Teaching Systems Thinking to Engineering Undergraduates Using the CLIOS Process

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Abstract - **The introductory science courses taken by engineering undergraduates are usually intensely reductionist in form, silos in physics, chemistry, biology, and so forth. Then, their engineering subjects in the early undergraduate years often tend to be reductionist as well, focusing on a fairly narrow view of the engineering issues practitioners face. Even the design classes often do not account for the socio-technical context for much of the engineering design space that involves a complex interaction between various technologies and the multiple stakeholder views.**

This paper describes a subject called Engineering System Design, which attempts to create a broader perspective for third-year students in engineering—and indeed in related disciplines in management and planning. It is a combination of lectures on methods related to systems thinking and a semester-long class-wide complex socio-technical system design utilizing these methods and concepts. In recent years, the case has focused on the transportation of spent nuclear fuel to Yucca Mountain, Nevada and related issues in global climate change.

Experiences in teaching this class will be discussed and some techniques adopted to enable learning are presented.

Index Terms – CLIOS Process, project-based learning, systems thinking.

INTRODUCTION

ESD.04/ 1.041—Engineering System Design—teaches *systems thinking* through a class-wide system design project, conducted in a complex technical environment and challenging societal context. This class, through lectures and recitation exercises, teaches systems thinking concepts and how one goes about conceiving and approaching complex system design problems. These learnings are then utilized by students as they address a major system design project working in competitive teams. The class is intended to be integrated, rather than reductionist, in its approach.

The intended learnings are as follows:

- Systems thinking as an integrative holistic approach to problem solving
- Basic ideas of design—making good choices among alternatives as a fundamental of engineering
- Abstracting a complex technical system into quantitative models and/or qualitative frameworks that represent that system
- Using those models and frameworks to reach effective design decisions
- Creating a strategy for implementing design decisions
- Identifying the key system stakeholders and balancing their diverse interests
- Organizing a set of individuals into an effective team and working in groups
- Operating as a “high-end engineering/policy” consulting firm with a demanding client

The class project for Spring 2007 is concerned with designing a system for transporting and storing spent nuclear fuel (SNF). This is an important problem in contemporary society. Nuclear power plants and research facilities around the United States have been producing SNF—as a byproduct of the production of electric power—a quite toxic substance, for some years. Until now, most SNF has been “temporarily” stored on site at the nuclear facilities. The nuclear power plant operators want that material removed. The current plan is to relocate it from about 130 reactors around the country to a below-ground repository, thought to be geologically stable, at Yucca Mountain, Nevada, about 100 miles northwest of Las Vegas.

Many questions arise as one considers how to proceed. Is it better to move this spent nuclear fuel to Yucca Mountain and store it below ground, or continue to store it on site at the nuclear plants or at other dedicated facilities? Are there feasible means of storing it on site? What are the relative risks of the different options? How does terrorism enter into our design considerations in the post 9/11 era? If we do choose to transport SNF, what mode of transportation should be used and what operating practices are appropriate? Who are the various stakeholders in this issue and how are they differentially affected by various decisions? Who benefits and who pays in the implementation of various strategic alternatives?

Those are but several of the *specific* questions one might consider in this system design project. But we also consider *the broader context of U.S. energy and environmental policy.* Design decisions we make will bear directly on the viability of nuclear energy as a way of meeting the energy needs of the United States. And there are environmental issues as well. Nuclear power can be produced without generation of further greenhouse gases, which has implications for global climate change. At the same time, many are concerned with the safety and environmental risks of nuclear power generation.

ESD.04/1.041 addresses this complex system design question. We conceptualize and structure the salient issues and move toward developing design alternatives using systems thinking principles, which are critical for understanding and approaching complex sociotechnical systems of this type.

CLASS CONCEPTS AND CONTENT: SOME TEACHING APPROACHES

A perennial problem in teaching systems thinking is that we want to create a mindset in our students that encourages them to think in an integrative "horizontal" manner, while still not overlooking the depth in models and frameworks that give "vertical" intellectual grounding to the work they are performing. In this class, Engineering System Design, we address this breadth-depth tension in various ways.

