Teaching Systems Engineering by Examining Engineering Education Systems

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Abstract
In recent years, there has been a growing demand in industry for undergraduate engineers to develop a stronger understanding of systems engineering concepts and principles. In some industry domains, such as aerospace engineering or healthcare engineering, the projected need for systems engineers far outstrips the projected supply of US trained engineers with appropriate undergraduate exposure to systems engineering topics or projects. However, it is difficult to provide undergraduates with an effective educational experience to a complex engineering environment (such as evaluation and improvement of an entire hospital network, or development of a new space vehicle assembly process) due to the size and complexity of the system. Perhaps equally important is that students rarely have substantial exposure to such systems before graduation.

This paper describes attempts to provide students with the opportunity to define, explore, and assess a complex engineering system for which they supposedly all have direct experience: engineering education. In essence, an engineering curriculum is an integration of systems at several levels of aggregation: design, evaluation, and improvement efforts can be described at the scale of the individual class, semester course, or undergraduate / graduate major. However, two issues limit students' understanding of their own experience as a systems engineering application. A lack of presentation of engineering concepts in a systems engineering context predisposes students to process material in a sequential aggregation (the model of presenting lecture material in a class). In addition, a lack of transparency of goals and processes may prevent students from understanding faculty, employer, or other university perspectives on the processes, outcomes, and success criteria of the engineering education enterprise. Examples of these issues are presented from the context of courses in industrial engineering.

I. Introduction

In recent years, there has been a tremendous upsurge in the demand for, and appreciation of, engineering students and professionals with expertise in the domains of systems engineering (SE). Although variously defined, SE may be seen as a set of skills that cross subdiscipline boundaries and focus on the ability to integrate and prioritize engineering components, tasks, and priorities to achieve broader economic, operational, or organizational goals. In order to address uncertainty about the nature and role of SE, and to help address demand for SE, a growing number of universities and professionals are working to develop consistencies of definitions, approaches, and roles for systems engineers [1]. A number of companies have announced aggressive plans to recruit and hire systems engineers, in order to meet the challenges of 21st Century engineering problems [2]. For instance, Lockheed Martin, who hires approximately 5% of the entire US output of undergraduate engineering majors, has expressed a strong need for a growing number of trained systems engineers [3].

Since the 1950's, SE has emerged as a critical aspect of developing, directing, and managing large, complex engineering projects [4, 5]. Among engineering disciplines, Industrial Engineering has often been seen as a natural home of SE, but the general problem solving skills of any engineering discipline are considered part of the required background of a competent systems engineer. Additional "soft skills" requirements of managing conflicting organizational demands, economic realities, and social dynamics in the workplace are also considered part of the system engineer's toolbox [6]. This combination of social and technical aspects of a complex engineering system (and hence, managing an engineering project in a large organization) can be described as a "sociotechnical systems" approach to SE and organizational dynamics [7].

Because of these factors, the author has increased his emphasis on providing students with exposure to, experience with, and an appreciation of, the challenges of SE in several of his courses. These courses, with a home in a School of Industrial Engineering (IE), range from sophomore level offerings in statistics or computer applications to IE, through a senior level required course in human factors work design and analysis, to a senior / graduate course in software usability and interactive systems design. Across this range of courses, a common problem exists: how to present material on SE in a way that is accessible to, and draws upon, the experience of the students in these courses?

II. Providing SE Context To Students

Within the first two weeks of each semester in most courses taught by the author, there is some significant (half- or full-lecture) treatment of the systems engineering (SE) context and approach of that course. Based on informal discussions with students in past years, there is a distinct presentation of the differences between different forms of presenting engineering material, and the context or focus of the course. Most students are used to an engineering course that presents component material, in the analysis of engineering components rather than integrated systems. In addition, engineering course presentation often provides independent presentation of equations and other segments of the course material, with interactions or combinations of segments later on in the semester (if at all). Students rarely see a presentation of SE as a distinct concept. Thus, the author's lectures distinguish between the traditional course presentation orientation:

COMPONENTS – INTERACTIONS – SYSTEMS

and the author's intended course presentation:

SYSTEMS – COMPONENTS – INTERACTIONS

The goal of this presentation order is to give students an overall sense of the SE approach to problem solving, and provide a general structure ("scaffolding") for how components and interactions fit within a general SE context.

Providing coherent SE examples that are within the experience of most undergraduate students, however, remains a continuing challenge. Although students with prior co-op or internship experiences are able to understand the industry-focused examples presented in some textbooks [5, 8], such students represent a low percentage of undergraduate students in many of the author's course rosters. In addition, many students come from a number of countries, as well as a large variety of childhood experiences. Thus, the design problem exists of selecting an SE context that is familiar to a majority of students, that also addresses the issues of SE problem definition and problem solving.

