An Overview of the

Systems Engineering Knowledge Domain

Assignment for ESD.83:
Research Seminar in Engineering Systems

Prepared by
Annalisa L. Weigel
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"Society is always taken by surprise at any new example of common sense."

—Ralph Waldo Emerson

Overview of the Approach

A succinct overview of the field of systems engineering can be gained from examining several definitions of systems engineering proposed by various authors over the years. Jerome Lake offers that "systems engineering is an interdisciplinary, comprehensive approach to solving complex problems and satisfying stakeholder requirements." [in Martin 1997, p. 244]

Robert Shishko provides more specific details than Lake, and adds in the notion that systems engineering is an iterative process and describes six phases of the systems engineering process. He says "…[systems engineering] consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals." [Shishko, 1995, p. 4]

Blanchard and Fabrycky, in their classic text on systems engineering, go another step beyond the Lake and Shishko definitions to include the idea that systems engineering is an iterative process. They define systems engineering as involving "the application of efforts necessary to

1. transform an operational need into a description of system performance parameters and a preferred system configuration through the use of an iterative process of functional analysis, synthesis, optimization, definition, design, test, and evaluation;
2. integrate related technical parameters and assure the compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and
3. integrate performance, producibility, reliability, maintainability, manability, supportability, and other specialities into the total engineering effort." [Blanchard & Fabrycky, 1981, p. 24]

As implied from the definitions above, systems engineering employs a reductionist approach to break down system requirements into small pieces, and then integrate the physical implementation of those requirements up into a complete functioning system. But the definitions do not give much insight into what a system is, or what level a system is or should be on. Perhaps as a consequence, in practice systems engineering is applied to systems at many different levels of integration. To use a spacecraft as an example, there are spacecraft system engineers, who worry about the whole spacecraft. There are also payload system engineers, who worry about just the payload (a subset of the spacecraft). And there are also many other so-called systems engineers – electrical power system engineers, thermal system engineers, communications system engineers, etc. – who each worry about their own still smaller part of the entire spacecraft. Yet they are all called "systems engineers" in many organizations. What has emerged is the notion that there are all kinds and sizes of systems around us, and systems engineering principles are general enough to be useful and applicable in a diverse settings of system types.

The field of systems engineering relies both on quantitative and qualitative tools. Quantitative tools are primarily used for the engineering analysis of candidate design solutions. These may include thermal analysis programs, mass balance programs, finite element modeling, and the like. Qualitative tools are primarily used in the non-engineering analysis aspects of the systems engineering process, such as requirements definition. Examples of qualitative tools are functional block diagrams, requirements management computer programs, trade trees, and design structure matrices.

But more than quantitative or qualitative tools, the field relies on a well-defined process by which systems engineering is accomplished. This process, more than any other attribute, seems to be what forms the common bond of systems engineering across various disciplines that employ it. The process of requirements, creation of alternative systems concepts, analysis of system concepts and trades, selection of the final design, and ultimately assembly, verification and deployment of the physical system, are common denominators.

Systems engineering is at the same time a design process and a management philosophy. Systems engineering is closely related to (or some would argue a synonym of) systems integration, systems architecture, the systems approach, systems engineering management, and systems design. Intentionally or unintentionally, these phrases may be used interchangeably with systems engineering by some people, and there is much discussion in the field today to try and precisely define the term “systems engineering.” In a broad sense, these phrases all describe a systems, or holistic, approach to breaking down a complex problem into parts and reintegrating those parts into the final solution. Perhaps the most classic example of systems engineering in practice was NASA’s Apollo program in the 1960s. Such a complex task as sending men to the moon was broken down into manageable parts that many hundreds of participating agencies and companies could work with and comprehend. These many parts were then integrated back into the whole solution with extremely careful attention and oversight, involving extensive testing and verification. Today, systems engineering is applied literally all over the industrial base and examples great and small can be found anywhere. Systems engineering has even been applied to social problems, though with arguably limited success.

Historical Background

It is difficult to pinpoint the exact origins of systems engineering, but many share the view that it began to emerge in the post-World War II development of large military systems such as missiles. In the 1940s, Bell Laboratories was the first to use the term “systems engineering”. In 1950, probably the first attempt to teach systems engineering was made at MIT by G. W. Gilman. Goode and Machol of the University of Michigan published *Systems Engineering* in 1957 in which they observed a phenomena of systems thinking and approaches to designing equipment. Later key figures in the field included Sage, Blanchard & Fabrycky, and Boonton & Ramo. Most of these people were engineers by training.

As early as 1966, the U.S. Department of Defense recognized the need for guidance on systems engineering, and began issuing standards that documented how to do systems engineering for various defense systems. NASA has just recently published a handbook on systems engineering written by Robert Shishko. Figure 1 shows a timeline of key individual and organizational contributors to the development of systems engineering. For a concise discussion of systems engineering history, see Brill 1998.

