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Integrating Engineering Systems Research and Undergraduate Education Through A Term-Length Case Study

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Introduction

The MIT-Portugal Program (MPP) was launched in 2007 with the dual objectives of conducting innovative research and establishing leading academic degree programs through international collaboration across a range of technical disciplines. Among the first attempts to integrate the research and teaching objectives of the MPP was the Spring 2009 offering of *Engineering System Design*, a required course for third- and fourth-year undergraduates in MIT's Department of Civil and Environmental Engineering. The course employed a semester-long case study, drawing heavily on active MPP transportation and engineering systems research for teaching and assignment content.

On the research side, MIT has been engaged with partner universities and agencies in Portugal on a variety of topics related to high-speed rail (HSR). These varied efforts demand a unifying engineering systems framework to ensure that the research delivered provides maximal value both individually and as part of a broader program. The integrating engineering systems framework chosen (Complex, Large-Scale, Interconnected, Open, Socio-technical, or CLIOS Process) was taught in *Engineering System Design* and applied using an active research program as the case study context.

After presenting the MPP and HSR research contexts, this paper summarizes the methodology used to implement the CLIOS Process in a classroom setting through an evolving, term-length group project that involved teaching and supervision by faculty and researchers. Next, the paper discusses the challenges of teaching engineering systems concepts to undergraduates, incorporating active research into a classroom setting, and managing large project groups. Finally, the paper summarizes the lessons learned from the course as well as prospects for future applications of engineering systems research in the classroom. It is hoped that those interested in designing undergraduate courses in engineering systems will benefit from the course's lessons learned, both positive and negative, as summarized here.

Background

MIT-Portugal Program High-Speed Rail Research. The MIT-Portugal Program brings together students, faculty, and researchers from MIT and several Portuguese universities to engage in research and teaching that have great promise in general and for Portugal in particular. High on the research agenda as well as the policy agenda for Portugal were questions about transportation systems including HSR.

Development of a HSR system has been under serious consideration in Portugal since the turn of the 21st century. Seen as an opportunity to improve intercity passenger transportation (and possibly freight transportation), if it comes to fruition, HSR will be a complex and expensive system capable of enhancing mobility and generating economic growth. There are also environmental and energy considerations, and HSR offers opportunities for economic integration with the European Union, which has agreed to fund a portion of the system. Still, one must consider whether this is the best way for Portugal to spend the considerable sum of money required to implement HSR, given the needs for other transportation enhancements, as well as investment needs in other sectors.

Recognizing the various challenges presented by a complex undertaking such as HSR, there are several active MPP research projects investigating such varied topics as life-cycle costing for rail

systems, construction safety, tunneling techniques, rail system financing, demand and revenue forecasting, passenger-freight integration, multi-modal competition and cooperation, strategic system decision-making, and economic and land development impacts at the urban and mega-region scales.

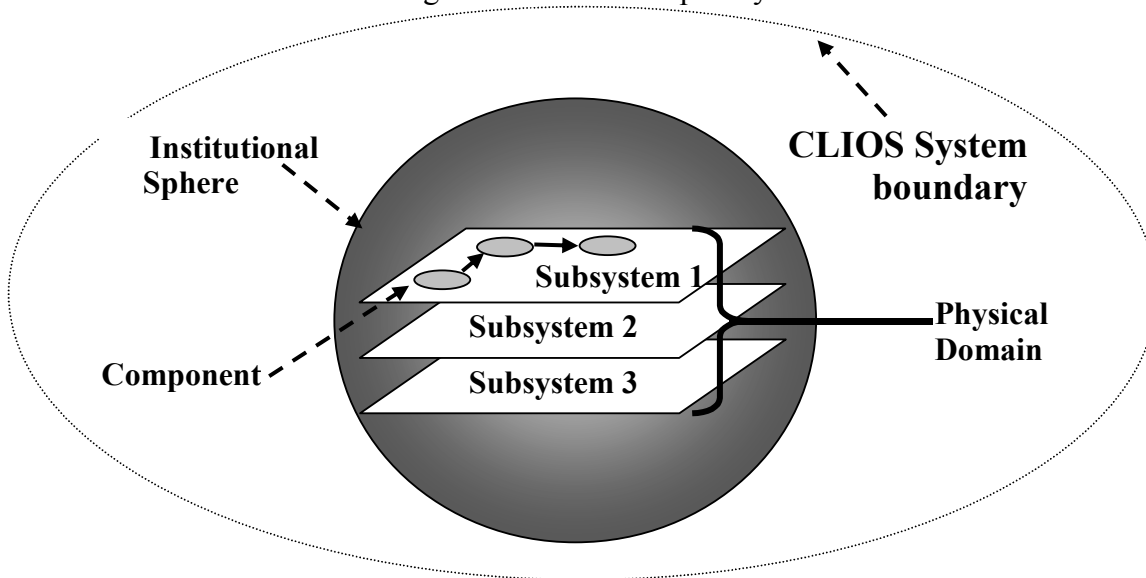
In order to serve as a useful teaching tool as well as a useful input to real policy and technical decisions in Portugal, these varied research efforts demanded a unifying engineering systems framework. The CLIOS Process was chosen as the integrating engineering systems framework. The rather ambitious challenge made to the students was to design at a relatively macro-level, using the CLIOS Process as well as inputs from active research and guidance from active researchers, a complete HSR system for Portugal (excluding detailed design of infrastructure elements and focusing more on the network level).

