The Case for Evolving Systems Engineering as a Field within Engineering Systems

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The solution lies in the direction of taking a systems view of things. When you have the view from space, you realize that the concept of fields within fields within fields, systems of functioning within systems of functioning, is the only approach that will work. -- Edgar D. Mitchell, Lunar Module Commander Apollo 14, 1971

Abstract. Engineering Systems is an important new field of study focusing on the complex engineering of systems in a broad human, societal, and industrial context. It takes an integrative holistic view of large-scale, complex, technologically-enabled systems which have significant enterprise level interactions and socio-technical interfaces. The establishment of this new field has been a significant step toward evolving the holistic engineering-management science needed to address the complex systems challenges of this century. Systems Engineering is proposed by the authors as an essential field that appropriately lies within the larger field of Engineering Systems.

Introduction

The question often arises when Engineering Systems is introduced to systems practitioners, educators, and researchers, "what is the difference between Systems Engineering and Engineering Systems?" The response to this question is highly dependent upon the beholder's view of Systems Engineering. The two coauthors of this paper acknowledge that Systems Engineering can be and often is viewed quite differently. The extremes represent the polarized views of the field today – which we will refer to as 'classical view' versus an 'expanded view'. We will examine how each view of Systems Engineering is contrasted with Engineering Systems. We assert that no matter which perspective is taken, Engineering Systems is broader than Systems Engineering, and that the evolution of Systems Engineering as a field within the larger field of Engineering Systems will enrich the practice of engineering and benefit stakeholders of complex technology-enabled systems.

The debate on the definition of Systems Engineering has been ongoing for several decades without conclusion, and we have yet to find our way out of what has been described by Brill (1994) as a "semantics jungle". We believe that placing it in the context of Engineering Systems will help to mitigate this debate by providing the much needed larger context field in which it can be viewed. In this sense, this is like the mathematical technique of "embedding" where broadening of the context of a problem enables the solution to be seen. Classical Systems Engineering which focuses on processes for moving from requirements to a system product is not well suited to dealing with the global and socio-technical aspects of the 21st century systems, and it does not adequately address the enterprise subsystem in the overall system. Classical Systems Engineering principles and practices need to be adapted and expanded to fully support the engineering of highly complex systems. Taking an expanded view of Systems Engineering (including the full lifecycle, systems architecting, and engineering management) seeks to solve these inadequacies but does not quite do so. In this paper, we begin to explore what distinguishes the engineering systems perspective from the systems

engineering perspective. By placing Systems Engineering within the context field of Engineering Systems, we believe Systems Engineering can be transformed to more effectively contribute to addressing the engineering challenges of this century.

Engineering Systems and Systems Engineering are both evolving fields, and we believe it is critical that they evolve synergistically and not as two distinct 'competing' fields. Systems Engineering educational programs have increased significantly in the past two decades, and if Engineering Systems becomes the context field for Systems Engineering there must be major transitions in engineering education strategies, policies, and structures. We highlight MIT's Engineering Systems Division as one model of a new education and research approach, and discuss issues and challenges faced in transforming engineering education and practice.

Definitions of Engineering Systems and Systems Engineering

The field of Engineering Systems is continuing to evolve through dialogue within MIT, between MIT and other universities, and MIT and its industry and government partners. Previous papers by MIT authors[1] provide an elaborated definition and additional discussions of the field. For the purposes of this paper, we present the following short definition to describe to the reader the field of Engineering Systems: *Engineering Systems is a field of study taking an integrative holistic view of large-scale, complex, technologically-enabled systems with significant enterprise level interactions and socio-technical interfaces.* We believe there are four underlying disciplines for Engineering Systems: (1) systems architecture/systems engineering and product development, (2) operations research and systems analysis, (3) engineering management and (4) technology and policy. One important point that needs to be made explicit is that Engineering Systems does not replace Systems Engineering, which remains the fundamental process for design and development of the system.

