Systems Engineering Education

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***Abstract*—We discuss some basic principles underlying systems engineering, and the translation of these principles to practices such as to enable the engineering of trustworthy systems of all types that meet client needs. This special issue is concerned with systems engineering education. Thus, it is inherently also concerned with systems engineering, as this provides a major component of the material that is important for systems engineering education. After setting forth some of the necessary ingredients for success in systems engineering, we devote some comments to objectives for and needs in systems engineering education.**

***Index Terms*—Engineering education, knowledge engineering, systems engineering.**

I. What is Systems Engineering?

THE PAPER is concerned with the engineering of systems, or **systems engineering**. It is also concerned with the **processes** needed to bring about trustworthy systems in an effective and efficient manner. We are also and especially concerned with strategic level systems engineering, or **systems management**, that is needed to select an appropriate process and ways to provide technical direction over this process. We begin our effort by first discussing the need for systems engineering, and then providing several definitions of systems engineering. We next present a structure describing the systems-engineering process. The result of this is a ***lifecycle model*** for systems engineering processes. This is used to motivate discussion of the functional levels, or considerations, involved in systems engineering efforts:

- systems engineering ***methods and tools***, or technologies
- a systems methodology, or ***process***, as a set of phased activities that support efforts to engineer the system, and
- ***systems management***.

Fig. 1 illustrates the natural hierarchical relationship among these levels. Systems engineers are very concerned with each of these three functional levels. Products (and services) are engineered through the use of an appropriate process, or processes. The tailoring of a process for use on a specific instance is accomplished through systems management. The drivers of systems management include the external opportunities and pressures, and the internal strengths and weaknesses of a given systems engineering organization, as well as the organizational leadership and culture associated with the organizations associated with the tasks at hand. There are a variety of tools and methods, and technologies needed at the level of product, process, and systems management. Appropriate measurements are also needed at all three levels.

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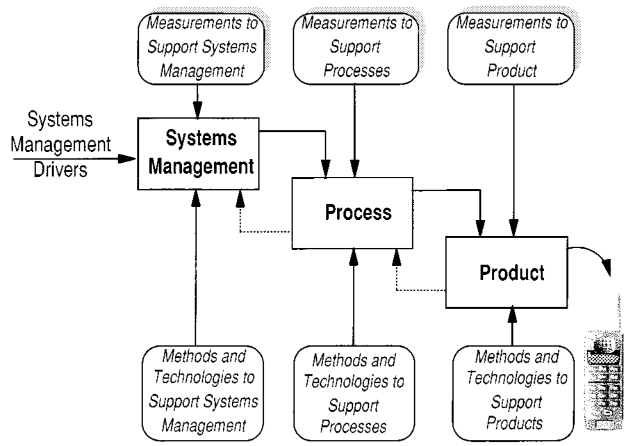

Fig. 1. Systems engineering as method, process, and management.

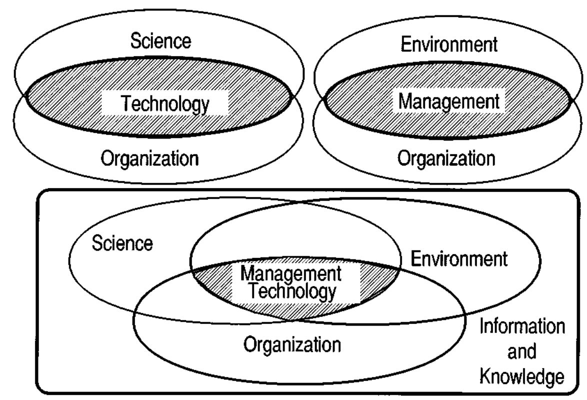

Fig. 2. Systems engineering as a management technology.

Systems engineering is a management technology—which involves the interactions of science, the organization, and the environment, and the information and knowledge base that supports each, as shown in Fig. 2. Technology is the result of, and represents the totality of, the organization, application, and delivery of scientific knowledge for the presumed enhancement of society. This is a functional definition of technology as a fundamentally human activity. Associated with this definition is the fact that a technology inherently involves a purposeful human extension of one or more natural processes. Management involves the interaction of the organization with the environment. Consequently, a management technology involves the interaction of science, the organization, and the environment. Associated with this must be the information and knowledge that enables understanding and action to effect change.

The purpose of systems engineering is to support individuals and organizations that desire improved performance through technology. This is generally obtained through the definition,

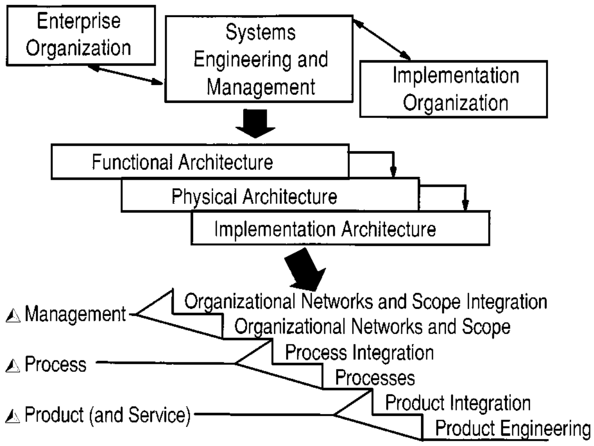

Fig. 3. Systems engineering as a broker of knowledge to enable specifications of system architecture and ultimate engineering solutions at any of six levels.

development, and deployment of technological products, services, or processes that support functional objectives and which fulfill needs. Thus, systems engineering is inherently associated with user organizations and humans in fulfillment of its objectives. The engineering of systems also involves the interaction with humans and organizations who are responsible for the physical implementation of systems. Systems engineers generally play an important role as brokers of information and knowledge, and in associated technical direction efforts, in working both with user enterprises and implementation specialists who accomplish the actual realization of physical systems. Fig. 3 illustrates these conceptual interactions. The using enterprise will have various functional needs and the functional architecting and conceptual design part of a systems engineering effort is concerned with expressing these needs in the form of a functional architecture. Systems engineers are also concerned with translation of this functional architecture into a physical architecture which describes the logical breakdown of the system ultimately to be constructed in such a way that partitioning of the systems into various subsystems is then possible. Each of these subsystems should be as independent as possible and should be such that integration of them after implementation is as straightforward and feasible as possible. This physical architecture, or logical design description of the system, is next translated into an implementation architecture that provides guidance for various implementation contractors in bringing about the various subsystems, which comprise the system. This is also represented in Fig. 3, which shows the three major architectural perspectives, or views, of a system.