III. An SE Course As An SE Context

Upon reflection, a trivial solution to the design problem is actually a strong starting point for addressing the problem of selecting a widely shared SE context. Of course, **all** of the students in the course share the experience of being in the engineering course, and the course itself represents a complex engineering system that operates at several levels. The course material itself (textbooks, lecture notes, problem assignments) represents critical components that are essential to student learning. However, the behaviors of those components are significantly mediated by other elements of the course. For example, the author's campus uses electronic course management software that is now used by over 80% of students. Presentation of, and student access to, lecture notes via the course management software can change the students' understanding of the textbook. Conversely, the selection of the textbook may allow (through supplemental websites or software examples) additional uses of the course management software and links to other online resources. The selection of the physical classroom itself will constrain the number of students who are taking the course; installation of computers, internet connections, and video presentation hardware in that classroom are prerequisites to the use of the course management software during lecture.
By presenting a framework of the engineering course as an engineering system (see Figure 1), the students have an immediately recognizable and intimately experienced sense of the system under study. The students, with some additional reflection, can see that the "educational system" perspective of the course can also be applied to engineering education at multiple levels. Interactions between components of the course management software used within a single course can be one definition of the system. That course management software is a single component in the system at the level of the semester course. The course, in turn, is a single component in the system at the level of the student's curriculum. (An interesting homework problem which has been given as a check on the student's understanding, is to have the student complete a writing assignment where the student defines the system at a single consistent level of analysis.)

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Figure 1: Class presentation figure of education (course level) as systems process.

The "systems analysis of educational process" discussion of a shared SE context allows students to examine the differences and relationships between system inputs (students), transformations (course learning activities as system components), and outputs (students who have succeeded in learning the course material). In addition, the different system components, and ability to consider each system component as a subsystem with its own subsystem components, directly relates to their ability to frame their own experience. Usually, students have some additional challenges to learn the sociotechnical factors affecting how and what faculty teach, or the accreditation and policy aspects of engineering education. However, because most of the other elements of the system diagram presented in Figure 1 directly draw on their experience, students are much more able to understand both the SE approach and the additional system elements with which they are less familiar.

IV. Challenge Of Engineering (A) Curriculum Reform Process

In addition to teaching systems engineering concepts, the author is involved in a College of Engineering initiative to consider curriculum reform, in response to issues raised in the National Academy of Engineering's *The Engineer of 2020* report [9]. There are many challenges of addressing engineering curriculum reform, most of which will not be addressed here. However, like any other SE analysis and design activity, a critical first step is to define the system under study, so that systems design and implementation problems can be addressed at the appropriate levels of analysis. Part of this initial system analysis process is the task of defining important systems engineering variables of interest, including system users, system customers, workers responsible for producing system outputs, the system outputs themselves, and criteria for measuring system success (see, for example, [5, 8]). From an engineering administration perspective, the system definition problem of curriculum reform can be framed in terms of human work analysis and design [10], considering that engineering faculty are asked to consider changes to their own, and the students', work tasks to achieve the goals of reform. The author used this work analysis and design context to present the curriculum reform question to undergraduate engineering students as a graded (exam) problem.

What began as a simple graded exercise became a significant epiphany as to the challenges facing the engineering curriculum reform process. As seen in Table 1, students generated at least eight distinct models of the engineering education system, at different levels of analysis, in response to the question. Since the "engineering system" of the curriculum is not clearly or explicitly defined, it is reasonable to conclude that this diversity of models (ranging from specific classroom pedagogy and use of course management software, through the role of the curriculum in preparing engineers as useful contributors to society) would be replicated among subgroups of any engineering stakeholder group. In other words, without an explicit and specific discussion of the SE level of analysis or system analysis variables under consideration, it is likely that debates on the needs, priorities, and responsibilities of curriculum reform will suffer from a similar lack of consensus among a multiplicity of potential system definitions.

Model	Scale	Users	Customers	Workers	Outputs	Success Criteria
A	Classroom Teaching #1	Professors	Students	Campus IT	Lecture Materials	Ease of learning, professor effort
B	Classroom Teaching #2	Students	Professors	Textbook Providers	Course Materials	Reference value, ease of understanding
C	Classroom Process	Students	University	Professors	Student Satisfaction	Student ratings, Purdue reputation
D	Course	Employers / Other Professors	ABET	Professors	Students	Preparation for new material, skills
E	Curriculum #1	Students	Employers	University	Student Skills	Employability, student preparation
F	Curriculum #2	University	Employers	Professors	Students	Education quality, Employer satisfaction
G	Curriculum #3	Students	Parents	Professors	Knowledge	Cost-effectiveness of learning, student satisfaction
H	Curriculum #4	Employers	Parents / Society	Purdue	Students	Participating, quality citizens, projects and efforts developed, economic gain

Table 1: Diversity of engineering curriculum system definitions generated by students.

Both the curriculum reform process and investigation of the range of implicit engineering systems models of the engineering curriculum are ongoing. The students' experience of engineering education is a powerful tool for teaching systems engineering. Unexpectedly, this process helps all members discover the complexity and variance associated with addressing engineering education as a systems engineering problem. Nonetheless, the students can continue to have a shared and relevant exposure to the real world challenges of being a systems engineer, and managing large and complex engineering projects.

V. References

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