AC 2012-3312: SYSTEMS ENGINEERING EDUCATION IN THE U.S.: TEXTBOOKS AND PROGRAMS

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Systems Engineering Education in the US: Textbooks and Programs

Abstract

Fraser and Gosavi[9] examined the nature of "systems engineering," described six possible meanings of the phrase, and made recommendations concerning what industrial engineering programs should teach about systems engineering. This paper expands on that work and provides more evidence for further conclusions by examining the topics covered in textbooks in systems engineering and the topics taught in MS in Systems Engineering programs in the US and elsewhere.

We take a fresh look at the textbooks on "systems engineering" and the similarities and differences in the topics covered in them. Although quite a few textbooks are available in the market, most authors have their own favorite theme that appears to run through the book. While this approach is understandable, it makes it difficult to define the essence of systems engineering. While some textbooks are geared towards what constitutes systems thinking, others focus on what systems engineers can do in terms of optimizing the system. Also, some of the newly emerging subjects that are taught within the core of systems engineering programs appear not to be covered in many textbooks. Examples of such topics include: "model-based systems engineering," "risk management," "network management," and "complex systems." We investigate in particular answers to the following questions. How many of books that provide an overview of systems engineering cover these topics? We will also present an analysis of how these topics are related to the overall philosophy of systems engineering.

We also analyze the content of Master's degree programs in systems engineering, primarily in the US, that offer degrees with the word "systems" in the title, focusing on the 25 largest programs, which accounted for 64% of the graduates of such programs in 2010. The programs have much in common, but differ in their focus on different industries and on different tools. Some programs seem to have been designed to meet the needs of specific industries and even of specific companies. We use these findings to support conclusions about the nature of systems engineering education and to make recommendations to industrial engineering programs about the appropriate education in this area for industrial engineering students at the undergraduate and graduate levels.

Introduction

Fraser and Gosavi[9] examined the nature of "systems engineering" and described six meanings of the phrase "systems engineering:"

1. The INCOSE definition. "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem." (http://www.incose.org/practice/whatissystemseng.aspx)

2. A sub-field of electrical engineering. “[E]mphasis is attached to the use of systems theory in applications [and] … tends to emphasize control techniques which are often software-intensive.”[9]
3. A sub-field of industrial and systems engineering. The word “system” is often added to industrial engineering to emphasize the interactions of parts of a system to create the overall behavior of the system.
4. A sub-field of engineering management or technology management. “[S]ystems engineering includes taking into consideration all aspects of the life cycle of the system. Thus the systems engineering approach is said to account for manufacturability, installation, operations, maintenance, repair, and disposal of a system.”[9]
5. The information technology definition, which focuses heavily on the interface of computers with the business world, and
6. Systems engineering based on systems theory. Systems theory has more philosophical roots including Churchman’s systems approach, von Bertalanffy’s general system theory, and Forrester’s systems dynamics.

In this paper, we continue that research focusing more closely on the textbooks in systems engineering and the content of degree programs. Our goal is to gain understanding of the meaning of the phrase “systems engineering” and the use of the word “systems” in the context of engineering in order to provide guidance to industrial engineering programs about what industrial engineering students should be taught about systems.

Textbooks

We studied a number of textbooks on systems engineering and found that most authors have their own favorite theme that appears to run through their books. Although this is understandable, it makes it difficult to define the essence of systems engineering. This finding was not surprising given that Fraser and Gosavi[9] uncovered a large number of definitions that have been used for systems engineering. While some textbooks are geared toward what constitutes systems thinking, others focus on what systems engineers can do in terms of optimizing the system.

On the basis of our study, we find that many if not most books can be unified under the following theme:

1. Define the problem in relation to the system being studied or the system to be designed; this is generally a statement of problem objectives
2. Study the alternative systems that can be designed to meet the objectives; this typically involves a study of the lifecycle cost of the system
3. Integrate the different options and operating (deploying) the system
4. Performance evaluation of the system
5. Improvement of the system

It is important to note that none of the books, however, define systems engineering using the precise theme described above, nor do they agree on any standard process to define systems engineering. However, a careful analysis of these books appeared to reveal the above pattern in their discussion to us. We now discuss the five steps named above.

