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Abstract

In the last decade there has been rapidly increasing interest in systems thinking in engineering design. Roughly, systems thinking labels how we should approach the understanding of engineering design, especially for complex engineered systems; such systems are characterized by their large scale, layered complexity and the intrinsic role of human individuals and organizations in their operation and evolution. The heightened interest in systems thinking is motivated by the recognition that this century’s challenges might require engineered systems with unprecedented levels of scale and complexity. How should engineering educators help students learn how to conceive of these systems and, more importantly, approach the design and analysis of them? While strides have been made in developing students’ awareness and appreciation of systems thinking, progress in using it in the practice of engineering design has been lacking. At the same time, the tool-based discipline of model-based systems engineering (MBSE) has been steadily advancing in the last decade in part due to leveraging software design tools. This paper describes a new interdisciplinary senior- and graduate-level course that motivates and describes systems thinking, and grounds it in practice via a design study using modern MBSE tools. The course consists of three focus areas and an integrative design study. The first focus area motivates and provides an overview of the study of complex engineered systems, and spans roughly the first three weeks of a semester. The second exposes students to a sampling of conceptual design techniques, such as the house of quality and failure mode and effects analysis. The third focus area exposes students to modern MBSE tools. The design studies provide project-based experiential learning of the content of the three focus areas and allow exploration of the strengths and limitations of design techniques and tools. Finally, we present preliminary results on student learning, attitudes, and perceptions.

Introduction

The challenges facing society and hence graduating engineers, including sustainable energy, climate change, plummeting biodiversity, and uncertain supplies of potable water and food, are fundamentally new; we now require engineered systems that will tackle these 21st-century challenges and that will be robust, efficient, and sustainable. These problems require that engineers bring a systems-thinking perspective to the solution—in short, the ability to conceive and design complex engineered systems. As these new systems are multi-layered and multi-faceted, with distributed interacting components, they require thinking across disciplines, multiple levels of abstraction, and modeling and analysis tools.
Overview

This paper describes a new course for senior undergraduate and graduate engineering and computer science students that targets learning of systems thinking. Taught under the course title EGR 502: Advanced Engineering Design, it has three objectives. The first is to improve students’ awareness of the complexity of important problems. The second is for students to develop an appreciation for the challenges inherent in designing the engineered systems that will contribute to their solutions. The third is to give students the opportunity to learn modern engineering design tools. From a pedagogical perspective, the course has an experiential component that employs project-based-learning, allowing students to apply modern tools and develop an understanding of their capabilities and limitations.

The course weaves several developing threads in engineering education. Its design theme builds on conceptual design and learning of systems thinking inspired by the design of wireless sensor networks. It draws on a number of closely related visions of modern engineering, including complex engineered systems, networked systems, engineering systems, all of which have been responses to needs at the interface of society and technology and application of these concepts to important 21st-century problems.

Course Learning Outcomes

Our overall aim is for students to improve their abilities related to the broad skill set encompassed by the term systems thinking. In the development of the course, we used the so-called backward design approach, identifying course learning outcomes that stem from this aim and flow down to learning activities. We developed three top-level learning outcomes, with each captured in a focus area (Figure 1):

1. **Defining complex engineered systems** – Students can demonstrate an appreciation for and an understanding of complex engineered systems (CES, Figure 1), and articulate and contrast different definitions of complex engineered systems in the literature.

2. **Understanding conceptual engineering design tools and techniques** – Students can describe and be conversant in modern conceptual design techniques, such as failure mode effects analysis (FMEA), design structure matrices (DSM), quality function deployment (QFD), and life cycle assessment (LCA).