CLIOS Process. Although engineering systems and systems thinking have been around for several decades, they continue to evolve and provide new insights into system behavior, which is often counter-intuitive and difficult to predict. There is an expansive literature capturing advances made with regards to systems thinking, all providing reasonable frameworks for understanding and approaching large transport problems like those tackled by the course (see, e.g., 1, 2, 3, 4). For the course at hand, the CLIOS Process was chosen because it is accessible, familiar, and has been previously tested using examples from the transportation field, which was particularly useful for the subject being taught (5).

The CLIOS Process has been developed and refined by researchers at MIT and has proven its value in a number of applications in transportation as well as in other sectors dating back over 10 years.¹ For example, CLIOS has been applied to develop policies for mitigating the impact of the transport sector on air quality in Mexico City, to evaluate public-private partnerships for toll roads in Malaysia, to incorporate stakeholder input into the controversial Cape Wind energy project in Nantucket Sound, Massachusetts and to design a broadband access systems for the nation of Kenya.

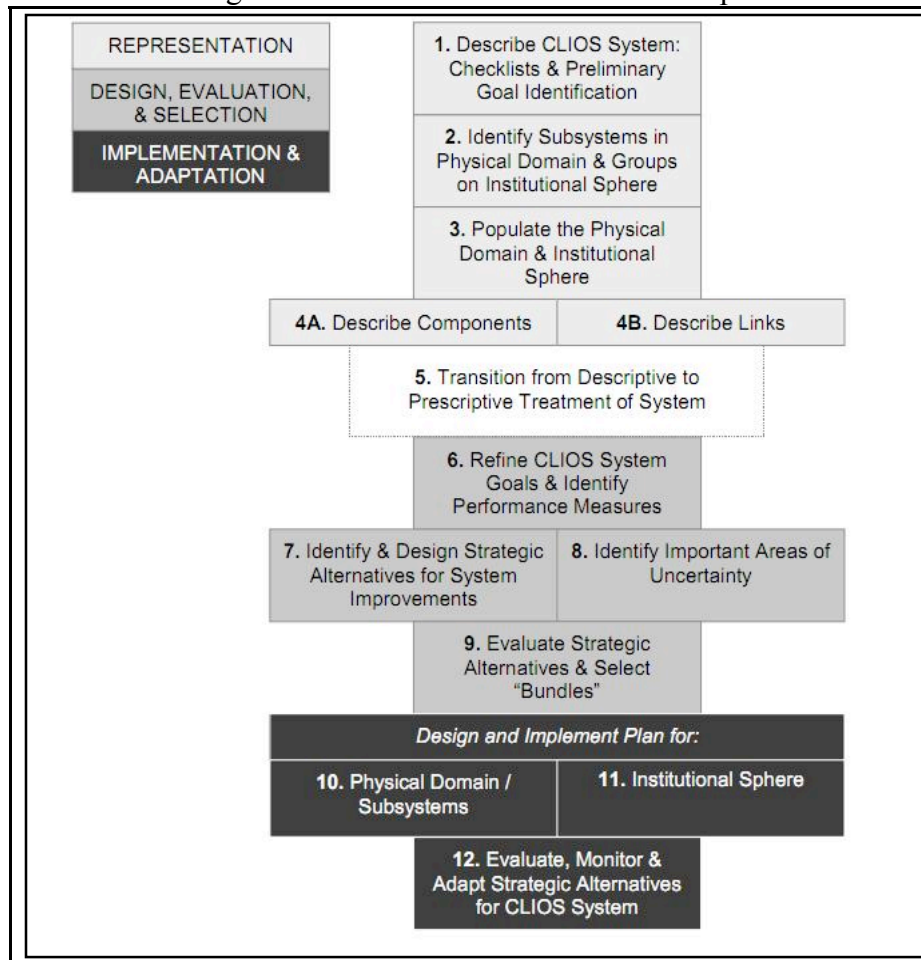
The hallmark of a CLIOS System is *nested complexity*, as illustrated by Figure 1. Nested complexity refers to the complex interactions between physical and institutional systems. The various organizations involved in a CLIOS System are represented as points resting on a sphere. The physical domain is represented as planes within the sphere. Interactions exist within physical subsystems, between subsystems, between organizations, and between organizations and subsystems.