Developing the problem statement requires a clear understanding of the problem or the goal. For instance, the goal can be to design a space shuttle that can carry humans to Mars, or it can be designing the layout for a new hospital. Understanding the issues involved is a critical part of systems engineering. This requires extracting information, data collection, and expertise in human relationships. Some of this work can be tedious, since it may involve reading numerous documents looking for information. As a result of this, the systems engineer is expected to be trained in reading documents and gathering data.

The second step, study of alternatives, is an important part of the systems engineering philosophy that is rooted in methods. Most books appear partial to decision analysis (Hazelrigg[11]) and probabilistic tools, e.g., probability trees, (Sage and Armstrong[22]). At least one chapter in each book appears to be devoted to this topic. The third step revolves around integrating all system components and launching the system. The fourth step is testing the performance of the system. The fourth step relies on techniques from operations research, e.g., queuing theory for discrete-event stochastic systems and scoring methods and objective function formulation etc. The final step essential captures the principle of continuous improvement.

It is not difficult to see that the five-step process discussed above is closely related to steps discussed in product design within industrial engineering curricula. See for instance, the text of Morse and Babcock,[19] which although focused on engineering management, provides a discussion on what they call “systems engineering phases” that is very closely aligned to our five-step process.

The other aspect that we study here is the role that the system engineer plays in the engineering firm. Sage and Armstrong[22] define the role of the systems engineer as follows: “Defining, developing, and deploying systems.” But that is not necessarily seen as the role of systems engineers in all the literature we reviewed. In Hazelrigg,[11] the role is more closely that played by the design engineer.

The book by Blanchard and Fabrycky[2] is widely used in many systems engineering programs in an introductory course to systems. In this text, an interesting case is made for how we as humans have transitioned from the machine age to the systems age. The concept of “general systems theory” is presented as a topic that can/should help in communication across disciplines when engineers of different disciplines have to work together to solve problems. Also, systems engineering is presented as having a top-down approach. The book presents an overview of a large number of optics typically taught to industrial engineers in different courses: Decision Theory, Engineering Economics, Deterministic and Stochastic Operations Research, Quality Control, Reliability and Human Factors. Perhaps the motivation for this is to present a top-down approach to the main ideas important for a systems engineer.

Some of the newly emerging subjects that are taught within the core of systems engineering programs appear not to be covered in many textbooks. Clearly, introductory texts are not expected to cover these topics in great detail; however, what is surprising is that many of these topics do not even find a passing reference. This leads us to believe that some of these topics are more recent and also indicate that the topic of systems engineering is still in its infancy and is evolving. Examples of such topics include: “model-based systems engineering,” “risk management,” and “complex systems.” Wymore[25] is an early reference to this topic and presents an overview of model-based systems engineering. In general, this topic relies heavily on generating mathematical models of systems and sub-systems which are then linked together to study the entire system. It is unclear how this differs from the traditional approach used in operations research to construct mathematical models for complex systems. Risk management is a topic that has been heavily studied in the literature outside of systems engineering. However, in the context of systems engineering, the topic is generally studied to understand the risks posed by large-scale systems before they are deployed. Complexity of systems is another relatively new topic that has attracted a great of attention within the industrial engineering community. Although the scope of this topic is broad, in systems engineering, a complex system is typically one composed of numerous components such that the properties of the overall system may not be defined by those of the individual components.

Degree programs in systems engineering

While our goal is to advise undergraduate and graduate programs in industrial engineering, we focused on master’s level programs as indicative of what is currently being taught about systems. Using the ASEE database, we identified 159 master’s level engineering degree programs with the word “systems” in the degree title, awarding a total of 2858 degrees in 2010. Many of the programs fall into the categories shown in Table 1.