The products, and associated knowledge, transferred to the enterprise, or user or client, organization through the engineering of systems may represent support at three levels: product, process, or management. Within each of these three levels, new products, processes, or organizational networks and scope may be enabled. In a very large number of situations, there will be the need to integrate these within existing or legacy systems of products, processes, or management. Thus, there are six levels of support provided by systems engineering, and the role of systems integration in these is very strong, as also suggested in Fig. 3.

We can think of a physical, or more properly stated natural, science basis for systems engineering, a organizational and social science basis, and an information science and knowledge basis. The natural science basis involves primarily matter and energy processing. The organizational and social science basis involves human, behavioral, economic, and enterprise concerns. The information science and knowledge basis is often very difficult to support effectively. This is so since knowledge is not a truly fundamental quantity but one that derives from the structure and organization inherent in the natural sciences, and the organizational and social sciences. It also results from the purposeful uses to which information is to be put, and the experiential familiarity of information holders with the task at hand and the environment into which the task is imbedded such as to enable interpretation of information, within an appropriate context, as knowledge. Thus the presence of information and knowledge, as information embedded within context, in Fig. 2 is especially important. This representation stresses the major ingredients that systems engineers must necessarily deal with in their approach to the management technology that is systems engineering: the natural and physical sciences, organizations and the humans that comprise them, information and knowledge brokering, and the broad scope environment in which these are imbedded.

There are several drivers of new technologies. The natural and physical sciences provide new discoveries that can be converted into technological innovations. There must be a marketplace need for technological innovations. Knowledge perspectives enable the forecasting of the need for innovation. Innovation results when new knowledge principles are applied to produce new and different products and services, and associated knowledge practices, that fulfill a societal need. There is a need to insure sustainable development and the intergenerational and intragenerational equity considerations associated with sustainability. This leads to the notion of a technical system, an enterprise system, and a knowledge system. Management, meaning management of the environment for each of these, is needed. Thus, systems engineers often act as brokers of knowledge across the enterprises having needs for support and the various implementation specialists whose efforts results in detailed construction of innovative products and services that provide this support. Fig. 4 illustrates these interrelations. It also indicates that systems engineering knowledge is comprised of:

1) **Knowledge Perspectives**—which represent the view that is held relative to future directions in the technological area under consideration;
2) **Knowledge Principles**—which generally represent formal problem solving approaches to knowledge, generally employed in new situations and/or unstructured environments; and
3) **Knowledge Practices**—which represent the accumulated wisdom and experiences that have led to the development of standard operating policies for well-structured problems.

These interact together and are associated with learning to enable continual improvement in performance over time. It is on the basis of the appropriate use of these knowledge types

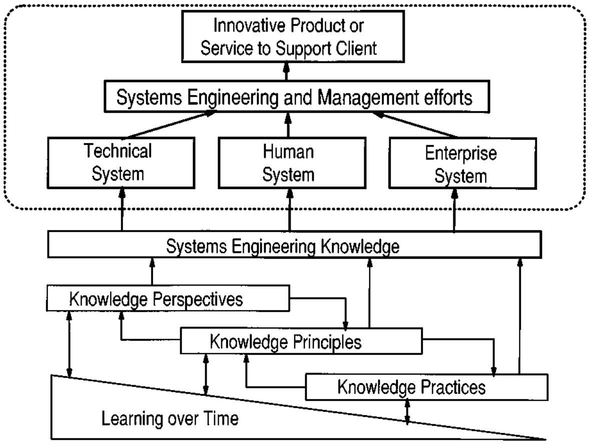

Fig. 4. Systems engineering knowledge and results of its effective use.

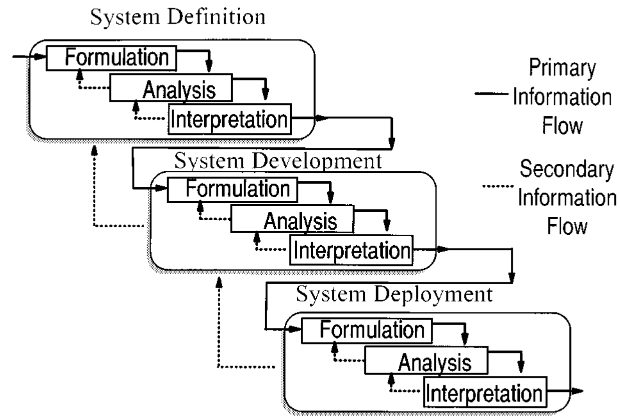

Fig. 5. A systems engineering framework comprised of three phases and three steps per phase.

