AC 2010-267: WHAT IS SYSTEMS ENGINEERING?

Jane Fraser, Colorado State University, Pueblo
Jane M. Fraser is chair of the Department of Engineering at Colorado State University-Pueblo. She was formerly on the faculty at the Ohio State University and Purdue University. She has a BA in mathematics from Swarthmore College and MS and PhD in industrial engineering and operations research from the University of California-Berkeley.

Abhijit Gosavi, Missouri University of Science and Technology
Abhijit Gosavi is an Assistant Professor at Missouri University of Science and Technology. He was formerly on the faculty at Colorado State University-Pueblo. His BS and MS is in Mechanical Engineering, and his Ph.D. in industrial engineering is from the University of South Florida.

What is systems engineering?

Abstract

ABET has recently proposed to expand its list of program criteria to include criteria for systems and similarly named engineering programs. Industrial engineers have often claimed the ownership of the phrase “systems engineering,” even incorporating it into the names of some departments, e.g., industrial and systems engineering. While defining terms can be a sterile exercise, in this paper we concentrate on the *practical* implications of defining “systems engineering.” Some of the questions we address here are as follows. What are the real-world problems that systems engineering claims to study, what are the principal methods of systems engineering and how different are they from those of industrial engineering, and what is and should be taught in programs in systems engineering? What can students expect to learn and what jobs can they obtain after completing their studies?

Introduction

With two recent actions, the industrial engineering community seems to have relinquished any exclusive claim on the use of the phrase “systems engineering.” Those actions are (1) the vote by IIE membership to reject a proposal to add “systems” to its name and (2) the determination that ABET’s new criteria for “systems engineering” programs will not apply to industrial and systems engineering programs.

In December 2008, members of the Institute of Industrial Engineering voted to retain the current name, rejecting the change to Institute of Industrial and Systems Engineering. In a September 2008 article in *Industrial Engineer*, Editor Monica Elliott[8] gave reasons for and against the change. As a point in favor of the change, she wrote: “The education and practice of industrial engineering encompasses complex systems, but other organizations are taking ownership of systems activities that fall within our profession.” As a point against the change, she wrote: “The word `systems’ means a lot of things to a lot of people, which could bring about confusion and dilute instead of strengthen our identity. Many people think of computer and electrical systems when they hear the word `systems’ in connection with engineering.”

After the vote rejecting the change, IIE Executive Director Don Greene commented:[7] “With this vote, the members have affirmed the breadth of industrial engineering. Although our profession undoubtedly encompasses a systems approach, it isn't necessary to communicate the broad reach that IE has through our name alone. Instead, industrial engineers around the world express who we are and what we do through our accomplishments. Particularly in our current economy, organizations are looking to industrial engineers to positively impact productivity and efficiency. Now is the time for IEs to step forward and make a difference.”

ABET has recently added program criteria for systems and similarly named engineering programs (with lead agencies American Society of Mechanical Engineers, Institute of Electrical and Electronics Engineers, Institute of Industrial Engineers, ISA, International Council on Systems Engineering, and SAE International). That document consists of the following two sentences**: "**These program criteria apply to systems engineering programs without modifiers in their title. There are no program-specific criteria beyond the General Criteria."

Together, the IIE vote and the ABET statement recognize that industrial engineering shares the phrase "systems engineering" with other fields. This paper explores the various meanings of this phrase with the goal of helping academic departments in industrial engineering (whatever they are called) decide (1) how to use or not use the word "systems" in describing industrial engineering and (2) what to teach students about systems engineering. What can we learn from the other fields that use the phrase "systems engineering"?

Meanings of "systems engineering"

When people use the phrase "systems engineering," they have in mind one of the following meanings:

1. The INCOSE definition,
2. A sub-field of electrical engineering,
3. A sub-field of industrial and systems engineering,
4. A sub-field of engineering management or technology management,
5. The information technology definition, or
6. Systems engineering based on systems theory.

We now discuss each of these meanings.

1. **INCOSE:** According to INCOSE (International Council on Systems Engineering),[13] "Systems Engineering is an interdisciplinary approach and a 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."

   Practitioners of system engineering in this meaning focus on one-time, large projects with a definite start and end, where a new system is to be designed and created to meet customer needs. Practitioners focus on industries such as information technology (IT), aerospace, and defense. On job posting sites (e.g., monster.com), the phrase "systems engineering" almost always describes a job in the INCOSE model, usually in the aerospace or defense industries.

2. **Electrical engineering:** Within the electrical engineering field, emphasis is attached to the use of systems theory in applications, e.g., spacecraft manufacture and

management. As such, systems engineering within electrical engineering tends to emphasize control techniques which are often software-intensive. It appears that one of the first uses of systems engineering was in Bell Labs.[18] Managing complexity is an important ingredient of many courses taught within these programs. Modeling, simulation, reliability, and safety analysis of complex systems are considered to be essential parts of the training needed for a successful systems engineer.