Table 1: Categorization of engineering programs with “systems” in the degree name

	Degrees	Programs	Average # 2010 grads
Systems Engineering	1005	28	35.9
Industrial and Systems Engineering	462	20	23.1
Information systems	360	11	32.7
Management	155	7	22.1
Computers	105	12	8.8
Manufacturing systems	90	12	7.5
Biological or agricultural	56	12	4.7
Not elsewhere categorized	625	57	10.9
Total	2858	159	30.7

In order to understand the content of programs with “systems” in the degree title, we examined more closely the 25 largest programs, shown in Table 3 (at the end of this paper), which awarded 1828 degrees (64% of the total). Note that three universities appear twice on our list of 25 universities. George Mason University offers degrees in Information Systems and in Systems Engineering. Concordia University, in Montreal, offers degrees in Information Systems Security Engineering and in Systems Engineering. Northeastern University offers degrees in Information Systems and in Telecommunication Systems Management. Interestingly, Northeastern offers 14 MS programs in engineering, and three of those MS program titles include the word “systems”; the third is Energy Systems.

The three largest programs, at George Washington University, Johns Hopkins, and Stevens, all offer the MS in Systems Engineering and all follow the INCOSE definition.. These three programs account for 22% of 2010 degrees awarded by the 25 largest programs in our table and 8% of all 2010 degrees with “systems” in the title. Other programs that we classify as following the INCOSE definition are the MS in Systems Engineering offered at the Naval Postgraduate School, Missouri University of Science and Technology, Southern Methodist University, and George Mason University.

We describe these programs as following an INCOSE definition of systems engineering. For example, SMU says:

> The goal of systems engineering is development and management of systems (products and services) that satisfy customer requirements considering engineering, technology, environmental, management, risk, and economic factors by viewing the system as a whole, over its life cycle.

However, the core courses in these programs overlap somewhat with the Industrial and Systems Engineering model, sometimes including, for example, coursework on deterministic and stochastic models from operations research, engineering economy, simulation, and reliability. Overlap is also sometimes present with information technology in coursework in software systems engineering.

Among these INCOSE like programs, GWU uses Dr. Eisner’s books *Essentials of Project and Systems Engineering Management*[6] and *Managing Complex Systems*,[7] as well as *Managing for the Future*[1] by Ancona, *Engineering Economy*[24] by Sullivan, and *Making Hard Decisions*[5] by Clemen. Textbooks used in core courses at MST include *Systems Engineering and Analysis*[2] by Benjamin S. Blanchard and Wolter J. Fabrycky, *Spreadsheet Modeling and Decision Analysis*[21] by Cliff T. Ragsdale, *Art of Systems Architecting*[16] by Mark W. Maier. At George Mason, books include *Requirements Engineering*[13] by Elizabeth Hull, Ken Jackson, and Jeremy Dick, *Engineering Design of Systems*[4] by Dennis M. Buede, and *Project Management: A Systems Approach to Planning, Scheduling, and Controlling*[15] by Harold Kerzner.

The MS in Systems Architecting and Engineering at the University of Southern California describes its program in a way that fits the INCOSE definition:

> This program is recommended to graduate engineers and engineering managers responsible for the conception and implementation of complex systems. Emphasis is on the creative process by which these systems are conceived, planned, designed, built, tested, certified, used and retired.

The USC core courses include a course in Systems Engineering Theory and Practice and another in Systems Architecting, but the remainder, and majority, of the core is made up of four courses on economic analysis (Engineering Economy, Economic Analysis of Engineering Projects, Financial Engineering, and Economic Considerations for Systems Engineering), making it difficult to conclude that the program is as similar to the INCOSE definition as other programs we listed above. The program is administered by the Department of Industrial and Systems

Engineering, in cooperation with four other engineering departments and the USC business school, and has tracks in 16 areas, including Engineering Management, Computer and Information Systems, and Computer Security.