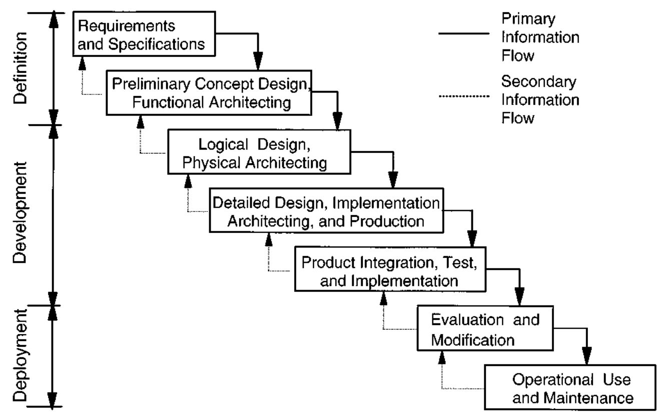

Fig. 6. One of several possible life cycle models for systems engineering.

that we are able to accomplish the technological system design and management system design that leads to a new innovative product or service.

We continue our discussion and definition of systems engineering by indicating one possible structural definition. Systems engineering is management technology to assist and support policymaking, planning, decision-making, and associated resource allocation or action deployment. It accomplishes this by quantitative and qualitative formulation, analysis, and interpretation of the impacts of action alternatives upon the needs perspectives, the institutional perspectives, and the value perspectives of clients to a systems engineering study. The key words in this definition are formulation, analysis, and interpretation. In fact, all of systems engineering can be thought of as consisting of formulation, analysis, and interpretation activities. We may exercise these in a formal sense, or in an as if or experientially based intuitive sense. Each of the essential phases of a systems engineering effort—definition, development, and deployment—is associated with formulation, analysis, and interpretation efforts. These enable us to define the needs for a system, develop the system, and deploy it in an operational setting and provide for maintenance over time. These are the components comprising a framework for systems engineering, as shown in Fig. 5. This framework is comprised of three phases—definition, development, and deployment—and three steps within each phase—formulation, analysis, and interpretation. This is a very aggregated representation of the systems engineering process. Generally, a more detailed representation is needed. Fig. 6, for example, represents a five phase representation of the systems engineering process. This provides a more realistic view of the efforts needed to engineer a system. It shows, for example, that one of the major activities of systems engineering is that of design. It represents the three perspectives, or views, on design and associated architecting that are taken by systems engineers:

- preliminary conceptual design and functional architecting;
- logical design or physical system architecting; and
- detailed design or implementation architecting.

A number of questions may be posed with respect to formulation, analysis, and interpretation that clearly indicate the role of values in every portion of a systems-engineering effort. Issue formulation questions of importance in this regard are the following.

- What is the problem? The needs? The constraints? The alterables?
- How do the client and the analyst bound the issue?
- What objectives are to be fulfilled?
- What alternative options are appropriate?
- How are the alternatives described?
- What alternative state of nature scenarios are relevant to the issue?

Analysis questions of importance are the following.

- How are pertinent state variables selected?
- How is the issue formulation disaggregated for analysis?
- What generic outcomes or impacts are relevant?
- How are outcomes and impacts described across various societal sectors?
- How are uncertainties described?
- How are ambiguities and other information imperfections described?
- How are questions of planning period and planning horizon dealt with?

Interpretation concerns with respect to value influence are the following.

- How are values and attributes disaggregated and structured?

- Does value and attribute structuring and associated formal elicitation augment or replace experience and intuitive affect?
- How are flawed judgment heuristics and cognitive information processing biases dealt with?
- Are value perspectives altered by the phase of the systems engineering effort being undertaken?

Finally, how is total issue resolution time divided between formulation, analysis, and interpretation? This is important because the allocation of resources to various systems engineering activities reflect the value perspectives of the analyst and the client. These questions associated with formulation, analysis, and interpretation need to be asked across all of the phases of systems engineering effort. This has very strong implications for the practice of systems engineering.

The efforts of some systems engineers may be primarily associated with the enterprise that ultimately is to become the client or user of the system to be engineered. They may also be associated with a systems engineering organization as an independent broker. Alternately, they may be associated with technical direction and management of the implementation system detailed design, production, and maintenance. Fig. 7 illustrates the primary involvement of these three major stakeholders in the engineering of a system. Often lifecycles are represented in a "V" fashion where the "downstroke" activities are associated with decomposition of the effort into smaller and smaller components, realization of the components at the bottom of the downstroke, and then an "upstroke" effort that is comprised of various integration efforts to form the complete system. The major efforts of the enterprise or user group is in conceptualizing the need for a system. The major efforts of an independent system engineering organization are in developing physical architectures for the system, and in taking on configuration control and management roles relative to implementation of the system. The major roles of implementation contractors include realization of the system. These roles are not mutually exclusive and they overlap over time and across the several phases of activity in engineering the system, rather than the seemingly abrupt transitions of activity shown in Fig. 7.

By adopting the management technology of systems engineering and properly applying it, we become very concerned with making sure that correct systems are engineered, and not just that the system is correct according to some potentially ill-conceived notions of what the system should do. To ensure that **correct systems are engineered** requires that considerable emphasis be placed on the front-end of the systems lifecycle. It also requires attention to various verification and validation efforts that ensure that the engineered system satisfies not only the technological specifications (verification that the system is correct) but that it performs in a manner such as to satisfy user needs (validation that it is a correct system) as well.

To support these ends, there needs to be considerable emphasis on the accurate definition of a system, what it should do, and how people should interact with it before one is produced and implemented. In turn, this requires emphasis upon conformance to system requirements specifications, and the development of standards to insure compatibility and integratibility of system products. Such areas as documentation and communication are important in all of this. Thus, we see the need for the technical direction and management technology efforts that comprise systems engineering across all phases associated with engineering a system.