3. **Model-based systems engineering (MBSE)** – Students can solve problems employing examples of modern MBSE design tools, synthesize the use of multiple models and tools in engineering design, and describe their strengths and weaknesses.
Course Focus Areas

Defining Complex Engineered Systems

One of the initial exercises in the course is designed to help students reflect on their attitudes toward technology. Students, like all people, view engineering and design through the lenses of their experiences and attitudes. Is technology a solution, a problem, or a mixed bag? For example, if our goal is to reduce US greenhouse gas emissions, should nuclear power be part of our energy portfolio? To enable students to reflect on their own attitudes and learn about classmates’ views, we conduct two exercises in the first week of the course. First, students are asked to characterize themselves with respect to their overall attitudes toward technology. As part of that discussion, we also explore the implications of labels: does one’s self-perception change if we use the labels of “chicken little vs. starry-eyed optimist” instead of “pessimist/optimist”? Students are first asked to make a binary pessimist/optimist decision. Then we extend this to a scale from −5 (pessimist) to +5 (optimist) to allow more nuanced reflection on and discussion of their attitudes and perceptions. The goal is not to change attitudes, or find the “correct” view, but to enable and encourage serious reflection.

A key theme of the course is complex engineered systems, their properties, and their challenges. To begin our exploration, we read the first three chapters of Charles Perrow’s classic Normal Accidents. The discussion requires two class sessions. This exercise has several explicit goals. One is to appreciate the difficulty of getting detailed factual information. To emphasize this point, additional materials are made available for reference. A second is to explore how to represent causal relationships between incidents and events as the accident unfolded. Here we develop an ad hoc graphical model of the course of events to clearly demonstrate that there was a web, rather than a simple chain, of failures that led to the 1979 accident at the Three Mile Island nuclear power plant. A third goal is to understand the relevance of the study of complex-engineered systems today; thus the final part of the discussion is dedicated to the March 2011 accident at the Fukushima Dai-Ichi plant, with a focus on differences and similarities to the Three Mile Island case.

A second exercise explores in more detail Perrow’s model of complexity that characterizes a system via two parameters: (1) interaction (2) coupling. These are plotted as relative quantities in a two-dimensional Interaction/Coupling (I/C) graph; for example, a state motor vehicle administration is considered to have “linear” interaction and loose coupling, while a nuclear power plant has “complex” interaction and tight coupling. The students perform two exercises. First, they are asked in a homework assignment to evaluate Perrow’s characterization of universities and junior (now community) colleges. Then, in an in-class written quiz, students study Perrow’s analysis of marine transport systems via analyzing the differences between high-seas and channel/harbor systems, and plot each in the I/C diagram relative to the marine transport system as a whole.

The instructor then separates students into groups based on their similarity of their evaluations of Perrow’s analysis, with each group selecting a reporter who summarized their evaluation (Figure 2). A key outcome of the presentations and ensuing discussion was that the I/C parameters were
limited because they hid information about differences in subsystems, e.g., academic, financial, administrative, and human resources.

Follow-on class sessions are dedicated to de Weck et al.\textsuperscript{7} (Chapters 1-3) and Alderson and Doyle.\textsuperscript{6} Key outcomes of discussions and informal presentations were (i) the difference between artifacts (“widgets”) and systems and (ii) that engineered systems acquire complexity to gain robustness to component-level and environmental uncertainties, but can as an unintended consequence become fragile to other unpredicted conditions. These discussions are enlivened by introduction of case studies and talks by invited speakers who present various examples of systems that have coupled social, technological, and environmental domains.

Understanding Conceptual Engineering Design Tools and Techniques

This focus area is designed to expose students to modern techniques and tools used in engineering design at primarily the conceptual level. Small student groups (of no more than three students) give presentations on the key ideas of FMEA, QFD, and DSM.\textsuperscript{15} We also discuss an analysis tool, LCA in the context of energy applications.\textsuperscript{16} To allow time for other learning activities, the objectives are for students to understand the key principles (e.g., mass transfer) in the context of the accounting process performed in LCA, with particular attention to the implicit chain of models employed to make the analysis tractable.