The field of Systems Engineering has existed much longer than this emerging field of Engineering Systems and this would lead one to conclude that there is an accepted standard definition. In reality, the number of definitions of Systems Engineering has increased significantly over the past decade or more. Classical definitions of Systems Engineering arose in the 1960s and 1970s, and are still widely in use today. The classical definitions of Systems Engineering are fairly similar in nature, with some variation regarding reference to it as a practice, process, method, or approach. An example of a definition taking the classical view of Systems Engineering is:

> *Chase (1974) – Systems Engineering is the process of selecting and synthesizing the application of the appropriate scientific and technical knowledge to translate system requirements into system design and subsequently to produce the composite of equipment, skills, and techniques that can be effectively employed as a coherent whole to achieve some stated goal or purpose.*

In the past decade, an expanded view of Systems Engineering has emerged that takes it beyond the translation of requirements to design as a core focus. There are many varied definitions at this end of the spectrum, and we highlight three examples:

> *Ramo (1993) – Systems Engineering is a branch of engineering that concentrates on the design and application of the whole as distinct from the parts…looking at the problem in its entirety, taking into account all the facets and variables and relating the social to the technical aspects.*
>
> *INCOSE (1996) -- Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems.*

[1] Refer to MIT Engineering System Division's website for many papers: http://esd.mit.edu/WPS/wps.html

Kossiakoff & Sweet (2003) – The function of Systems Engineering is to guide the engineering of complex systems. Systems Engineering is focused on the system as the whole – it emphasizes total operation. It looks at systems from the outside, that is, at its interactions with other systems and its environment, as well as from the inside.

Issues and Criticisms of Systems Engineering

The fundamental definition and scope of Systems Engineering continue to be debated. The highly polarized "classical" versus "expanded" views can lead to misunderstandings between system development stakeholders regarding roles, functions, and authorities. When taking a classical view, a major fault cited with Systems Engineering is that it does not take an adequate holistic perspective and is too introspective. Additionally, it is often viewed as taking too much of a top-down approach. Systems Engineering as a field is often cited as being too focused on processes and not enough on systems themselves. Further, Systems Engineering is sometimes criticized for focusing too extensively on requirements and not enough on system properties and behaviors. It is often seen as having too much of the "aerospace view" of systems as opposed to the "civil engineering view" of systems or the "information view" of systems.

Another highly debated issue related to Systems Engineering concerns the specific value it contributes to the acquisition, development, and sustainment of systems, and in particular an often cited shortfall is that we lack quantitative data to show this value. This led in some programs in the nineties to systems engineering being cut from the program with the attendant damage only becoming evident much later on. Recent initiatives by INCOSE, NASA, and others are attempting to collect and document the evidence to demonstrate the value of Systems Engineering on a project.

Systems Engineering assumes that the parameters related to system context and environments are constraints, and this can result in system failures and shortfalls. Engineering Systems, on the other hand, sees context and environment as variables rather than constraints. For example, when taking an engineering systems perspective, a policy that impacts the system will be viewed by Systems Engineering as fixed. Engineering Systems involves the broader view of considering changes to policy in order to optimize the overall engineering system. An illustrative case for the need for considering policy changes when beginning a systems effort is described in a case study by Buede (1998) on the failure of the initial air bag design.

The strongest heritage of Systems Engineering comes from the aerospace and defense industries, and the terminology and language of these industries tends to put artificial boundaries and constraints around it as a discipline and practice. Other domain areas such as telecommunications or public works projects may practice some of the same activities, however the terminology and flow of these activities varies and leads to a separation between the various engineering domain cultures. Another key issue with the present practice of Systems Engineering is that it is often applied at the subsystem level, sometimes applied at the higher systems level, but rarely applied at the system-of-systems or extended enterprise level. An issue in the successful application of Systems Engineering, particularly in defense programs, is that its organizational placement under program management results in system performance, operational effectiveness, and human-system requirements traded for cost and schedule.

Impacts & Influence of Positioning Systems Engineering within Engineering Systems

Over the years, Systems Engineering has suffered from an identity crisis in the sense that it has never quite fit as an engineering science, nor has it quite fit as a management science. This ambiguity has resulted in organizations being unsure of where Systems Engineering practitioners should be placed within the overall organizational structure. Similarly,

in universities we have seen that schools, divisions, or colleges are often reluctant to serve as the host for Systems Engineering departments or programs. The field of Engineering Systems provides a home for Systems Engineering, at least from a conceptual standpoint via a hybrid engineering-management science into which it can more logically fit. While it may be some time before the emerging field of Engineering Systems changes the organizational structures in corporations, we may sooner see changes to educational institutions in this regard, as exemplified by MIT's Engineering Systems Division.