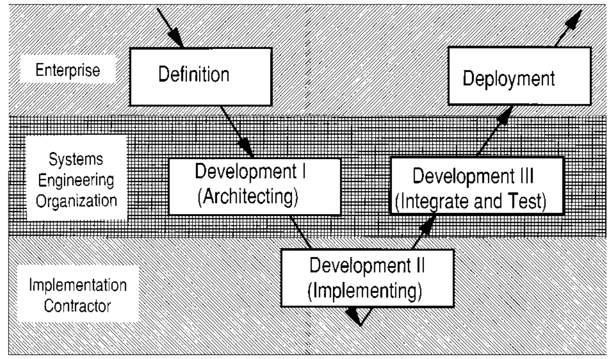

Fig. 7. "V" representation of the systems engineering process illustrating major roles for three primary stakeholders in the engineering of a system.

II. Knowledge in Systems Engineering

Clearly, one form of knowledge leads to another. Knowledge perspectives may create the incentive for research that leads to the discovery of new knowledge principles. As knowledge principles emerge and are refined, they generally become imbedded in the form of knowledge practices. Knowledge practices are generally the major influences of the systems that can be acquired or fielded. These knowledge types interact together, as suggested in Fig. 4, which illustrates how these knowledge types support one another. In a nonexclusive way, they each support one of the principle lifecycles associated with systems engineering. Knowledge practices are generally very much associated with the acquisition, or manufacturing, or production, of new systems. Knowledge principles are very much associated with the fundamental knowledge that is needed for research and development, and knowledge perspectives suggest systems planning and marketing directions. These knowledge forms flow naturally from one to the other and Fig. 4 also illustrates a number of feedback loops that are associated with learning to enable continual improvement in performance over time.

The use of the term knowledge is very purposeful here. It has long been regarded as essential in systems engineering and management to distinguish between data and information. Information is generally defined as data that is of value for decision making. For information to be successfully used in decision making, it is necessary to associate context and environment with it. The resulting information, as enhanced by context and environment, results in knowledge. Appropriate information management and knowledge management are each necessary for high quality systems engineering and management.

It is on the basis of the appropriate use of the three knowledge types depicted in Fig. 3, that we are able to accomplish the technological system planning and development and the management system planning and development, that lead to a new innovative product or service. All three types of knowledge are needed. The environment associated with this knowledge needs to be managed, and this is generally what is intended by use of the term knowledge management. Also, the learning that results from these efforts is very much needed, both on an individual and an organizational basis.

As indicated in [1]–[3], and the references contained therein, there are three different primary systems engineering lifecycles for technology growth and change:

- System Planning and Marketing
- Research, Development, Test and Evaluation (RDT&E), and
- System Acquisition, Production, or Procurement.

These are each generally needed, and each primarily involves use of one of the three types of knowledge. There are a number of needed interactions across these lifecycles for one particular realization of a system acquisition lifecycle. It is important that efforts across these three major systems engineering lifecycles be integrated. There are many illustrations of efforts that were dramatically successful efforts in RDT&E, but where the overall results represent failure because of lack of consideration of planning, or of ultimate manufacturing needs of a product while it is in RDT&E.

In our definition of systems engineering, we indicated that systems engineers are concerned with the appropriate

- **definition**,
- **development**, and
- **deployment** of systems.

These comprise a set of phases for a systems engineering lifecycle, as illustrated in Fig. 5. There are many ways to characterize the lifecycle phases of systems engineering processes, and a considerable number of them are described in [1]–[3]. Each of the lifecycle models, and those with are outgrowths of them, are comprised of these three phases. For pragmatic reasons, a typical lifecycle will contain more than three phases, as we shall soon indicate.

III. The Importance of Technical Direction and Systems Management

In order to resolve large scale and complex problems, or to manage large systems of humans and machines, we must be able to deal with important contemporary issues that involve and require:

1) many considerations and interrelations;
2) many different and perhaps controversial value judgments;
3) knowledge from several disciplines;
4) knowledge at the levels of principles, practices, and perspectives;
5) considerations involving definition, development, and deployment of systems;
6) considerations that cut across the three different lifecycles associated with systems planning and marketing, RDT&E, and system acquisition or production;
7) risks and uncertainties involving future events which are difficult to predict;
8) a fragmented decision making structure;
9) human and organizational need and value perspectives, as well as technology perspectives; and
10) resolution of issues at the level of institutions and values as well as the level of symptoms.

Those involved with the professional practice of systems engineering must use of a variety of formulation, analysis, and interpretation aids for evolution of technological systems and management systems. Clients and system developers alike need this support to enable them to cope with multifarious large-scale issues. This support must avoid several potential pitfalls. These include the following 12 deadly systems engineering transgressions.

1) There is an over-reliance upon a specific analytical method or tool, or a specific technology, that is advocated by a particular group.
2) There is a consideration of perceived problems and issues only at the level of symptoms, and the development and deployment of "solutions" that only address symptoms.
3) There is a failure to develop and apply appropriate methodologies for issue resolution that will allow identification of major pertinent issue formulation elements, a fully robust analysis of the variety of impacts on stakeholders and the associated interactions among steps of the problem solution procedure, and an interpretation of these impacts in terms of institutional and value considerations.
4) There is a failure to involve the client, to the extent necessary, in the development of problem resolution alternatives and systemic aids to problem resolution.
5) There is a failure to consider the effects of cognitive biases that result from poor information processing heuristics.
6) There is a failure to identify a sufficiently robust set of options, or alternative courses of action.
7) There is a failure to make and properly utilize reactive, interactive, and proactive measurements to guide the systems engineering efforts.
8) There is a failure to identify risks associated with the costs and benefits, or effectiveness, of the system to be acquired, produced, or otherwise fielded.
9) There is a failure to properly relate the system that is designed and implemented with the cognitive style and behavioral constraints that effect the user of the system, and an associate failure of not properly designing the system for effective user interaction.
10) There is a failure to consider the implications of strategies adopted in one of the three lifecycles (RDT&E, acquisition and production, and planning and marketing) on the other two lifecycles.
11) There is a failure to address quality issues in a comprehensive manner throughout all phases of the lifecycle, especially in terms of reliability, availability, and maintainability.
12) There is a failure to properly integrate a new system together with heritage or legacy systems that already exist and which the new system should support.