3. **Industrial and systems engineering:** This meaning is the hardest to pin down. Often the phrase "industrial and systems engineering" is used interchangeably with "industrial engineering." Industrial engineers create a new system or improve an existing system, The word "system" is meant to remind the IE of three key points which IEs emphasize more than other engineering disciplines: (1) components (including machines and people) interact with each other to create the overall behavior of the system; (2) the system being studied is always a subsystem of a larger system and these interactions must also be considered; and (3) systems include humans. The word "system" is a caution against sub-optimization of the larger system through optimization of a subsystem. Because Industrial Engineering academic departments often include a wide range of areas (physical and cognitive human factors, manufacturing processes, operations research, engineering management, etc.), the word "systems" often appears to be an attempt to be inclusive. Also, some think that the word "industrial" doesn't include the full range of what industrial engineers do. "Industrial and systems engineering" can apply to service companies, hospitals, insurance, etc.

4. **Technology management or engineering management:** In technology management, systems 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. When manufacturing or selling a product, a systems engineer is likely to view the current technological phase of the product as a critical feature. For instance, in the early 1990s, cell phones were in their early technological phases. Designing, manufacturing, and selling cell phones in those years were activities achieved with objectives and mechanisms that were different than those employed in the first decade of this century. A systems engineer is acutely aware of this issue when considering every aspect of managing a business and designing a product.

   For managing a project, system engineering forces the manager to define the goals and objectives of the project. The project manager with an understanding of the systems viewpoint is capable of knowing the difference between the long-term goals and short-term goals, and can focus on the long-term goals when making strategic decisions. Indeed, the issues of life cycle development are prominent within the literature on project management, and hence they have had an impact on systems thinking by project managers.

   Another important focus of systems in engineering is from the so-called perspective of engineering design. In this setting, designing a "complex" system often requires an evaluation of different alternatives available to the designer. The systems engineering approach is a framework that can *provide data* "on the many disparate variables that lead to different alternatives" and ultimately influence the choice of design.[12] It is often said that the systems viewpoint is also adopted when there are significant inter-related variables within the problem domain that need to be accounted for in a unified holistic approach. A mastery of mathematical, statistical, and quantitative techniques is expected of a systems engineer in order to successfully design a product and manage a product.[1] The design perspective of systems engineering, also emphasized within engineering management, stresses the importance of measuring risks associated to a decision.[12] Decision analysis can then be used to make intelligent decisions with respect to choices.

5. **Information technology:** A new discipline has emerged in the business schools and computer science departments that goes by the name information systems (which is often a minor in computer science departments) or management of information systems (usually in business schools). This definition of systems engineering tends to focus heavily on the interface of computers with the business world.[14] While this has emerged as a discipline in its own right, it appears that this definition is also related to the INCOSE definition. Students in this discipline are expected to become experts in database management, computer security, and transaction processing. In this respect, this definition significantly deviates from what is understood as systems engineering in industrial and electrical engineering departments. However, from the perspective of potential employers, this definition seems to be widely used on jobsites.

6. **Systems theory and philosophical origins of systems engineering:** Various authors have written on the more philosophical roots of systems. Some of them are: Churchman[5,6] on the systems approach, von Bertalanffy[19] on General System Theory, Stafford Beer[2] on the Viable Systems Model, Jay Forrester[10,11] on systems dynamics, and Peter Senge.[17] We now discuss some of their ideas in order to expose the roots of systems engineering in other disciplines. These foundations also perhaps explain why systems engineering has naturally become an inter-disciplinary approach.

   Ludwig von Bertalanffy's General Systems Theory has roots in biology. He wrote:[19] "In order to understand an organized whole we must know both the parts and the relations between them." The primary model is that of an open system, that is, a system "exchanging matter with environment as every 'living' system does." Cybernetics emerged from military work, says Bertalanffy, yet ended up also challenging the mechanistic description of systems. A central tool of *systems science* is a mathematical model, often described in differential equations. A central notion is stability, "that is, the response of a system to perturbation." Thus, dynamical system theory is closely related to control theory. Applying general systems theory to problems in hardware and software leads to *systems technology.* Finally, the "re-orientation of thought and world view following the introduction of 'system' as a new scientific paradigm (in contrast to the analytic, mechanistic, linear-causal paradigm of classical science)" is in the realm of *systems philosophy.*

Stafford Beer[3] applied ideas of cybernetics to human organizations in works such as *Brain of the Firm* and *Diagnosing the System for Organizations.* Jay Forrester[10,11] created Systems Dynamics, in which complex systems are simulated, using key concepts of stocks, flows, feedback, and time delay. Even simple systems lead to nonlinearities, creating complex behavior. Peter Senge[17] popularized many of these systems ideas in his best selling book *The Fifth Discipline.* He argues that organizations must become learning organizations by building knowledge of four disciplines: personal mastery, mental models, shared vision, and team learning. Systems thinking is the fifth discipline, which is required to integrate the other four disciplines.