Figure 1: Nested Complexity



The CLIOS Process is an approach for representing, evaluating, and implementing changes to a CLIOS System as illustrated by Figure 2. The 3 phases of the CLIOS Process can be further broken down into 12 steps as follows: representation phase (steps 1-4), evaluation phase (steps 5-9), and implementation phase (steps 10-12). The steps are deliberately non-prescriptive in that they allow for the adaptation and application of a wide range of descriptive, analytical, and other technical tools and approaches.

Figure 2: CLIOS Process Phases and Steps



In the course, students were taught the CLIOS Process and asked to conduct the representation and evaluation phases, leading to a detailed design of a system solution for HSR in Portugal.

Engineering System Design Course Description. *Engineering System Design* teaches systems thinking through a semester-long system design project, conducted in a complex technical environment and challenging societal context.

Through lectures and recitation exercises, the course teaches systems thinking as well as how one goes about conceiving and approaching complex system design problems. The learning objectives of the course, as presented to the students, are summarized as follows:

- Systems thinking: learning to use systems thinking as an integrative holistic approach to problem solving.
- Abstracting: learning how to abstract and represent complex technical systems through quantitative models and/or qualitative frameworks.
- Designing: learning to make good choices among alternatives using the models and frameworks developed in Abstracting as a fundamental part of engineering.
- Stakeholders: learning to identify the key system stakeholders and how to balance their diverse interests.
- Groups: learning to work in small groups in an efficient, effective and equitable manner.

- Teams: learning to integrate the work of various groups into an integrated team project.
- Presentation: improving oral presentation skills.

Although the objectives remained unchanged from previous years, instructors radically redesigned the course for the Spring 2009 semester by updating the term project from the previous topic (transportation of spent nuclear fuel) to HSR in Portugal. This shift was motivated by the timeliness of HSR as a topic as well as the availability of an extensive research effort on HSR in parallel and in collaboration with Portugal from which it was hoped the students could benefit. This decision to incorporate active research projects into classroom teaching and student assignments required additional research to obtain, synthesize, and present both domain expertise and the data necessary for the students to carry out the term project.

The objective for the students was to apply systems thinking through the CLIOS Process in the design of a HSR system for Portugal. This was achieved through five project-related deliverables. Each of the deliverables was produced by groups of varying sizes, which required collaboration among the students and challenged them to develop designs that incorporated diverse points of view. The five deliverables are briefly described below:

- Assignment 1: The first project assignment asked the students to take a high-level view of the transportation problem in Portugal and consider six alternative solutions ranging from “no change” to constructing new highways, to building HSR, to building a Mag-Lev rail network. The students were asked to recommend through analysis which high-level alternative the country should pursue. In the end, instructors chose HSR as the preferred, albeit predestined, alternative.
- Assignment 2: The second project assignment involved the application of the CLIOS process to the intercity transportation system in Portugal, specifically focusing on the Representation phase. Students diagrammatically represented the institutional sphere as well as physical subsystems of the transportation system, with a specific focus on HSR and its implications.
- Assignment 3: The third assignment asked students to apply the second phase (design, evaluation and selection) of the CLIOS process. They specified goals and performance measures for the HSR system, developed strategic alternatives for it based on these goals (six in total), and grouped them into two distinct bundles. They also identified risks and uncertainties in their designs.
- Assignment 4: The fourth assignment involved a “down-select” from the bundles of strategic alternatives developed by the students using an evaluative framework also developed by them. At this stage the students were working in two teams of 15 members each, which required a high level of coordination and collaboration. A competitive element was introduced with the two teams competing to produce the better design. The evaluative frameworks, as well as the result of their application to select a bundle for final design were presented through a brief memorandum and oral presentations.
- Assignment 5: The final and most extensive assignment asked the students to use their selected bundle as an input and divide into five working groups within each team of 15 members. The five working groups consisted of three students focused on analyzing and designing one of each of the following: HSR network configuration/infrastructure (alignment), operations, construction, organizational support (including finance and marketing), and demand forecasting. A sixth group composed of one representative from each of the five groups coordinated activities across all areas. This assignment led to the completion of a final report and presentation for each of the two teams. In support of the final assignment, domain expertise was provided to each of the groups through a series of workshops where guest lecturers participated. Project resources to assist with the final design included data, access to researchers, and teaching notes.