Systems engineers take on technical roles associated with the engineering of systems. They take on management roles associated both with identification of appropriate processes and with technical direction of implementation efforts and associated overall configuration control. They take on roles associated with management of the environment surrounding the engineering of systems. Failures can occur in any of these. Most of the failures are generally associated with systems management failures.

In general, we may approach issues from an inactive, reactive, interactive, or proactive perspective.

- ***Inactive***—This denotes an organization that does not worry about issues and which does not take efforts to resolve them. It is a very hopeful perspective, but generally one that will lead to issues becoming serious problems.
- ***Reactive***—This denotes an organization that will examine a potential issue only after it has developed into a real problem. It will perform an outcomes assessment and after it has detected a problem, or failure, will diagnose the cause of the problem and, often, will get rid of the symptoms that produce the problem.
- ***Interactive***—This denotes an organization that will attempt to examine issues while they are in the process of evolution such as to detect them at the earliest possible time. Issues that may cause difficulties will not only be detected, but efforts at diagnosis and correction will be implemented as soon as they have been detected. This will involve detect of problems as soon as they occur, diagnose of their causes, and correction of difficulty through recycling, feedback and retrofit to and through that portion of the lifecycle process in which the problem occurred. Thus, the term interactive is, indeed, very appropriate.
- ***Proactive***—This denotes an organization that predicts the potential for debilitating issues and which will synthesize an appropriate lifecycle process that is sufficiently mature such that the potential for issues developing is as small as possible.

It should be noted that there is much to be gained by a focus on process improvements in efforts from any of the last three perspectives. While proactive and interactive efforts are associated with greater capability and process maturity that are reactive efforts, reactive efforts are still needed [2]. Inactivity is associated with failure, in most cases.

Management of systems engineering processes, which we call ***systems management***, is very necessary for success. There are many evidences of systems engineering failures at the level of systems management. Often, one result of these failures is that the purpose, function, and structure of a new system are not identified sufficiently before the system is defined, developed, and deployed. These failures generally cause costly mistakes that could truly have been avoided. Invariably this occurs because either the formulation, the analysis, or the interpretation efforts (or all of them perhaps) are deficient. A major objective of systems engineering, at the strategic level of systems management, is to take proactive measures to avoid these difficulties. Contemporary efforts in ***systems engineering*** contain a focus on: tools and methods, and technologies for the engineering of systems, and associated metrics; systems methodology for the lifecycle process of definition, development and deployment that enables appropriate use of these tools, methods, and technologies; and systems management approaches that enables the proper imbedding of systems engineering product and process evolution approaches within organizations and environments. In this way, systems engineering and management provides very necessary support to the role of conventional and classical engineering endeavors through the implementation of various physical systems architectures as useful technological products. Fig. 1 attempts to show this conceptual model of systems engineering.

System management and integration issues are of major importance in determining the effectiveness, efficiency, and overall **functionality** of system designs. To achieve a high measure of functionality, it must be possible for a system, meaning a product or a service, to be **efficiently** and **effectively** produced, used, maintained, retrofitted, and modified throughout all phases of a lifecycle. This lifecycle begins with need conceptualization and identification, through specification of system requirements and architectures, to ultimate system installation, operational implementation or deployment, evaluation, and maintenance throughout a productive lifetime. It is important to note that a system, product or service, that is produced by one organization may well be used as a process, or to support a process, by another organization.

Virtually all studies of the engineering of systems show that the major problems associated with the production of trustworthy systems have more do with the ***organization and management of complexity*** than with direct technological concerns that affect individual subsystems and specific physical science areas. Often the major concern should be more associated with the definition, development, and use of an appropriate process, or product line, for production of a product than it is with the actual product itself, in the sense that direct attention to the product or service without appropriate attention to the process leads to the fielding of a low quality and expensive product or service.

IV. Lifecycle Methodologies, or Processes, for Systems Engineering

As we have noted, systems engineering is the creative process through which products, services, or systems that are presumed to be responsive to client needs and requirements are conceptualized or specified or defined, and ultimately developed and deployed. There are at least twelve primary assertions implied by this not uncommon definition of systems engineering, and they apply to the development of software intensive systems, as well as to hardware and physical systems.

1) Systems planning and marketing is the first strategic level effort in systems engineering. It results in the determination of whether or not a given organization should undertake the engineering of a given product or service. It also results in a, at least preliminary, determination of the amount of effort to be devoted to RDT&E and the amount to actual system acquisition or production.
2) Creation of an appropriate process or product line for RDT&E and one for acquisition is one result of system planning and marketing. The initial systems planning and marketing efforts determine the extent to which RDT&E is a need, and also determine the acquisition process characteristics that are most appropriate.

3) An appropriate planning process leads to efficient and effective RDT&E, and to the actual system acquisition which follows appropriate RDT&E.
4) The first phase of any systems engineering lifecycle effort results in the identification or definition of specifications for the product or service that is to result from the process.
5) Systems engineering is a creative process based effort.
6) Systems engineering activities are conceptual in nature at the initial phases of effort, for either of the three generic lifecycles, and become operational in later phases.
7) A successful systems engineering product or service must be of high quality and responsive to client needs and requirements.
8) A successful systems engineering product, or service, generally results only from a successful systems engineering process.
9) An appropriate systems engineering process is, generally, the result of successful systems management, and appropriate planning and marketing.
10) Appropriate systems engineering efforts need necessarily be associated with systematic measurements to insure high quality information as a basis for decision making across the three generic systems engineering lifecycles.
11) Appropriate systems engineering efforts are necessarily attuned to organizational and environmental realities as they affect both the client organization and the systems engineering organization.
12) Systems engineering efforts are, of necessity interactive. However, they transcend interactivity to include proactivity.