A secondary effect of this placement can, perhaps, end the debate on the scope of Systems Engineering as "*little SE"* or *"big SE".* Taking the classical view of Systems Engineering, it clearly fits within the overall Engineering Systems field. The expanded view of Systems Engineering includes for example systems architecture and engineering project management, which the classical view assumes as separate. This "big SE" field in its definition approaches equivalence with Engineering Systems, but does not quite achieve it. For example, Engineering Systems includes the enterprise as an essential part of the system, while Systems Engineering views enterprise as a consideration or major influence on the system. Some key differences in taking a systems engineering perspective versus an engineering systems perspective are illustrated in Table 1.

Table 1. Systems Engineering Perspective versus Engineering Systems Perspective

	Systems Engineering Perspective	***Engineering Systems Perspective***
Scope	May be applied to small scale to large scale efforts including subsystems, systems, system of systems	Applies to very large-scale, complex open systems which are technologically enabled
Policy	Policies and standards are viewed as fixed and constrain the system solution	Policies and standards are viewed as variables that can be created or adapted to optimize the overall system solution
Socio-technical	Socio-technical aspects of the system are viewed as considerations in engineering	Socio-technical aspects of the system are viewed as primary in an overall system solution
Stakeholders	Primary focus on the customer and the end-users of the product system	Balanced focus on all stakeholders impacted by engineering system including product system, enterprise system, environment
Engineering Processes	Architecting, design, and development is applied to the product system	Architecting, design, and development is applied to both product system and enterprise system
Practitioners	Practitioners are systems architects, systems engineers, and related specialists performing systems engineering process	Practitioners include systems architects, enterprise architects, systems engineers, operations analysis, project managers, policy makers, social scientists, and many more involved in total engineering system
Future Vision	Predictably develop systems with optimized performance for value to satisfy primary stakeholders	Predictably develop sustainable engineering systems with optimized value to society as a whole

The authors believe that positioning Systems Engineering within the field of Engineering Systems can also serve to bring about a convergence in the definition of Systems Engineering and clarify its boundaries and interfaces. Further, Engineering Systems will influence Systems Engineering in a very positive way in making it a more robust approach, with increased focus on socio-technical issues, the enterprise producing the end system, and overall system properties. Engineering Systems and Systems Engineering are both evolving fields, and we assert that they

must be evolved synergistically. The negative scenario is that if we fail to do so, they will compete with one another and result in increasing ambiguity about the respective fields.

Engineering Systems, because of its very broad nature, has a risk of being viewed as so broad that it has nothing practical to say about real systems. For the field to directly contribute to real-world systems challenges, it must include the practical methods needed to create and sustain large-scale complex systems and enterprises. The inclusion of Systems Engineering as a sub-field provides principles and proven methods to serve as the essential applied engineering activity.

Systems Engineering practices and activities will also be influenced by engineering systems thinking. Engineering Systems may introduce new inputs or demands on classical systems engineering practices. The engineering systems perspective may put more focus on environmental requirements; drive more studies on human-systems interrelationship; widen the parameters to be considered in robust design; and have many other influences.

Over forty years ago, Arthur D. Hall (1962) identified five traits of the ideal systems engineer and these certainly still stand today; these traits are: (1) an affinity for the systems point of view, (2) faculty of judgment, (3) creativity, (4) facility in human relations, and (5) a gift for expression. The specific role of the systems engineer has traditionally been rather inwardly focused, with considerations to environment and external systems. In this broader field of Engineering Systems, the systems engineering practitioners may need to re-evaluate their roles and responsibilities in the overall systems effort.

Additionally, these practitioners may find that they need new knowledge to function in this broader context, and that they may require an expanded vocabulary and set of practices in order to collaborate with specialists they have not typically been involved with. For example, as the product system becomes increasing complex and intertwined with environment and enterprise system, systems engineers may find themselves working side by side with a public policy maker or an environmental scientist. This collaboration may already be happening today in certain types of systems efforts such as large public works projects, but it has not been typical for some of the heritage aerospace systems engineers, for example. The result is that it is likely that systems leaders will need to expand both knowledge and viewpoint, and as a result more robust education and practice will be required.

Realizing the Vision

Our vision is for Systems Engineering as an evolving and thriving field within the emerging field of Engineering Systems. To realize such a vision, there are many changes and shifts in perception and pragmatic practice that must take place. We highlight three imperatives for the realization of our 'field within a field' vision.

