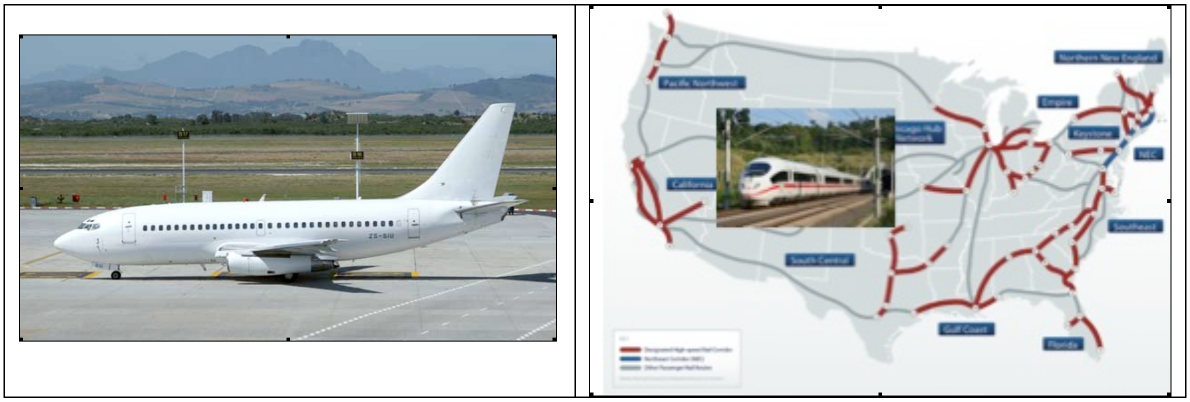

Figure 4a. Left – Boeing -737, used for short haul flights, Right – Proposed High-Speed Rail Corridors in the US [14]

The team examined future projections of demand for both modes of transportation, and then analyzed the associated CO_2 emissions of that travel demand as well as emissions associated with air and rail infrastructure in the region (see Fig. 4b).

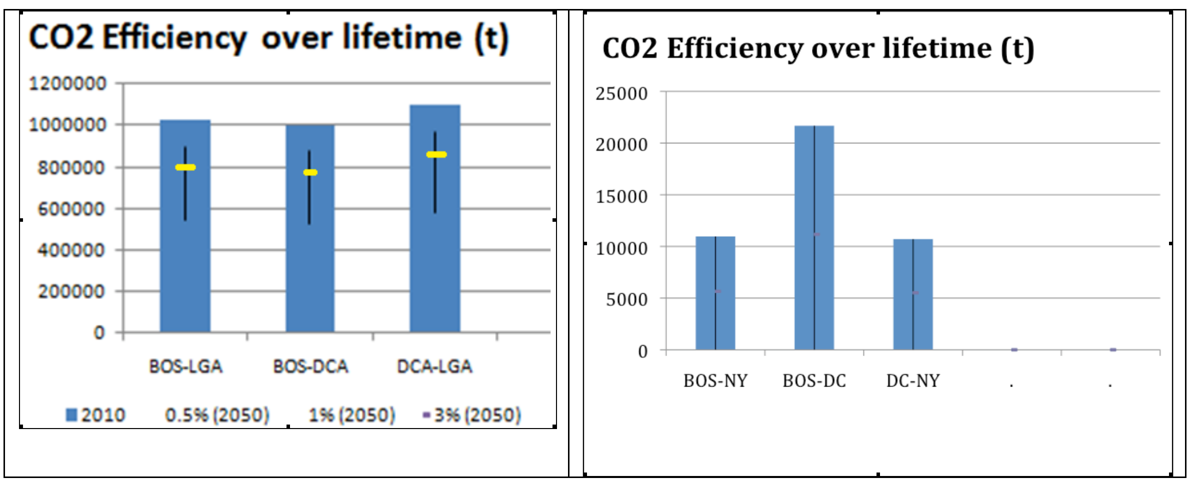

Figure 4b. Sample Analysis results for CO_2 efficiency of rail and air transport options [14]

4.4 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).