Outcomes: Innovations in Engineering Systems Teaching

Instructors and students together encountered and worked to overcome several challenges in the course of the semester that, in retrospect, could be classified as innovations in engineering systems teaching. These are summarized below.

Teaching engineering systems concepts through a hands-on, research-oriented term-long mega-project. The project-based approach presented a number of real-world engineering systems challenges for students. The design challenge presented in the course cannot be solved through application of a straightforward, analytical, or repeatable methodology or mathematical process. Instead, the complexity of the problem of designing an entire HSR system necessarily results in interactions between system components that are often non-intuitive and rarely “solvable” with a single answer. A highway interchange or water treatment facility design problem, for example, can be presented with sufficient constraints that only one or several solutions are available and obtainable using the traditional tools taught in undergraduate engineering courses. By contrast, designing an HSR system leaves open an extremely large solution space, which requires students to combine analytical approaches with creative systems thinking about feedback loops, multi-criteria objectives, and policy implications of their designs. In this regard, the selection of HSR as a term design project successfully demonstrated the principles and challenges of engineering systems that separate it from traditional engineering problems.

Incorporation of active research in the undergraduate classroom. Another innovation of this course was the incorporation of elements of an active research agenda into the term project. Students were asked to address ongoing research questions in their system design, including application of innovative methodologies and justification of final recommendations. For example, one active research project sought to develop a new approach for examining the relative advantages and disadvantages of using HSR for freight in Portugal. Students were likewise asked to consider whether and to what extent their system design would incorporate freight on HSR and, by extension, asked to develop and justify a methodology for their answers. Another example relates to the requirement that students outline the funding sources and accompanying financing strategy. At the same time, a research project was underway investigating innovative approaches to funding and financing HSR. Students were exposed to this research material and were able to criticize it, revise it, and incorporate it into their final designs.

Large student project teams. Instructors considered several alternative strategies for the students before settling on the large team approach, which called for two teams of 15 students in the final project phase. This approach was risky for several reasons. First, given the many commitments of students, coordination across 15 team members for working sessions and other meetings would be difficult to achieve. Secondly, having only two teams meant that the students would create only two system designs, which would make evaluation difficult. Finally, it could be difficult to evaluate individual student performance in such a large team setting. Although students were evaluated through several individual assignments and exams, a substantial portion of their grades was derived from their team’s performance on the project, so mechanisms had to be included which made individual performance distinguishable from group performance. These trade-offs should be considered in designing student project teaming arrangements. Some recommendations are presented in the next section, including how to mitigate some of the potentially negative effects of the large team approach.

Lessons Learned and Recommendations

Based on the experience of *Engineering System Design*, several lessons were learned. Below is a summary of recommendations for instructors interested in pursuing any of the aspects of the

course described above: teaching engineering systems concepts, incorporating active research into the undergraduate classroom, and using large project teams. A final set of recommendations is offered for adapting these ideas to a graduate-level course.

Teaching Engineering Systems Concepts to Undergraduates. The typical undergraduate engineering curriculum teaches quantitative tools and skills, bringing together tools of mathematics and hard sciences to solve challenging design and other technical problems. Engineering systems can be thought of as a collection of engineering problems solved simultaneously. The traditional tools of engineering may be sufficient for solving the individual engineering problems, but they do not address the complex interactions and behaviors observed across problems. Teaching and practicing the tools of engineering systems, itself an emerging field, represents a special challenge in an undergraduate setting. Four lessons learned include the importance of an overarching engineering systems framework, the challenge of communicating the benefits of systems thinking, the value of project-based learning, and the need to balance ambiguity with guidance.

Overarching framework. Perhaps the most instructive lesson of *Engineering System Design* is recognizing the importance of using an overarching framework to guide the teaching of engineering systems and any related project work. The CLIOS Process was chosen for this course, but other methodologies exist and can be selected. The key is to give order to the “chaos” of complex engineering systems problems. Although no single framework is necessarily correct or incorrect, students benefitted from viewing and designing a complex system using a structured approach.