From a breadth point of view we teach students the CLIOS Process [1] (see **Figure 1**) as an overarching way of thinking about problem solving and design for complex systems. They are taught the CLIOS Process and then apply it to the case. The CLIOS Process is a three-stage process as follows:

Stage 1 *Representation*
Stage 2 *Design, Evaluation and Selection*
Stage 3 *Implementation*

The stages of the CLIOS Process allow the students to go through an organized step-by-step procedure for complex system design, as shown in **Table 1**.

TABLE I
THE THREE STAGES OF THE CLIOS PROCESS

Stage 1 *Representation*	Primarily Qualitative *Key Ideas*: Understanding the CLIOS System Establishing Overarching Goals
Stage 2 *Design, Evaluation and Selection*	Both Qualitative and Quantitative Aimed at improvement of the CLIOS System *Key Idea*: Developing bundles of strategic alternatives
Stage 3 Implementation	Pragmatic in nature How to implement bundles of strategic alternatives *Key Idea*: Follow-through: changing and monitoring the performance of the CLIOS System

The first stage, *Representation*, gives them a structured method for thinking through—in text as well as diagrammatically—the physical aspects of the system (we call these the physical subsystems) and the organizational and institutional structure within which they exist. We usually have complexity of both types, physical and institutional; we must think explicitly about interactions between the physical and the institutional in any complex socio-technical system.

In the second stage, *Design, Evaluation and Selection*, we build on the representation to create what we call "strategic alternatives". We characterize this as the "imaginative" part of the process involving innovative, yet sound, design alternatives; then we evaluate these strategic alternatives through various qualitative and quantitative approaches, and form the strategic alternatives into a robust bundle. Special concern with uncertainty is part of the CLIOS Process and we emphasize that in the class as well.

The final stage, *Implementation*, teaches the students that simply coming up with a robust bundle of strategic alternatives is not adequate; one must also think in terms of how one will actually deploy the physical and institutional strategic alternatives contained in their bundle in both physical and institutional terms.

The CLIOS Process gives them an overview of what a complex system design would entail in an integrative fashion, but students are still required to "drill down deeply" to do both qualitative and quantitative analyses through models and frameworks to address key design issues in the case, although of course the depth into which we can go is limited by class time and the sophistication of the students, who are mostly in the third year of their undergraduate program.

The reader should bear in mind that while we show the CLIOS Process as a set of ordered steps, we emphasize to the students that this is an iterative process, and not a rigid, once-through process. Indeed, as shown in **Figure 1**, there are several important points where iteration can occur. As we go through the steps of the CLIOS Process, with our student we highlight for them where and how iteration back to earlier steps should take place (having labeled some of these iterations as A, B, and so on, for reference).

As one identifies and analyzes strategic alternatives to change the CLIOS system, additional insights and constraints may surface. In other words, as one thinks about how to change the system, it often becomes clear that one does not fully understand the ways that the whole system will react in response to these changes, both in the short and long run, so one may have to "re-represent" the CLIOS System or alter or add strategic alternatives.

We teach the CLIOS Process and various models and frameworks in a lecture setting. However, we emphasize that a substantial part of the learning takes place through the project.

For the project, the class is structured into consulting teams—the last several semesters we have had enough students for two teams of about seven people each—who work collectively to do their engineering system design. Each team has a mentor, usually a graduate student, with whom they interact outside of the class. The graduate student is instructed to guide, but not steer, and *certainly* not to do the work for their team.

The role of the graduate teaching assistants is important since they serve as mentors to the students. They serve as "senior managers" of their consulting team and also serve as the eyes and ears of the faculty in being able to best sense what the students are learning and what they are not so that the professor in charge can reinforce various points during lecture.