Model-Based Systems Engineering

In addition to promoting the learning of systems thinking, the course is designed to provide opportunities for students to put their knowledge to use via a learn-by-doing approach. It is well-known that the complexity of modern systems makes traditional document-tree based approaches unwieldy, and almost always out-of-date as the design process proceeds.\textsuperscript{20,19} Thus there has been increasing interest in MBSE and its implementation in tools. The hope is that the paradigm of computer-aided design that has been extremely successful in the design of digital hardware and signal processing and communication systems\textsuperscript{17,18} can be exploited in systems engineering\textsuperscript{19,20,21}. The aim is to replace complex and brittle document trees with methods based on more natural languages for design; this is summarized by the notion of an executable specification, whereby the documentation process naturally leads to a tangible engineered system.

One of the key goals of the course is for students to learn the value of developing multiple models of a system. The complexity of modern systems means that a range of modeling and simulation tools may be brought to bear on their design. The number and variety of available
tools is immense; for example, a recent effort used two SysML tools (MagicDraw and ParaMagic), MATLAB, Simulink, Mathematica, and the Excel spreadsheet software. Here we summarize a few of the more popular ones. There are a number of general-purpose computational tools such as MATLAB, Scilab, R, and Mathematica, as well as numerous extensions to the Python language, such as Numpy and Scipy. Tools offering dynamical systems and process-level modeling with graphical design capture include Simulink and Scicos (based on MATLAB and Scilab, respectively), Stella, Modelica, and MLDesigner. RePast and Netlogo are environments for modeling and simulation of the dynamics of multi-agent systems.

A different class of tools, based on system modeling languages, has developed for what is known as model-based systems engineering (MBSE). One branch was inspired by the Unified Modeling Language (UML) used in software engineering, and resulted in the SysML language specification and associated design environments, e.g., IBM Rational Rhapsody, TOPCASED, and MagicDraw. An alternative is object-process modeling (OPM), which is implemented in the OPCAT environment.

The course content and activities in this focus area are driven by three topic-level learning outcomes. First, students gain exposure via short lecture and reading materials to a survey of modeling and simulation tools. We also want students to become conversant, if not fluent, in modeling (i) the dynamics and (ii) the structure and function of systems. Thus our second outcome is for students to become conversant in one widely-used tool that allows exploration of the dynamics of systems. We are using Simulink, in part due to its ubiquitous use in industry, and in part due to our students’ comfort with MATLAB, upon which Simulink is based.

Our third learning outcome—modeling system structure and function—is enabled by the use of an MBSE tool. The SysML language is well-established, supported by a professional organization (the International Council on Systems Engineering (INCOSE)), and, as noted earlier, has a number of commercial and open-source implementations. However, it is complex: it inherits considerable intricacy from UML, steepening and lengthening the learning curve. On the other hand, OPM is relatively both simple and abstract, eschewing detailed constructs found in SysML. Choosing one is not a matter of which is better overall (a common misconception in evaluating software programming languages), but which is more suited to the task. For this course, we use the OPM tool OPCAT II. Though it may not scale as well as SysML to detailed representation of large-scale systems, it may be better suited for conceptual or early-stage design activities and has two specific advantages for this course. First, it is based on only two entities: objects (which may or may not be physical) and processes that change the states of objects. This simplicity invites learning, exploration, and productive use in the confines of a one-semester course. Secondly, it encourages students to analyze the problem of modeling (system representation) itself, and brings to the fore higher-level cognitive skills related to evaluation and critical thinking.

Students gain proficiency with the tools in four exercises. First, they simulate a non-linear dynamical system using MATLAB or R, and repeat the model development using Simulink. We use a classic discrete-time predator-prey model that demonstrates the rich dynamics of these systems and exposes students to thinking about systems in new ways, such as phase plane representations, and encourages discussion of model fidelity. The second exercise builds on
skills gained in the first by starting with a simple model of an anti-lock brake system (ABS) in Simulink and then introducing a model of the same system in OPCAT II. This reinforces understanding of the strengths and limitations of specific representations and why the use of multiple modeling techniques is important. A third exercise, control of a satellite communication base station antenna, integrates principles from both electrical and mechanical engineering. For students with a background in control systems, it reinforces modeling with Simulink, while for others, it introduces the importance of feedback control. In a fourth exercise, students estimate parameters from the noisy, sampled step response of a linear system, addressing system identification in the real world.