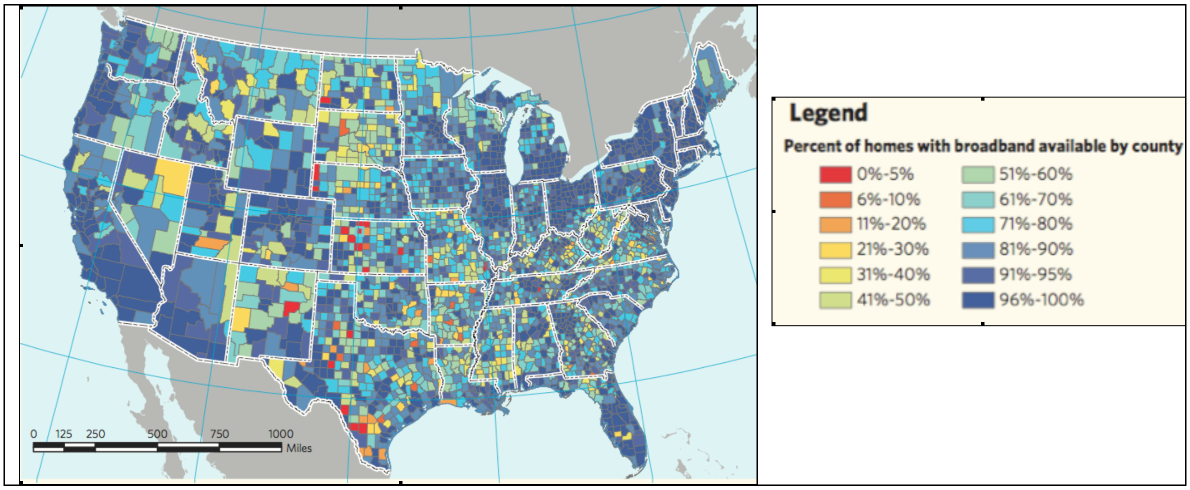

Figure 5a. Sample Analysis results for CO_2 efficiency of rail and air transport options [15]

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.

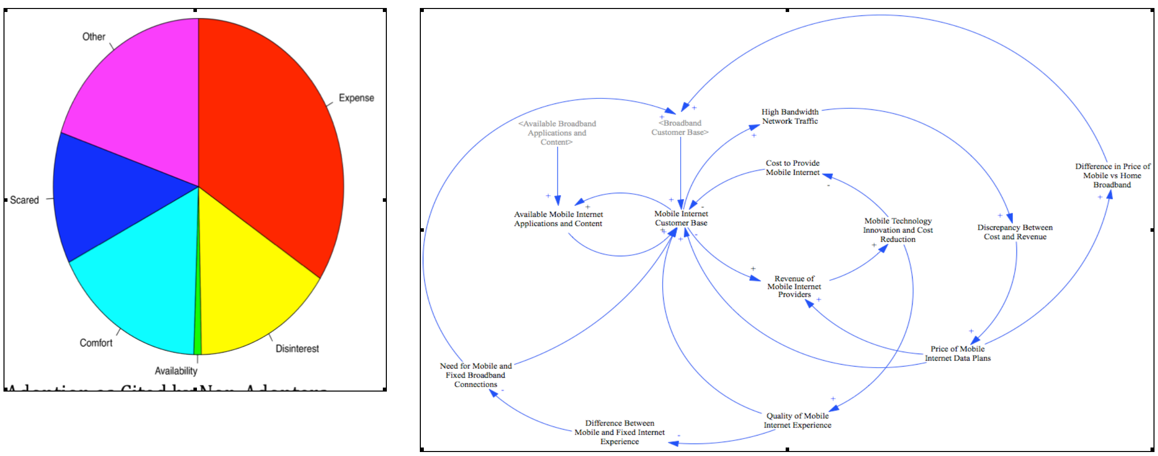

Figure 5b: Left – Top barriers to adoption as cited by non-adopters, Right – Causal Loop Diagram to explain mobile vs home broadband adoption [15].

Note to the reader: As this is being written, the semester has just ended. We are grading the term projects and await the formal feedback that students routinely provide. Our sense is that the students had a positive experience and certainly we did. But we will report soon more formally.

5. Summary and Future Directions

The establishment of MIT's Engineering Systems Division (ESD) 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 ESD.00, 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 departments at MIT. Future iterations of the syllabus may add further depth to the topics that are introduced (by turning this course into a 12-unit class as opposed to a 9-unit class as it was initially offered). 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.

ESD.00 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 major in engineering systems, for undergraduate students of a new generation – a generation that becomes well prepared for successfully meeting the *grand challenges* [16] of its times.

6. Acknowledgements

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