A challenge for some of the graduate assistants has been to separate themselves from the team. Some have perhaps given too much "guidance" and have confused their own success in being a good TA with the success of the students in the final report and presentation they make. But with proper mentoring by the faculty member, usually we have

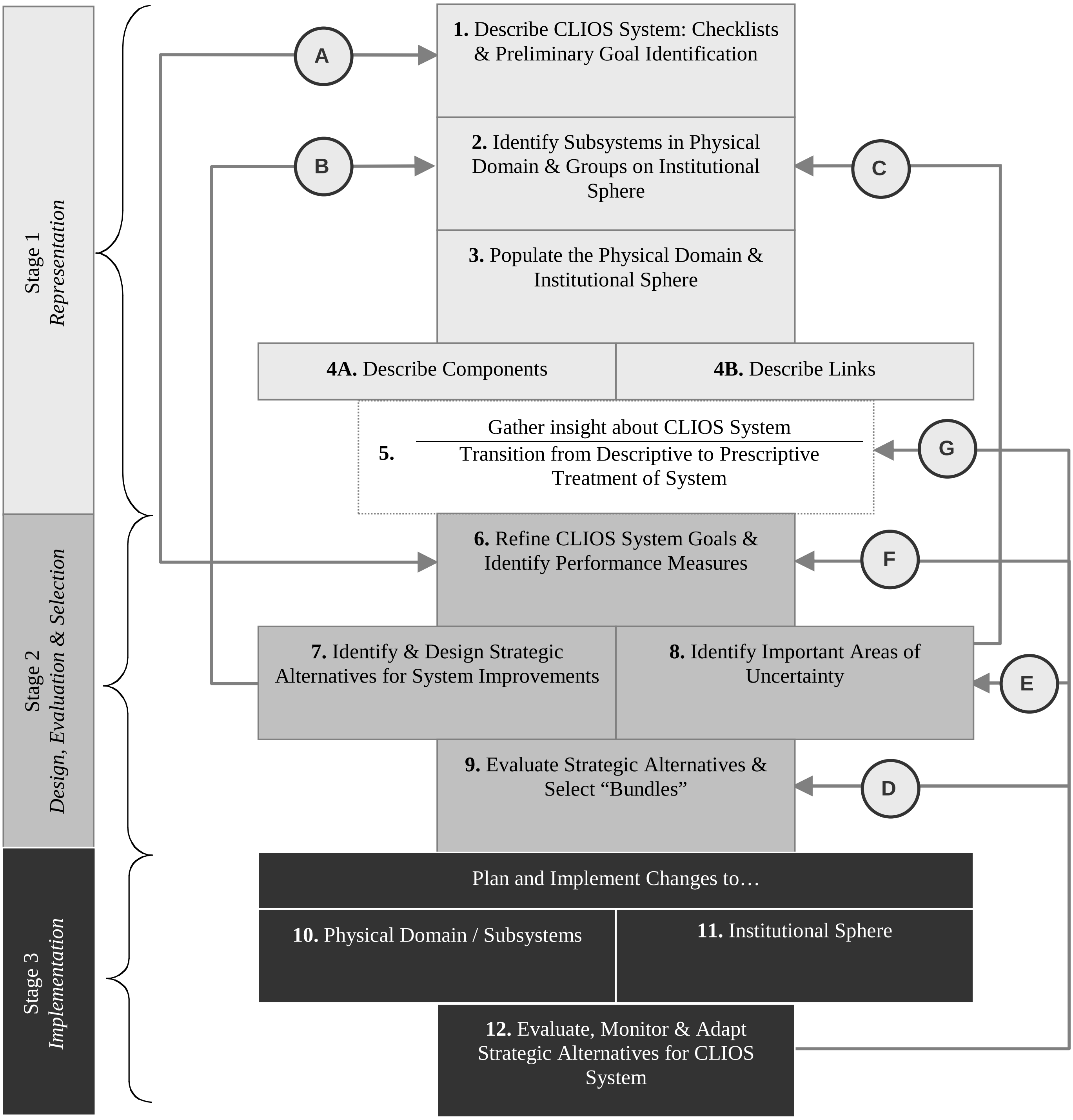

FIGURE 1
ITERATION IN THE CLIOS PROCESS

been able to rebalance that. Experienced graduate students, PhD candidates, who have professed some interest in getting involved in teaching, are generally good candidates to serve as teaching assistant. Personality traits enter into selection of the TAs as well, of course.

We occasionally devote some time in lecture to team meetings and also meetings with the client, in this case the "Department of Energy Secretary", played by the faculty member in charge.

As in any team-oriented exercise, a chronic problem is keeping track of the students who are really contributing, and the "free riders". So, we have to walk a fine line between telling the students that they will be graded mostly on the work of the team as a whole, but also reflecting relative performances in the final grade the students receive. The close interaction they have with the mentor and with the faculty, has proven adequate to make these judgments, although in candor we tend to err on the side of grading the individual students too high rather than too low, which, of course, penalizes the best students.