MS degrees in systems engineering

We surveyed the websites of numerous universities in the US that offer degrees in systems engineering, including, listed in order by the number of master's degrees in systems engineering awarded in 2008: Johns Hopkins University, Stevens Institute of Technology, Southern Methodist University, George Washington University, Missouri University of Science and Technology, University of Virginia, University of Pennsylvania, Cornell University, Massachusetts Institute of Technology, George Mason University, Air Force Institute of Technology, University of Virginia, Iowa State University, Oakland University, University of Arizona, Virginia Polytechnic Institute and State University, Florida Institute of Technology, the University of Texas at Arlington, Old Dominion University, Portland State University, University of Colorado at Colorado Springs, and the University of Maryland. The first nine institutions in this list produced 515 graduates in 2008, making up 76% of the M.S. graduates.

Although widely varying definitions have been provided in the different disciplines, it seems that all definitions do agree in one important way. All the definitions tend to include a set of techniques that work for a system with multiple entities working together to provide a service or a product. It is the interaction of these entities that the systems engineer is expected to focus on. However, this is where the similarity ends. The nature of techniques to be adopted can range from operations research through electrical engineering to project management. Programs in electrical engineering appear to draw upon the aerospace component of the INCOSE definition, but their focus on control engineering seems to distinguish them from other fields where systems engineering is taught. Programs in engineering management tend to use the ideas of project management from the INCOSE definition. Since INCOSE is the only agency that has provided a formal definition, some departments appear to have used it either in developing their programs or in some cases to justify how their program is related to systems engineering.

Textbooks

We have found at least four books that focus on systems engineering: Blanchard and Fabrycky,[4] Hazelrigg,[12] Kosiakoff and Sweet,[15] and Sage.[16] The book of Babcock and Morse[1] discusses systems engineering within the framework of engineering management. Some of these books provide an extensive treatment of the topic, albeit under their own interpretation of systems engineering. The choice of the textbook in a given department for a course in systems engineering, hence, clearly, depends on what the goals of the department are. Thus, an engineering management department and an electrical engineering department are likely to choose different texts in their main courses.

While we do not recommend specific books, our general recommendation is that in an industrial engineering or an engineering management department, books that cover ideas of project management will be more useful. In an electrical engineering department, books that cover control theory based are likely to be more appropriate, while in a computer science department, books that look at issues surrounding management of information systems are likely to serve the best purpose. Based on our research, we find that a book that combines all the aspects of systems engineering that we have covered here is missing in the literature.

Student expectations

Our survey of systems engineering programs reveals that what students can expect to learn from a degree in systems engineering depends heavily on the department they choose to enroll in. This result, as is perhaps obvious from our discussion above, is due to the fact that different programs tend to have differing goals for systems engineers. However, from any of these programs, with the exception of programs in information systems, the student does learn to master the idea of the so-called systems approach and how it can be used to make an organization effective.

Systems engineers can expect to be employed as managers in manufacturing companies (industrial engineering and engineering management), database managers (computer science), and aerospace engineers (electrical engineers). Many online websites that students use in searching for jobs often use the word "systems engineer" synonymously with that used in the information technology definition. Hence, although the information technology definition tends to significantly differ from that used in other disciplines, it seems that it is actually better recognized in the world of industry.

The second author recently visited a local manufacturing firm where a computer programmer and the supply chain manager were both required to use their knowledge of systems engineering. While their expertise was in computer science and industrial engineering, they are required to solve problems that arise due to lack of a systems approach in understanding how the factory works and how costs are incurred because of myopic planning. Although, this is increasingly true of all engineers, it appears that those who specialize in manufacturing management profit greatly from a knowledge of systems engineering.

Conclusions and recommendations for IE/ISE programs

The historical roots have created some of the differences in these definitions of "systems engineering." For example, the INCOSE definition comes from its roots in electrical engineering and its early application in places like Bell Labs, the defense industry, and space programs.

As we noted, industrial engineers rejected the addition of the word "systems" to the name of the Institute for Industrial Engineering, and the proposed new ABET criteria for programs title "systems engineering" will not apply to industrial and systems engineering programs. Other fields and other organizations, especially INCOSE, have enthusiastically embraced the term phrase "systems engineering," and the job market applies the phrase mostly to jobs that pertain to the INCOSE definition or to information technology. Thus, in industrial engineering, we conclude that the phrase "systems engineering," standing alone, is no longer viable, even though the phrase "industrial and systems engineering" continues to be useful.