The Cornell ME in Systems Engineering also has a core that somewhat fits the INCOSE definition, including courses on Applied Systems Engineering; System Architecture, Behavior, and Optimization; Systems Engineering Project; and Project Management. The program offers 19 specializations, including chemical systems engineering, communications systems engineering, logistics engineering, and web applications and information systems (see http://www.systemseng.cornell.edu/academics/meng_campus/specializations.cfm)

The four programs that offer the MS in Industrial and Systems Engineering (University of Florida, Virginia Polytechnic Institute and State University, San Jose State, and University of Southern California) include material on the traditional topics of industrial engineering: efficiency, productivity, quality, human factors, but most of these programs have a small (or nonexistent) core, allowing students to focus in an area within industrial engineering, such as operations research, human factors, or manufacturing processes. The word "systems" is used in statements such as:

> The goal of ISE is to ensure that a manufacturing or service organization's **systems** are efficient, productive, safe, and well designed against cumulative injury, and that the systems incorporate the right tools and equipment (San Jose State, emphasis added)
>
> As the application of ISE tools have migrated beyond the plant, they have also migrated to other fields. Methods in which to improve operations are not relegated to the world of manufacturing and its associated logistics. Any system in general can be studied and optimization — whether a manufacturing or service system. Hospitals are complex systems that are turning to ISE majors for optimization. Financial systems are looking for efficiencies as well as the mathematical modeling that is fundamental ISE knowledge. Telecommunications, electrical, and water distribution networks must be designed for efficiency, often with the help of ISEs. Even biomedical and biological systems are being studied by traditional scientists along with ISEs and their toolkit. (University of Florida)

These ISE programs have a wide range of tracks. The University of Florida allows a focus on Information Technology, which looks similar to the Information Technology programs described below, a focus on Quality Engineering and Management, which looks similar to the Concordia University program, and a focus on Quantitative Finance, which looks like no other program on our list. Virginia Tech has a track in management systems, which looks similar to some of the MS in Systems Engineering programs and uses the Blanchard and Fabrycky text for its course titled The Systems Engineering Process.

Two programs combine the INCOSE and ISE definitions. The MS in Systems Engineering at Florida Institute of Technology has a core course in Systems Engineering Principles which uses the Blanchard and Fabrycky book and a second core course on System Life Cycle Cost Estimation, thus appearing to be an INCOSE like program. However, the other three courses in the core fit the ISE model: Systems Modeling and Analysis (a course in simulation, using

Simulation with Arena,[14] by Kelton), Decisions and Risk Analysis (using *Spreadsheet Modeling*[21] by Ragsdale), and Research Methods in Systems Engineering (a course covering statistical hypothesis testing, statistical process control, and design of experiments, among other topics, and using *Design and Analysis of Experiments*[18] by Douglas Montgomery). Similarly the ME in Systems Engineering at the University of Virginia has a core course Introduction to Systems Engineering, with texts *How to Do Systems Analysis*[10] by Gibson *et al.* and *Innumeracy*[20] by John Allen Paulos. The other two courses in the University of Virginia core are Mathematical Programming and Stochastic Systems, courses that would form the core of an ISE program, especially one in operations research.

Four universities in our list (New Jersey Institute of Technology, George Mason, Concordia, and Northeastern) offer programs that fall into the information technology definition of systems engineering, but often with considerable overlap with other definitions. The NJIT program (Information Systems) and the two programs at Northeastern (Information Systems and Telecommunication Systems Management) are similar to our technology management definition, offering IT professionals the opportunity to move into the business side of information technology. The George Mason program (Information Systems) is more similar to the INCOSE definition, focusing on designing, building, and maintaining information systems. The Concordia program (Information Systems Security Engineering) uniquely focuses on security of information systems.

The Concordia program in Quality Systems Engineering also has a unique focus, but its elective courses overlap with information technology and industrial engineering, and we thus label it a combination program.