Good systems engineering practice requires that the systems engineer be responsive to each of these twelve ingredients for quality effort. Clearly, not all members of a systems engineering team are responsible for, and participate in, each and every systems engineering activity.

V. Evolution of Engineering and Engineering Education

Many conventional definitions of engineering suggest that it is the application of scientific principles to the optimal conversion of natural resources into products and systems for the benefit of humankind. The notion that engineering is concerned with effective and efficient use of resources for the betterment of humankind is certainly correct. There are many constraints affecting this use and engineering is much concerned with developing solutions under constraints. Initially, these resources were considered to be natural resources. Today, they are considered to be any of the four major resources or capital, as unspent resources are often now called:

- natural resources, or natural capital;
- human resources, or human capital;
- financial resources, or financial capital; and
- information and knowledge resources, or information and knowledge capital.

This enlarged concept of resources enables us to include such important contemporary knowledge intensive efforts as biotechnology and biomedical engineering. Science, on the other hand, is primarily concerned with the discovery of new knowledge. There is no inherent notion of purpose in scientific discoveries, although obviously many scientific investigations are directed at knowledge that will be of ultimate beneficial use to humanity.

Much of the world has been transformed by technology, as evidenced in an excellent work [4] that describes the history of American invention and innovation over the century from 1870–1970. While this period of time could hardly be called the information age, Beniger [5] indicates that it was actually during this period that the essence of the contemporary information age began in America. Microelectronics and integrated circuit related efforts, including digital computers and communications, became the “glamour” technologies of the 1970s and 1980s. These technologies have produced profound impacts on society and on the engineering profession. The ease of development and the power of integrated circuits have actually changed the implementation architecture for electrical circuits and the performance characteristics of the resulting systems. This has led engineers to actively search for digital solutions to problems that are not themselves inherently digital. For example, the simulation of continuous time dynamic physical systems, such as aircraft, is now accomplished almost totally digitally, even though the physical systems themselves are continuous time systems for which much analog computer technology had been developed in the 1950s and 60s. This “digital everything” trend has resulted from the major developments in semiconductors, abilities at very large scale integration of electronic circuits, the resulting microprocessor based systems, and associated major reductions in size and cost of digital computer components and systems.

The digital revolution [6] has led to a death of distance [7], the merging of telecommunications technology and computer technology into information technology, and networked individuals and organizations. Major characteristics of this change include great speed [8]. More importantly, they enable networking and communications. They also result in the major necessity for all of engineering, especially systems engineering, to be especially concerned with social choice and value conflicts issues [9] that surround strategic management of the intellectual capital [10] as a major new form of capital resource that has been in very large part brought about by the information technology revolution and the use of information technology for organizational and societal improvement. We have seen the initial focus on data in the early days of computers shift to a focus on information and information technology in the decade of the 1990s. Now we sense the imbedding of information concerns into greater concerns that affect knowledge resources and knowledge management. Transdiciplinary issues of knowledge integration need to be addressed well if we are able to address the concerns of the early part of the 21st Century. There are many influences of these innovative changes [11] [12]. These are bringing about major changes [13] and needs for engineering education to adapt programs to these changes such that the customers of engineering education, students and employers, remain satisfied with educational product quality.

Comments on the changing environment for engineering and engineering education are commonplace and issues such as the following are often cited [14].

1) Availability of a many new engineered materials, and an associated much larger "design space" from which the engineer must choose.
2) Pervasive use of information technology in the products and processes of engineering.
3) Increasing number and complexity of constraints on acceptable engineering solutions. Where cost and functionality were once the dominant concerns, ecological and natural resource concerns, sustainability, safety, and reliability and maintainability are now also major concerns.
4) Globalization of industry and the associated shift from a nationally differentiated engineering enterprise to one that is far more global.
5) Major increases in the technical depth needed in manufacturing and service sectors, both in terms of absolute specific technical knowledge and the breadth of knowledge needed.
6) Expanded role of the engineer as part of integrated product and process teams, and the broad business knowledge required.
7) Increased pace of change in which there appears to be less time to assimilate and adapt.

Each of these, individually and particularly in combination, lead to many new challenges for engineering education, especially as they relate to the technical direction and knowledge brokerage needed to bring about trustworthy systems through systems engineering.

In one notable and particularly relevant work [15], relevant, attractive, and connected engineering education is outlined as education that results from engineering programs that undertake several important action items.

1) **Establish Individual Missions for Engineering Colleges**, such that an effective planning process that enacts a clear vision supportive of excellence drives each program.
2) **Re-Examine Faculty Rewards**, such as to identify incentives that assure commitment and which support the programmatic mission.
3) **Reshape the Curriculum** to enable relevance, attractiveness, and connectivity.
4) **Ensure Lifelong Learning** of all, supported in part by new and innovative technologies for education [16].
5) **Broaden Educational Responsibility**; such that engineering programs provide support for elementary and secondary education.
6) **Accomplish Personnel Exchanges**, such that faculty are able to obtain relevant experience in industry and government, and such that industry and government experience are able to contribute their talents to programs in engineering education.
7) **Establish Across the Campus Outreach**, such that high quality and relevant courses in engineering are made available throughout the university.
8) **Encourage Research/Resource Sharing, Open Competition Based on Peer Review, and Enhanced Technology Transfer**.

The attributes associated with reshaping the curriculum are of special importance in that these are directly focused on educating students for careers as professional engineers, for research, for planning and marketing, and for the many other functions performed by engineers. The major ingredients associated with reshaping the curriculum were suggested as:

- team skills, and collaborative, active learning;
- communication skills;
- a systems perspective;
- an understanding and appreciation of diversity;
- appreciation of different cultures and business practices, and understanding that engineering practice is now global;
- integration of knowledge throughout the curriculum a multidisciplinary perspective;
- commitment to quality, timeliness, continuous improvement;
- undergraduate research and engineering work experience;
- understanding of social, economic, and environmental impact of engineering decisions;
- ethics.