Communicating the value of systems thinking. Nevertheless, student evaluations do point to a gap between perceived and actual learning in the class, particularly with regards to the value of an overarching framework and more conceptual but nevertheless systematic qualitative approaches. In course evaluations, one student wrote, “This was a great class to zoom in and out and see CEE (civil and environmental engineering) in context. I am not sure how much I actually learned, though.” Two causes might underlie this gap. First, many of the approaches within CLIOS can seem like common sense at the outset. For example, undergraduates already have a degree of intuition regarding the importance of stakeholders in design. Less clear is the value-add offered by more systematic approaches—the Mitchell stakeholder salience framework (6), for example—over and above what might be intuitively obvious. This (at least initial) gap is obvious in the following comment: “Although most things seemed intuitive at first, it was interesting to know there are systematic steps/algorithms for going through problem solutions.”

The second cause is highlighted by yet another student comment on the contents of the course: “Too much qualitative stuff.” Within traditional engineering education systematic thinking automatically implies quantitative methodology. Approaches like CLIOS, on the other hand, make the argument that an approach can be both qualitative *and* systematic in its implementation. The newness of this idea may make both the concept and the benefits of systems approaches harder to grasp. That is, even though students are indeed learning by doing, the newness of engineering systems creates a gap between perceived and actual learning. In the future, educators might focus not only on simulating the design of a complex system but also on emphasizing how specific systems methodologies can be used to tame the “chaos” and generate non-intuitive insights. Successful communication of goals and benefits would ensure that students not only learn through experience but also achieve the second level of reflection needed to recognize what they learn and carry it forward.

Term project. The most effective tool for making engineering systems thinking less abstract was the term project. Using a term project provides context that helps students learn to recognize systems and systems behavior and to apply engineering systems evaluation and design tools. Systems thinking is inherently process-based. In this course, it is not so much the diagrams

themselves as the process of creating them that creates learning and insight. As Edward Tufte said, “The act of arranging information becomes an act of insight.” Future iterations of this class would benefit from devoting even greater time and resources to the term project, with less time devoted to theory alone. One student said, “The project was the best part of the class, but it started too late.” We certainly concur.

The selection of the particular project is also critical. Many students have relatively narrow interests by their third and fourth years as undergraduates. For example, in Civil and Environmental Engineering, students may have selected a specialty in structures, geotechnical, water resources, transportation, or another area. Selecting a project that is overly focused on any one discipline inhibits learning in many students. Although HSR is a decidedly transport-focused project, it contains sufficient richness to attract students from other specialty areas, including planning, economics, solid mechanics and others.

Balancing ambiguity. The course could have been improved by better balancing Result Ambiguity and Process Ambiguity. Result ambiguity can be thought of as the deliberate absence of a concrete final state for a particular project, in this case the “optimal” design of a HSR system and its components for Portugal. Students were faced with open-ended and interconnected design problems, with no particular end-point to their task except their reliance on their own decision-making processes. This aspect was positive in that it allowed students to apply skills learned in other courses to reach a conclusion, testing the soundness of the logical process in which they reached their final designs rather than the specific aspects that make the final design.

On the other hand, based on student feedback, Process Ambiguity seemed to detract from the class. Process Ambiguity refers to the lack of clarity in outlining a path of discrete tasks for the students to perform in pursuit of a final outcome or objective. Regardless of the openness of the result, students noted that untimely sharing of information as well as overly frequent changes in group size led to additional difficulties in meeting deadlines. This aspect can be ameliorated in future applications of complex group exercises by having a clear project management structure required of the staff and student groups and matching project input needs with the material provided by the course instructors.

Finally, although students ultimately were able to overcome ambiguity to develop complete designs, many felt uncomfortable doing so because of a lack of understanding of the reasons or implications of their design choices. For example, the interactions among the demand forecasting, HSR network connectivity, and operations were exceedingly challenging to manage. In this regard, some Process and Result constraints could have benefited the students’ efforts without sacrificing their ability to see firsthand and understand the notion of trade-offs, feedback loops, and uncertainty in a complex system environment.

Incorporation of Active Research into the Undergraduate Classroom. Incorporating elements of an active research project into the classroom carries risks as well as rewards. Students were able to hear perspectives of researchers, expanding their exposure beyond the typical lecture format. They were also challenged by advanced research concepts. However, the inevitable uncertainties and unknowns of active research are difficult to translate well into a classroom setting and must be managed.