What should IE programs teach about systems engineering to their students? This question is, of course, the crucial one. Based on our review of the meanings of "systems engineering" and what is being taught under those names in degree programs and textbooks, we recommend that IE programs include the following material. In particular, we focus on three main ideas that we believe capture the essence of systems engineering for students in IE.

Using the INCOSE definition, we should more explicitly teach our students about tools that will help them design a system that meets the needs of the customers or clients. While all engineers design to meet needs, and while we all claim that we teach our students to design to meet needs (indeed ABET requires that as an outcome), we should be more explicit about tools that can help students identify and meet client needs. For example, INCOSE methods require an explicit documentation of the requirements of the client, the key elements of the system architecture, and the way those key elements can meet the requirements.

From the technology management approach, we should include material on the technological phases of products, because industrial engineers need to select appropriate methods for each state of the life cycle of a product. We need to teach our students methods for making intelligent design decisions, evaluating alternatives on costs, benefits, and risks. Decisions that are appropriate in one part of the life cycle may be inappropriate in other parts. Identifying the phase through which a product is going should be taught as a key idea in strategic decision-making.

Finally, we should include material to teach our students about the philosophical underpinnings of systems engineering. At a minimum, we should be explicit with our students about properties of systems (for example, the property that components interact to create the behavior of the system). Providing them with this background should help strengthen their ability to look at the big picture and at the interactions when making decisions.

All systems engineering definitions and all industrial engineering programs share a focus on a set of methods and techniques, although the particular methods and techniques vary. What is often missing is an overarching framework that helps our students organize their thoughts and select fruitfully from among those techniques. We believe that our account will provide a valuable source of information to someone interested in pursuing a career in "systems engineering" but is unsure which department to choose. It is likely that the material that we have gathered above will be useful at both the master's and the undergraduate level. An undergraduate introductory course on this topic, we recommend, should explain all the definitions out there before delving into the details of the three main ideas that we summarized above.

The lack of a textbook that synthesizes ideas from the different disciplines is perhaps an indicator that the different players in this field, namely the different engineering disciplines, are, at least as of now, unwilling to come together to form a single major – one that encompasses different discipline-specific ideas under one umbrella. The rejection of the vote by members of IIE to add "systems" to the name also shows that there is unwillingness on the part of majority of IEs to associate with the idea of "systems engineering." However, this situation may change in the future.

Bibliography:

[1] Babcock, D.L., and L.C. Morse. *Managing Engineering and Technology*, third edition, Prentice Hall, 2002.

[2] Beer, Stafford. *Brain of the Firm*; Allen Lane, The Penguin Press, London, Herder and Herder, USA, 1972.

[3] Beer, Stafford. *Diagnosing the System for Organizations*; John Wiley, London and New York, 1985

[4] Blanchard, B.S., and W.S. Fabrycky. *Systems Engineering and Analysis*, 2nd edition, Prentice Hall, Englewoods Cliffs, NJ, 1990.

[5] Churchman, C. West. *The Systems Approach.* Delacorte Press, New York, 1968.

[6] Churchman, C. West. *The Design of Inquiring Systems: Basic Concepts of Systems and Organizations.* Basic Books, New York, 1971.

[7] Editorial. "Changing of the guard." *Industrial Engineer*, **41**(4) April 2009, 62–63.

[8] Elliott, Monica. "The Great Debate." *Industrial Engineer*, **40**(9), September 2008, 46–47.

[9] Engineering Accreditation Commission, ABET, Inc. "Criteria for Accrediting Engineering Programs. Effective for Evaluations During the 2010-2011 Accreditation Cycle." Accessed December 30, 2009 at http://www.abet.org

[10] Forrester, Jay W. *Industrial Dynamics*. Pegasus Communications, 1961.

[11] Forrester, Jay W. *Urban Dynamics*. Pegasus Communication, 1969.

[12] Hazelrigg, G.A. *Systems Engineering: An Approach to Information-Based Design.* Prentice Hall, 1996.

[13] INCOSE. "What is Systems Engineering?" Accessed December 30, 2009 at http://www.incose.org/practice/whatissystemseng.aspx

[14] Kroenke, D. *Using Management Information Systems*. Prentice Hall, 2nd edition, 2008.

[15] Kossiakof, A., and W. Sweet. *Systems Engineering Principles and Practice,* Wiley, 2002.

[16] Sage, A.P. *Systems Engineering*, Wiley, 1992.

[17] Senge, Peter M. *The Fifth Discipline: The Art and Practice of the Learning Organization.* Doubleday, New York, 1990.

[18] Schlager, J. "Systems engineering: key to modern development." *IRE Transactions*, **EM-3**: 64–66, 1956.

[19] Von Bertalanffy, Ludwig. "The History and Status of General Systems Theory." *Academy of Management Journal*, **15**(4), December 1972, 407-426.