Each of these is particularly important for engineering education, and especially for systems engineering education. This is especially so in light of relevant works that examine the role of technology and values in contemporary society [17] and which stress the need for engineering to become more integrated with societal and humanistic concerns, such as to enable engineers to better cope with issues and questions of economic growth and development, and sustainability and the environment [18].

VI. Objectives for Systems Engineering Education

Engineering education is a professional activity and an intellectual activity. It is necessary that the faculty responsible for this educational delivery in engineering remain at the cutting edge of relevant technologies, including emerging technologies, as technology does change rapidly over time. Research is, therefore, an absolute essential in engineering education. It is possible through relevant research, and associated knowledge principles, to develop new engineering knowledge principles and practices that are relevant to societal improvements that result from better use of information and technological innovations. Research is exceptionally important for engineering education, as it is strongly supportive of the primary educational objective of the university. It is vital to remain vigilant relative to the educational mission, and this requires that faculty remain at the cutting edge of technology in order that they are able to provide education, meaning **teaching**, at that forefront. It is because of the need to remain current in the classroom in order to deliver education for professional practice that the strong need and a mandate for faculty research in engineering necessarily emerges.

This suggests that research activities in engineering education should generally be very student oriented. It suggests that students are an inseparable and integral part of faculty research. It suggests a major role for students in development and cooperative/internship ventures with industry and government. This creates the strong need for sponsored research and internships that assure the needed industry- government-university interactions. In addition to being intimately associated with the educational process, sponsored research also provides faculty with released time from exclusively teaching efforts for scholarly pursuits necessary to retain currency in the classroom. Also needed are innovative efforts to transfer research in emerging technologies with potential marketplace success to a position where these results are useful in system acquisition. To bring this about satisfactorily requires much attention to risk management and the necessary determination of the intersections where marketing, RTD&E and acquisition can each enjoy success.

The knowledge and skills required in engineering, and in engineering education, come from all of the sciences, and from the world of professional practice. This suggests that faculty in a professional school of engineering need to keep abreast of progress in relevant sciences, both the natural sciences and the economic and social sciences, and the mathematical and engineering sciences. Taken together, these comprise knowledge principles. It suggests also that engineering educators must keep abreast of and contribute to industrial practices in relevant professional practice areas. It is for this reason that engineering schools are and must remain ***professional schools***. This is also why close ***industry-university and government–university interactions***, becomes a most desirable, and in fact essential, part of successful, high-quality engineering education programs.

Efforts in engineering must necessarily involve likely future technological developments as well, if the customers for systems engineering education are to be satisfied. Thus, we see the need for ***knowledge practices, knowledge principles***, and ***knowledge perspectives*** in engineering education. These knowledge components, and the necessary learning to enable transition and natural evolution of one form of knowledge into the other, are very important for both technology transfer and for engineering education as they relate to engineering in general and systems engineering in particular.

A number of issues relative to engineering education are discussed in [19] and the references therein. One of the major new developments in engineering education is ***Engineering Criteria 2000*** [20], which is comprised of criteria intended to emphasize quality and preparation for professional practice. The criteria retains the traditional core of engineering, math, and science requirements. However, they also place importance on formal efforts that stress teamwork, communications, and collaboration as well as global, economic, social, and environmental awareness. They are based on the premises that:

- technology has been a driver of many of the changes occurring in society over the last several years;
- it will take on an even larger role in the future;
- the engineering education accreditation process must promote innovation and continuous improvement to enable institutions to prepare professional engineers for exciting future opportunities.

These criteria are focused on insuring competence, commitment, communications, collaboration, and the courage needed for individual responsibility. These, augmenting the usual listing of competence and assumption of individual responsibility as the two traditionally accepted key characteristics of a professional, might be accepted as the new augmented attributes of a mature professional. They should truly support the definition, development, and deployment of relevant, attractive and connected (quality) engineering education that will:

- include the necessary foundations for knowledge principles, practices, and perspectives;
- integrate these fundamentals well through meaningful design, problem solving, and decision-making efforts;
- be sufficiently practice oriented to prepare students for entry into professional practice;
- emphasize teamwork and communications, as well as individual efforts;
- incorporate social, cultural, ethical, and equity issues, and a sense of economic and organizational realities—and a sense of globalization of engineering efforts;
- instill an appreciation of the values of personal responsibility for individual and group stewardship of the natural, techno-economic, and cultural environment.
- instill a knowledge of how to learn, and a desire to learn, and to adapt to changing societal needs over a successful professional career.

The unprecedented technological advances in the information technologies of computation, communication, software, and networking create numerous opportunities for enhancing: our life quality, the quality of such critical societal services such as health and education, and the productivity and effectiveness of organizations. We are witnesses to the emergence of new human activities that demand new processes and management strategies for the engineering of systems. The major need is for appropriate management of people, organizations, and technology as a social system. Systems engineering is basically concerned with finding integrated solutions to issues that are of large scale and scope. Educational programs in systems engineering need to be especially concerned with the emergence of systems engineers who can cope with these challenges. They need especially to be concerned with: the three levels of support for systems engineering efforts—methods, tools, technologies, and metrics; processes, and systems management. They need to be especially concerned with the evolution of technological innovations through life cycle processes that involve: research, development, test, and evaluation, planning and marketing; and systems acquisition, procurement, and manufacturing. They need to be concerned with efforts that are reactive to observed deficiencies, interactive to avoid errors to the extent possible; and proactive, such as to enable the determination of processes and systems management procedures based on realistic future perspectives. They must pay critical attention to integration at the level of product, processes, and systems management; and they must be aware of the need for knowledge integration itself. Also, there is much need to be concerned with the knowledge brokerage and technical directions necessary to insure success in the engineering of trustworthy and useful large-scale systems of humans, organizations, and technologies.