The description of the MS in Technological Systems Management in Stony Brook falls into the category of technological management:

> Managing modern technologies calls upon a synthesis of tools drawn from many areas: science and engineering, computers and information, economics and regulation, psychology and community values, design and assessment. The Master's Degree in Technological Systems Management provides professionals in all fields and people planning such careers with state-of-the-art concepts, analytical tools, and practical skills for managing specific technological systems and improving their performance.

However, the two core courses involve elements of ISE and of systems theory. The core course Methods of Socio-Technological Decision Making includes topics on quantitative decision making and uses the Clemen book cited above, *Making Hard Decisions.*[5] The core course Systems Approach to Human-Machine Systems is an introduction to system modeling, using *Thinking in Systems: A Primer*[17] by Donella H. Meadows, and *Critical Transitions in Nature and Society*[23] by Marten Scheffer.

The Loyola Marymount and Iowa State University programs (both called Systems Engineering) are so broad and allow students such a wide selection of courses that they seem to defy any definition of systems engineering. We have therefore labeled these two programs as Engineering.

The program at University of Michigan, the fourth largest in our list, with 104 graduates is a special case. In the ASEE database graduates from the University of Michigan with a MS or MSE in Electrical Engineering (EE) or Electrical Engineering Systems (EE:S) are combined, leading to a total number of graduates of 104 and placing this university in 4th place in our table. We have no way of knowing how many of these 104 students received a degree with the word "systems" in the title. The department web pages offer little guidance as to the difference between EE and EE:S, except in listing different technical areas for each. The EE degree includes: applied electromagnetic, energy science and engineering, integrated circuits and VLSI, MEMS and Microsystems, optics and photonics, plasma science and engineering, quantum science and devices, solid-state devices and nanotechnology. The EE:S technical areas are: communications, control systems, power and energy, robotics and computer vision, signal and image processing. We are unable to see why some of these are "systems" topics and others are not.

While having the University of Michigan programs appear in 4th place almost seems like a mistake, it is a salutary mistake in that it helps us see that the phrase "systems engineering" is widely used and resists any single definition.

Conclusions

Since this paper is intended for an industrial engineering audience, we focus below on conclusions related to industrial engineering.

We have argued previously that systems engineering has many possible definitions, and we enunciated six. As shown in the following table, we found that the top 25 programs in degree production mostly fit into four of our categories (INCOSE, information technology, ISE, and electrical engineering), but that some programs combine categories and others defy categorization.

Table 2: Summary of categorization of 25 largest "systems" programs

Definition	Number of programs
INCOSE	8
Information technology	5
Combination	5
ISE	4
Engineering	2
Electrical engineering	1

From our review of the textbooks we find that our definitions have more in common than we had believed. In particular, textbooks used in programs with the INCOSE definition often include much material that would be taught in industrial and systems engineering programs. INCOSE programs focus more on determining and meeting customer requirements and on designing and building new systems. Often the INCOSE system has a specific mission and a specific time span (e.g. a mission to Mars). Industrial engineering programs focus more on the efficient operation of an existing system. Certain methods and tools are common in the textbooks and programs: economic analysis, decision making, optimization, and simulation.

Comparing our findings with those of Brown and Scherer,[3] we conclude that the number of programs labeled as "systems engineering" without the word "industrial" or other modified is growing. Those programs are increasingly offering curricula that follow the INCOSE definition of systems engineering; in 2000, Brown and Scherer found[3] "few of the programs offer multiple courses in the major topic areas suggested by INCOSE," noting George Mason as the exception, while we found eight such program among the 25 largest programs. INCOSE is continuing to define "systems engineering" in a way that separates these degree programs from, for example, industrial and systems engineering programs and information technology programs. At the same time, we found a wide variety of programs with the term "systems engineering" in the degree title.