Imperative One: C*lassical Systems Engineering principles and practices need to be adapted and expanded to fully support the engineering of highly complex systems.*

The principles and practices today which are at the core of Systems Engineering are sound and widely accepted. We assert, however, that these current principles and practices are too limited to deal with all of the issues that we see in today's large-scale complex systems (Hughes, 1998). There needs to be additional research and practice to determine how to best adapt and build on these proven practices to accommodate increased complexity (for example, in system of systems efforts). Some of the questions to be considered include:

1. What Systems Engineering principles and practices are too limited at present to effectively deal with large-scale complex systems with socio-technical interfaces?
2. How can these be adapted and expanded to take the more robust view of the field of Engineering Systems?

3. What new methodologies and tools are needed to implement an expanded set of systems principles and practices?
4. What case studies can show positive/negative impacts of taking/not taking the engineering systems perspective in designing, developing and sustaining complex systems?

Research is also needed to determine how systems architecting can be adapted for architecting the enterprises that are part of the overall engineering system. MIT and many other leading universities such as USC have already initiated research projects to address this question. Systems thinking practices have been studied for some time now, but now at MIT and other universities (Frank, 2000) we are beginning to explore what distinguishes "engineering systems thinking" from "systems engineering thinking". As an example, there is a critical difference in thinking about policy as a variable (Engineering Systems) versus thinking about policy as a constraint (Systems Engineering) – both are necessary but applied uniquely based on lifecycle considerations.

Imperative Two: ***Engineering Systems and Systems Engineering are both evolving fields… it is critical that they evolve synergistically and not as two 'competing' fields.***

Systems Engineering is not a new discipline, yet it is undergoing significant evolution driven by the increasing technological complexity, globalization, information age, and new systems paradigms such as network-centric systems, spiral development approaches, and model-based development. Engineering Systems is an emergent field, and as a meta-level field it is faced with evolution within its sub-fields, as well as the larger holistic field. This challenge involves a continuous need to harmonize the practices of the subfields as they evolve, and in the process bring a convergence in definitions and perspectives. Some of the questions to be considered include:

1. How can the varied definitions and views of Systems Engineering converge within the context of Engineering Systems so a comprehensive approach is consistently taken?
2. What is the common taxonomy that will serve the needs of Engineering Systems and Systems Engineering, as well as the other subfields of Engineering Systems?
3. What other sub-fields of Engineering Systems are highly interrelated to Systems Engineering, and what research is needed to explore convergence or cooperation of these sub-fields?
4. What lifecycles, practices and methods, when harmonized or adapted, can result in an emergent approach that can better serve the needs of the whole engineering system (product system, enterprise system, and environment)?

Imperative Three: ***For engineering systems to become the context field for Systems Engineering there must be major transitions in systems education strategies, policies, and structures.***

The number of Systems Engineering degree and non-degree programs has been rapidly growing in recent years. In the early 1980s, according to a study cited by Gasparski (1982), there were 22 Masters and PhD programs in systems studies in universities in the United States. According to an ongoing study by INCOSE, there are now at least 94 Masters and PhD programs in the US related to Systems Engineering (Fabrycky, 2003). Additionally, there are a number of short courses and certificate programs. Although we cite solely the figures for the US, this growth in programs is a trend that is international. These programs are firmly embedded in many universities today, and the structure varies from standalone departments to cross-departmental programs. Curriculum varies, with each university having a specific positioning to offer. The core Systems Engineering fundamentals have experienced some

convergence with collaboration through professional societies and consortiums, and can be expected to increase in the coming years.

As Engineering Systems continues to evolve, these existing Systems Engineering programs will need to respond in some way. Some of the questions to be considered regarding the future of educational policies, structures, and practices include:

1. What new knowledge, skills, and abilities will systems practitioners need for a more robust engineering systems perspective?
2. How will existing Systems Engineering curricula need to change to embrace Engineering Systems as its context field? For example, the issues emphasized in rocket propulsion are different when it is embedded in space system engineering as compared to missile engineering.
3. How will universities need to evolve their structures and policies to support this vision?
4. What strategy can be used to transition the current educational model(s) to a new model with Systems Engineering field within context of the Engineering Systems field?
5. Does the Engineering Systems context field enable the development of better systems leadership for addressing 21st century engineering challenges?

MIT's Engineering Systems Division has now had a five year history of addressing this issue, and in the next section we highlight our program and current challenges faced. The contributions of Engineering Systems as a new model for educating engineering leaders is further developed in (Hastings, 2004).