Much more could be said and has been said relative to these important issues as they effect engineering education in general and systems engineering education in particular [21]–[29]. The recent Electronic Industries Association Interim Standard 731, Systems Engineering Capability Model (SECM) [30] identifies 19 focus areas for systems engineering that fall into three natural groupings, or categories: Technical, Management, and Environment. These three groupings correspond closely to the notions of product, process, and systems management described here and in [1]–[3], and elsewhere. The technical focus areas support practices which are indicative of the technical aspects of systems engineering. They generally correspond well with definitions and practices contained in two important standards for Systems Engineering, EIA 632, Processes for Engineering a System [31], and IEEE STD 1220, Trial-Use Standard for Application and Management of the Systems Engineering Process [32]. The systems management focus area practices support the technical focus areas through planning, control and information management. These are attempted to incorporate and practices from systems engineering standards with industry-wide best practices such as to enhance cost-effectiveness in the engineering of systems, or systems engineering. The environment focus areas in the SECM standard represent those practices that facilitate sustained execution of systems engineering processes throughout the systems engineering organization. These are intended to ensure alignment of process and technology development with systems engineering business objectives. These practices support the technology and management focus areas. Fig. 8 represents these 19 focus areas. These comprise a very useful set of needed abilities for systems engineers. A major goal of systems engineering education should be to provide relevant courses and laboratories that support the attainment of abilities relative to each of these focus areas. There are a variety of tools and methods that support satisfactory performance in each of these focus areas and provision of support from these will allow for incorporation of the what to do delineated so well in the standard with the how to do it that is also needed for trustworthy systems engineering. This is a never ending continuous improvement effort, as also represented in Fig. 8. In a similar way, systems engineering education is a never ending lifelong process that cuts across the three major dimensions for systems engineering effort shown in Fig. 9 and which includes appropriate lifecycle processes phases and steps within each.

VII. Summary

We have presented a wide scope discussion of systems engineering education. We have discussed the emergence of concerns for large systems of humans, organizations, and technologies. We have discusses some of the principles of systems engineering that need necessarily be incorporated into relevant curricula. We have stressed systems engineering education as preparation for professional practice as well as for the development of knowledge principles through research. We have focused on contemporary concerns relative to educational quality and responses to these, and educational needs and accreditation standards for the 21st Century to achieve this quality. A flow chart of interactions of systems engineering education would show a very large number of linkages across many related elements thereby indicating that engineering education itself is a

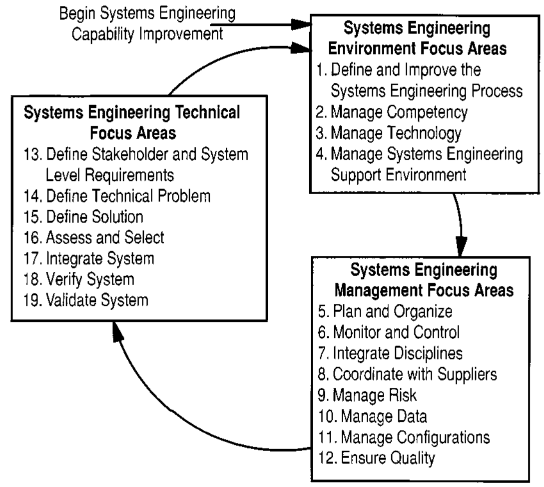

Fig. 8. Systems engineering capability model focus areas.

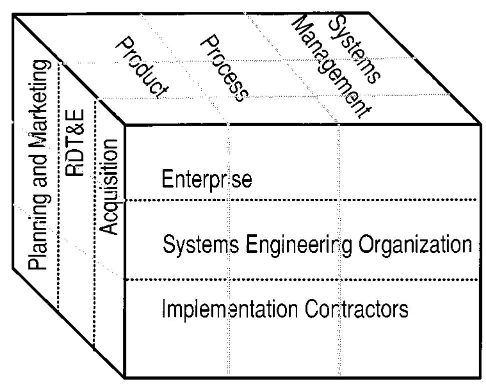

Fig. 9. One of the many possible 3-D frameworks for systems engineering.

system of large scale and scope. Our discussion is necessarily wide scope in that systems engineering education itself is necessarily wide scope.

A systems engineer must surely understand the principles of the natural and mathematical sciences. They must have this understanding in order know how to use these to support the definition, development, and deployment of cost effective and trustworthy systems and also to have the background necessary to retain intellectual currency throughout a lifetime of continued learning. The purpose behind the engineering of systems is the development of products, services, and processes that are successful in the marketplace through fulfillment of societal needs. Technological, organizational, and societal change are the order of the day, just as they have been throughout history. If these changes are to be truly effective and effective, over the long term especially, they must serve societal needs. This suggests that change needs necessarily to be guided by principles of social equity and justice, as well as by concerns for sustainable development and marketplace competition. There is strong evidence that this needed guidance does not always occur and that the hoped for productivity gains from technological advances may be elusive [33]–[36]. This provides the mandate for a major component of the social and behavioral sciences, and the political and policy sciences, in systems engineering education and in engineering practice as necessary ingredients for success. It also provides a mandate for major integrative knowledge components in systems engineering education and for educational accreditation standards that reflect these needs, as recognized in the reengineering efforts for education and engineering education suggested by a large number of the sources cited here. While many of these are personal references, there are a vast number of references to the excellent work of many others contained therein. These support the emergence of a multidimensional framework for systems engineering and systems engineering education, some of the many components of which have been discussed here.

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