We conclude that the meaning of "systems engineering" is quite rich and the definitions are quite varied. We found much overlap in the content of the textbooks and the programs but we also found many distinctive and even unique features. We found the variety of approaches and content positive; each program has used a framework worth, in some definition, being called "systems engineering."

In writing this paper, one author met with a writing group including professors from a wide variety of fields. One colleague from sociology asked: "isn't all engineering systems engineering?" In support of answering "yes" to that question, we cite this quote from the papers of Thomas Edison, as given by Thomas P. Hughes:[12]

> "It was not only necessary that the lamps should give light and the dynamos generate current, but the lamps must be adapted to the current of the dynamos, and the dynamos must be constructed to give the character of current required by the lamps, and likewise all parts of the system must be constructed with reference to all other parts, since, in one sense, all the parts form one machine, and the connections between the parts being electrical instead of mechanical. Like any other machine the failure of one part to cooperate properly with the other part disorganizes the whole and renders it inoperative for the purpose intended.
>
> "The problem then that I undertook to solve was stated generally, the production of the multifarious apparatus, methods, and devices, each adapted for use with every other, and all forming a comprehensive system." (Hughes page 73)

In arguing against inclusive definitions of "systems engineering" and in favor of the INCOSE narrower definition, Brown and Scherer said[3] "Of course if everything is systems engineering then nothing is systems engineering." We disagree and argue that indeed everything is systems engineering. We believe that industrial engineers – as well as electrical engineers, civil engineers, and more – should be cautious in allowing one definition of "systems engineering" to prevail. Rather than refining one limited definition of systems engineering, all engineering educators should seek to teach engineering students that all engineering is systems engineering, but that such education should take place within the framework of that type of engineering. How electrical engineering teaches its students about systems engineering should differ from how civil engineering does that task.

We thus urge industrial engineers, whether their program includes the word "systems" or not, to teach industrial engineers about systems engineering, in the context of industrial engineering.

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Table 3: “Systems” degrees

		Number		
School	Degree Name	2008	2010	Type
The George Washington Univ	Systems Engineering (MS)	66	191	INCOSE
The Johns Hopkins University	Systems Engineering (MS)	89	112	INCOSE
Stevens Institute of Technology	Systems Engineering (ME)	81	107	INCOSE
University of Michigan	Electrical Engineering (MS, MSE)		104	Electrical
Naval Postgraduate School	Systems Engineering (MS)		101	INCOSE
University of Florida	Industrial and Systems Engineering (MS, ME)	91	101	ISE
New Jersey Institute of Technology	Information Systems (MS)		94	Info tech
George Mason University	Information Systems (MS)	77	85	Info tech
U of Southern California	Systems Architecture and Engineering (MS)	97	84	Combination
Stony Brook University	Technological Systems Management (MS)	39	84	Combination
Missouri S & T	Systems Engineering (MS)	61	68	INCOSE
Southern Methodist U	Systems Engineering (MS)	76	68	INCOSE
Virginia Tech	Industrial and Systems Engr. (MS, ME, MEA)	49	64	ISE
Concordia U-Montreal	Information Systems Security Engineering (MEng. & MASc)	29	62	Info tech
Northeastern University	Information Systems (MS)	30	58	Info tech
Northeastern University	Telecommunication Systems Management (MS)	19	57	Info tech
Florida Institute of Technology	Systems Engineering (MS)	15	57	Combination
San Jose State University	Industrial & Systems Engineering (MS)	41	49	ISE
George Mason University	Systems Engineering (MS)	25	49	INCOSE
University of Virginia	Systems Engineering (ME)	40	47	Combination
Cornell University	Systems Engineering (ME)	37	40	INCOSE
Concordia U-Montreal	Quality Systems Engineering (MEng &MASc)	35	39	Combination
U of Southern California	Industrial and Systems Engineering (MS)	40	38	ISE
Iowa State University	Systems Engineering (MEng)	19	35	Engineering
Loyola Marymount University	Mechanical Engg (MSE); Systems Eng (MS)	19	34	Engineering