One of the most positive outcomes of incorporating HSR research into the class project was the ability to tap researchers to participate in lectures and project work with the students, including two teaching assistants both of whom were engaged in research on HSR or similar topics, three HSR researchers who volunteered to mentor the project teams, visiting doctoral student Diana Leal (from the University of Coimbra in Portugal) who served as the in-house expert on Portuguese culture and attitudes towards high-speed rail, two guest lectures from the MIT

faculty, and one guest lecturer from a partner university in Portugal. The incorporation of research into the classroom was exciting to all of these individuals, attracting their attention and ultimately their participation—perhaps the most beneficial and enriching “unintended consequence” for students.

Fortunately, given the existence of MPP, instructors were able to access a large amount of data from the research activities and furnish it to students. This proved invaluable to students in conducting their project work. However, given that much of the data was in raw format and not yet well organized, students would have benefited from a more structured, organized provision of data (see Process Ambiguity above). While a ubiquitous challenge of research is data collection, organization, and management, these tasks are not central to the teaching of engineering systems and detracted from the students’ ability to focus their efforts on project work.

Large Groups for Term Project Work. The utilization of large groups in the course was borne of necessity but resulted in both benefits and lessons learned. First, group size should be carefully managed (see Process Ambiguity above). Although for the final design phase of the class each team had 15 students, these teams were broken into more manageable 3-member working groups. The size of the overall teams enabled students to achieve a level of depth in expertise suited to supporting meaningful systems thinking. It is essential for instructors to anticipate and manage the level of collaboration required of these various group arrangements. A common complaint was that, like a complex system, the extra-large teams required an unexpectedly large amount of collaboration both in and out of class that was impractical for many students. One area in which the course could have improved is in this anticipation and management; instructors should be realistic about the time and effort required to collaborate on class projects and reduce group sizes and collaboration points as necessary. In parallel, instructors can set explicit collaboration expectations or limits to help students achieve an instructive level of collaboration without committing a disproportionate amount of resources to it. Internally within their groups, students might benefit from diagramming the interrelationships between design decisions and then setting internal deadlines to manage simultaneity of design.

Another issue that commonly arises is unequal levels of participation by team members within groups. Students should be encouraged to report this as early as possible, and instructors should be sensitive to groups where the contributions of one or two members lag. Too often, students wait until near the end of the project or the semester to report such problems, so instructors should be proactive about identifying and correcting these problems before they negatively impact overall group performance.

Potential Applications in Graduate Classrooms. Engineering systems, both the concepts and the application, are just as relevant to teach in a graduate setting. However, a few distinctions should be made between the undergraduate and graduate levels. First, the level of ambiguity should be higher in a graduate setting than in an undergraduate setting. The “ambiguity-guidance” balance discussed earlier should lean heavier toward ambiguity, allowing the students to develop techniques for analyzing and understanding complex aspects of the system.

Secondly, the “connections” between system elements should be more heavily emphasized at the graduate level. For undergraduates, teaching and attaining facility with particular design elements should be emphasized, while approaching the “complex systems” aspect (connections between components) in a more introductory fashion, to expose students to the concept and challenges. For graduate students, on the other hand, the emphasis should be on the connections, as we would expect they already have facility with the more straightforward approach to detailed design of a particular component.

Conclusions

Engineering systems is an emerging field that requires methodologies that connect across traditional engineering disciplines. Teaching engineering systems at the undergraduate level represents a challenge for instructors because it introduces complexity as a topic and asks students to abandon traditional thinking and analytical approaches to solving problems in favor of systems thinking and multi-disciplinary approaches to solving problems.

This paper has summarized the objectives and assignments of an undergraduate course in engineering systems. The course sought to address the challenges of teaching engineering systems by incorporating ongoing research activities and a contemporary real-world engineering systems project into the curriculum, asking students to participate in the analysis, evaluation, and design of an innovative solution, all in a large-group setting.

The challenges encountered in the design and execution of this course also constitute opportunities for others to learn lessons from the experience. Ultimately, the decisions to incorporate research into a term project on HSR were positive ones. Selection of a project with broad appeal supported by an overarching engineering systems methodology were critical for organizing what otherwise could quickly become a chaotic topic for students. The overall performance of the course could have been improved by better organizing the data made available to students, more explicitly communicating course objectives to fill the gap between perceived and actual learning, constraining the design parameters to reduce the level of ambiguity, and better anticipating and managing the amount of collaboration required among students. It is hoped that the experiences and lessons as described here prove useful to others interested in teaching engineering systems.

Bibilography

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