A New Education Model

At the Massachusetts Institute of Technology a new educational model and organization for engineering education has been established to address the large-scale engineering challenges of the 21st century, as the Engineering Systems Division (ESD)[2]. The motivation behind ESD is described by Professor Daniel Roos, Associate Dean for Engineering Systems and ESD Co-Director:

> *As you look at what's happening in society, you see technology taking a more important role in our lives, and the systems and products that we use are much more complex. There is a great concern for not only the use of a particular product but the impact of that product or system on people and on the natural environment. This suggests that the role of the engineer is changing significantly, particularly as engineers assume leadership positions. In addition to technical expertise, engineers need an understanding of the broader implications of their profession and the work that they do. That's really the motivation for the Division-it's dealing with complex products and systems. We believe we are defining engineering systems as a new field of study, broadening engineering education and practice. (Roos, 1999)*

The Engineering Systems Division (ESD) creates and shares interdisciplinary knowledge about complex engineering systems through initiatives in education, research, and industry partnerships. ESD takes a broad perspective and enriches engineering practice to include the context of systems challenges as well as the consequences of technological advancement. ESD has a dual mission: (1) to define and evolve engineering systems as a new field of study; and (2) to embed this understanding in engineering education and practice. It serves as the intellectual home for key programs and centers, engages faculty across many departments and disciplines, facilitating new dialogues about engineering innovation.

ESD bring together a number of existing academic programs with some 350 graduate students, and has added a masters level and doctoral level degree in Engineering Systems.

[2] For more information, refer to Engineering Systems Division website at http://esd.mit.edu

Degrees are also offered under programs that preceded ESD, including Leaders for Manufacturing (LFM), System Design and Management (SDM), Master of Engineering in Logistics (MLOG) and Technology and Policy Program (TPP). Under the umbrella of ESD, there are four research centers with an annual research volume of nearly $20M including Center for Technology, Policy, and Industrial Development; the Center for Transportation and Logistics; the Industrial Performance Center; and the Center for Innovation in Product Development. ESD has influenced the collaboration of the various departments and programs within these research centers. The development of ESD System Studies is a key focus, involving interdisciplinary exercises for teaching engineering systems. They combine traditional "case study" methods with technical models and data sets to teach students how to analyze and develop solutions for complex engineering systems.

The ESD organization includes faculty holding dual appointments that commit their time and efforts to both an academic department and to the Division. These dual appointments support the development of new interdisciplinary frameworks and methodologies that define Engineering Systems as a field of study while faculty remain involved with their engineering, management, or social science departments. ESD presently has over 45 faculty and teaching staff from seven engineering departments, and MIT's Sloan School of Management and School of Humanities, Arts, and Social Sciences.

ESD is developing new intellectual infrastructures as well, including the Engineering Systems Learning Center which serves as a repository and enabler for cases, simulators, and other educational material on complex systems. The Engineering Systems Knowledge Network engages peer institutions, such as Cambridge University and the Technical University of Delft, as partners. ESD is also building on established strengths in policy issues and expanding productive relationships with both industry and government.

ESD has been operating for almost five years as of the writing of the paper and a comprehensive review of progress and results is underway. The fundamental question for an academic institution like MIT is whether this model of organizing the faculty will bring added value to the intellectual study of complex systems.

Summary

The authors propose that Systems Engineering will most effectively evolve if it is positioned as one of the essential sub-fields within the broader field of Engineering Systems. We believe that “classical” Systems Engineering is not well suited to dealing with the global and socio-technical aspects of the 21st century engineering systems, and it does not adequately address the enterprise subsystem in the overall system. The move to expand Systems Engineering to a broader field seeks to solve these inadequacies but does not quite do so.

Engineering Systems is an emerging field that is enriched by directly embracing the principles, practices, and methods of Systems Engineering, in addition to extending and adapting these to accommodate an even broader purpose. Two decades ago, Booton and Ramo (1984), observing the trend in increasing complexity of complex systems, said “we should anticipate the use of systems engineering techniques on an even wider range of systems than in the past”. These authors also asserted “the need for a systems approach to major problems of society” and that “the fundamental concepts of systems engineering, even if not all of its specific tools, would improve handling of such problems in the future”. We believe that placing Systems Engineering within the context field of Engineering Systems will further enable its transformation to more effectively contribute to addressing the engineering challenges of this century. Realizing our vision will only be achieved if we take a true systems perspective of fields within fields within fields.

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