Of course one cannot, in a one-semester subject, teach a wide variety of systems methods in any kind of depth. So what we have done is, depending upon the case, select certain core methods and teach those in lecture. In the SNF case, risk assessment and benefit-cost analysis are the core methods we teach in lecture. But also, we ask the students, at the beginning of the semester, what additional systems methods would be of interest to them, and then try to provide out-of-class tutorial help from the instructing staff in those methods to those students. They can learn more about those methods and utilize them together with their teammates in the case study application. We call this "just-in-time" methodology delivery. Not all students obtain depth in all methods, but we hope, by creating a team environment and having individual students working on methods of particular interest to them, some of this knowledge will rub off on their fellow students within the team. Of course this puts a substantial burden on the teaching staff in that the faculty and graduate student assistants need to pull together materials in a variety of areas and work out of class with students on particular methods.

PROFESSIONAL PRACTICE

An important component of the class is to give the student some flavor of what doing a complex system design working as a consulting team with a "demanding" client would entail. What we do here is engage them in a series of playacting experiences where they interact with the teaching staff playing various roles as the students present their work.

In the Yucca Mountain case, what we do is have the professor play the role of Secretary of the Department of Energy, who has taken a special interest in their project which involves spent nuclear fuel and global climate change issues. There are two encounters designed into the syllabus.

In the first, the students meet with the "Secretary" about halfway through the semester to get a sign-off on their bundle of strategic alternatives that they will consider for deeper analytic treatment during the rest of the semester. The teams meet separately with the Secretary for about 45 minutes, and the role-playing professor tries to give the students a sense of what it would be like interacting with a senior government official who is under time constraints, political pressure, and so forth. The students and the teaching staff all have to enter into this in a spirit of seriousness if the exercise is to have value.

A second encounter involves the students again visiting the Secretary ostensibly to present their report outline, but in fact, what we have adopted is a "surprise", where another player—usually one of the faculty members' grad student (not one of the TAs) urgently knocks on the door about 5 or 10 minutes into the session and says to the Secretary that there is an emergency that "turns out" to be related to the project.

So, for example, we have had a "surprise" where the graduate student plays the role of the congressional liaison for the DoE Secretary. The liaison has just gotten an emergency call from a key senator who is very concerned about the spent nuclear fuel going to a site in his state. The liaison "needs" to go within the next hour to visit that senator. So, the Secretary and his congressional liaison say, "well, we need to focus on this question rather than our meeting agenda; my liaison needs some talking points. Why don't we leave you (their mentor stays) for 15 minutes while we get a cup of coffee and when we come back we want you to have talking points for my liaison organized in an effective and cogent manner".

Another surprise dealt with the question of nuclear proliferation and an urgent call from the State Department who had in turn heard from the Secretary General of the UN concerned with a reversal of US policy on reprocessing of spent nuclear fuel with its implications for proliferation. In our experience, the students perform well.

Again, it is important that everybody play his or her roles. Our experience with this "surprise" has been positive as we try to give the students as much real life experience in what a policy-related, high-level consulting project might, in fact, subject them to in "real-time". And it can be *fun*!

CONCLUSIONS

From the perspective of a veteran faculty member this is a very interesting and challenging course to teach. It is clearly a great deal of work, much more than traditional lecture subjects.

The main learning clearly is through the project. The challenge there is creating a simulation of a realistic environment when indeed there are various artificialities introduced by the pragmatic nature of dealing with a complex systems design issue over a 14-week period while students are typically taking three or four other subjects. We believe the current state of the art in teaching systems thinking requires this time-intensive approach. Learning by doing is fundamental to the concept of teaching systems thinking.

It is a real challenge to balance the teaching of various methods and systems thinking from an abstract point of view with work on the project. One could easily design a course that was fully engaged in teaching of one or the other—a methods class and a subsequent projects class. But integrating the two into one subject has substantial benefits in terms of giving students direct applications of methods as they are taught.

We will continue to refine this subject, and the author looks forward to updating the faculty learnings from this exercise in the future.

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