Figure 1: Timeline of Systems Engineering Contributors and Systems Engineering Government Standards [Brill, 1998]

Social and Institutional Outlines

The typical education for a systems engineer is a bachelor or masters degree in any field of engineering, particularly electrical, aerospace and mechanical. Historically, the systems engineer was encouraged to get a good educational grounding in an engineering discipline, and then gain practical experience and expertise in designing and building small parts of a system (subsystems). After an engineer has spent considerable time learning various subsystems, he or she is considered ready to move into a systems engineering role. This is usually (but not necessarily) proceeded by some company-provided or university-provided training on systems engineering processes. Of late, several universities have begun offering systems engineering as a major that can be studied at the undergraduate or graduate level. This creates systems engineers in the workforce that have not had the traditional long years of subsystem experience prior to becoming a systems engineer. The jury is perhaps still out on the benefits or drawbacks of this new approach.

The field of systems engineering is closely associated with the aerospace engineering industry, software engineering industry, and other large, complex technical industries. Systems engineering is being widely recognized by universities as a field of study in its own right, and many institutions now offer systems engineering degree programs and have systems engineering departments. MIT's new Engineering Systems Division is just one example.

Systems engineering got its own professional society in 1990 with the formation of the International Council on Systems Engineering (INCOSE). INCOSE had 3,400 members in 1999 in 33 chapters around the world, and it sponsors several conferences and symposia annually. More information on INCOSE can be found on the organization's web page at http://www.incose.org. Other professional societies, such as the Institute of Electrical and Electronics Engineers (IEEE) and the American Institute of Aeronautics and Astronautics (AIAA), each have subsections that focus on systems engineering as applied to electrical engineering and aerospace, respectively. INCOSE, IEEE and AIAA frequently work together and jointly sponsor workshops on systems engineering topics.

Applications

Systems engineering as it has been developed over the last fifty years has been applied very prominently in aerospace, defense and software projects. It has also been applied to automotive, civil engineering and nuclear engineering projects, as well as general commercial product development. As mentioned previously, it has even been applied to societal projects. The systems engineering approach is typically applied (and typically successful) when the requirements of the customer are known and can be stated clearly.

The Apollo lunar program is often cited as the classic or typical example of systems engineering. President Kennedy's directive to "send a man to the moon and return him safely to earth before the decade is out" is pointed out frequently as a clear statement of the requirements of the Apollo system. Sending a man to the moon was a complex task, and required the coordination of hundreds of separate organizations. The principles of systems engineering (laid out in the first section of this paper) helped ensure a technically capable system solution which ultimately contributed to Apollo's success.

Current Research

Several major areas of research and work are currently ongoing in the field of systems engineering.

- *Systems Engineering Capability Maturity Model* (SECMM) – There is a feeling that systems engineering has been around long enough now, and it is time to start finding ways to measure how well we do systems engineering. Proposed SECMMs have several levels of progress focused around how well an organization follows accepted and documented best practices for systems engineering.

- *Systems Engineering Definition and Lexicon* – There is also a feeling by some in systems engineering that there is a need for a common and accepted definition of systems engineering and its associated terminology. It's the author's opinion that creating a translation dictionary would be more appropriate than forcing all systems engineering practitioners to abandon their field-specific lexicon in favor of a universal standard. Field-specific lexicon usually exists for efficiency and other beneficial reasons.
- *Applying Information Technology to Systems Engineering Processes* – With the increase in computing power and software capabilities, many are researching how systems engineering should best take advantage of the growing IT capabilities. There exists the possibility to link analysts, designers, and customers in a collaborative, seamless systems engineering and design environment with the possibility of rapidly accelerated systems development.
- *Limitations of Systems Engineering* – In light of recent visible failures in systems engineering (NASA Mars spacecraft failures, for example), some researchers are looking into the limitations of systems engineering. The purpose of this research is to understand where other project pressures (such as cost and schedule) interact with systems engineering and undermine the ability of the systems engineering process to produce a successful product.

Evaluation

The field of systems engineering has been very successful. I postulate the success criteria of a field as:

- The pace at which its knowledge is generated, adopted and spread within its field
- The degree to which other fields embrace/adopt its ideas and concepts
- The degree to which is spawns further fields and areas of thinking and research

Systems engineering scores quite highly in all these areas. The systems engineering approach was adopted and spread quickly in the complex technical programs arena and was imported into other areas of industry within decades. Today it pervades much thinking on all sorts of product and system development efforts. It even influenced social thinking and social problem solving, as people attempted to apply the principles of systems engineering to solving societal issues in the 1960s and 1970s.

If it was difficult to establish the origins of systems engineering, it would be equally as difficult to determine exactly what other fields of thinking were born from systems engineering. But it is likely that systems engineering has helped give rise to general systems-oriented thinking in other fields.

Despite its past success, systems engineering is a reductionist approach, and may be reaching its limits applied to today's network-based complex adaptive systems, which are not well served by reductionist techniques. It is too early to tell if the field of systems engineering will adapt to these new kinds of systems, or whether the field will give way to a successor field and become another stepping stone in the history of systems studies.

References

Journals

Systems Engineering is a quarterly journal published by the International Council on Systems Engineering (INCOSE). It can be found at MIT in the Barker Engineering Library, or accessed online via the MIT libraries website. An annual international conference (with proceedings) and several smaller regional conferences are sponsored by INCOSE annually. Journals from other fields such as aeronautical and electrical engineering frequently contain systems engineering-related articles.

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