**Design Studies**

The course incorporates a strong learn-by-doing thread of activity wherein students perform a *design study* that allows them to put into practice knowledge gained in the three focus areas. They are referred to as design studies rather than design projects in part to allow students to leave behind any expectations related to capstone projects in earlier courses. In particular, (i) the goal is not a prototype of an artifact, but development of multiple models of a system that may lead to an innovative design, its improvement, or its optimization; (ii) the design study is not designed to be a comprehensive semester- or year-long project, but a focused study using core engineering principles and the OPCAT II and Simulink tools.

Activities around the design studies start early, so that students can begin envisioning their efforts in the context of the focus area topics. The first activity is known as Three Minute Madness, where students give short talks on a design study idea. The activity’s title reduces pressure to propose a “safe” design study and instead encourage creativity and innovation. Each idea is discussed in the spirit of brainstorming. In subsequent weeks, after students meet with each other and with the instructor, teams are formed around written proposals that include clear objectives based on rigorous engineering principles. About two thirds of the way through the semester, the teams prepare presentations as part of critical design study reviews (CSDR’s), allowing mid-course corrections and additional work before final reports and presentations that count as the final exam in the course.

**Assessment Results**

We explored students’ attitudes toward and perceptions of the course via a mid-semester survey (Box 1). Students seemed to especially enjoy a course that had a significant discussion component. Responses to Question 1 included “[t]he open discussions are stimulating and fun…”,”I like the seminar/discussion style…””, and “The most interesting aspects of this course have been in the readings and discussions of the complexity and failures of specific engineering systems.” In their responses to Questions 2 and 3, students reported an increase in appreciation, awareness and understanding of complex engineering systems, with one student describing a “huge increase” in awareness. Most students also seemed to value the introduction of modern engineering design tools; one said “there are nonobvious steps to modeling systems that I was not aware of previously, and another reported that “OPCAT is a valuable tool to know, and Simulink even more so.”
Students noted the contrast between the portions of the course dedicated to understanding the design of complex-engineered systems via discussion and the more technical assignments that addressed modeling and simulation. Some students suggested in response to Question 2 that the technical assignments be placed first, rather than following the qualitative introduction.

**Box 1. Mid-Semester Survey Questions.**

1. What are your perceptions of the course at this time?
   a. What do you most like about it? What has been most interesting?
   b. What would you change to make it better?
2. How has the project affected your appreciation/awareness of complex engineered systems?
3. How has the course affected your understanding of complex engineered systems?
4. Do you think that learning Simulink and OPCAT has improved your ability to design systems?
5. How has this course changed the way you will approach engineering design projects?

**Conclusion**

This paper describes a new interdisciplinary course for upper-level undergraduate and graduate students in engineering and computer science. It specifically targets the learning of systems thinking in engineering design. Key goals of the course are to increase awareness and appreciation of complex engineered systems, and to build on them to motivate use of modern tools to tackle design of these systems.

**Biographical Information**

Paul G. Flikkema received the PhD in Electrical Engineering from the University of Maryland, College Park. From 1993-1998 he was an Assistant Professor at the University of South Florida, and joined Northern Arizona University as an Associate Professor in January 1999, where he is currently Professor of Electrical Engineering. He has been a JSPS Visiting Researcher at Yokohama National University, a Visiting Research Scientist at Sony Computer Science Laboratories, Tokyo, and a Nokia Fellow at Helsinki University of Technology. In 2007, he co-organized the US-France Workshop on Sensor Networks and the Environment sponsored by the French government. In Spring 2008 he was a Visitor at SAMSI, where was Program Leader of SAMSI’s Program on Environmental Sensor Networks.

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