Using systems engineering to address socio-technical global challenges

Cecilia Haskins, CSEP
NTNU, Trondheim, Norway
cecilia.haskins@incose.org

Abstract

The discipline of systems engineering continues to mature, but no systems engineer has ever been awarded the Nobel Peace Prize, while economists, politicians and others are putting more attention to the global socio-technical challenges that face the planet today. This paper will explore the essence of the systems engineering discipline and suggest ways in which systems engineering practitioners, researchers and educators can meet the global challenges.

Introduction

The past four Nobel Peace Prize winners have received their award based on contributions to some of the global challenges facing the planet; housing, financial equity, and climate change. Equally remarkable is the long history of esteemed systems thinkers who have espoused the application of various systems approaches to address the global socio-technical challenges that man has created for himself. The list includes Simon Ramo,[1] Andrew Sage,[2] Jay Forrester,[3] Bela Banathy,[4] and Buckminster Fuller,[5] to name a few. Peter Senge (1994) popularised the term 'systems thinking' by earmarking it as the Fifth Discipline that an organization needs to embrace for survival. But in spite of the best efforts of these visionaries, there is insufficient evidence that governmental or business decision-makers consciously use systems approaches in making decisions, notwithstanding that the majority of these decisions involve solutions that address both social and technological concerns.

Those of us in the systems engineering community should be dissatisfied with the negative byproducts of the world created by systems engineers – industrial pollution, traffic congestion on the land and in the air, imbalances in global lifestyle, to name a few. If systems engineers are to remain relevant in the 21st Century, the solutions for these issues can not be relegated to the realms of other disciplines alone. Systems engineers must build both their 'box' (read technology) and the (social) systems that provide a context for the box.[6]

This paper begins with a critical assessment of systems engineering as a discipline. A backward look at the variety of system engineering frameworks and perspectives is analysed to find their strongest common attributes. An overview of cases where systems approaches have been applied to real-world (social or socio-technical) solutions is then presented followed by a discussion of the implications for the application of systems engineering. The paper concludes with suggestions for future research and adjustments in educational content.

Systems Engineering – the discipline

Systems engineering exists as both a process and a method (Kossiakoff and Sweet, 2003). Checkland (1999) offers an extensive discussion of the philosophical and practical roots of systems engineering. Much has changed since Martin's (2000b) evaluation of the scope of the systems engineering profession. The practices have matured into a body of literature that supports a body of knowledge, an organization dedicated to the dissemination of this body of knowledge, and an increasing number of schools and universities offering certificates and degrees in systems engineering at every level.

This paper will not repeat again the myriad definitions for systems or engineering. Suffice it to say, the earliest mention of systems engineering in the title of a book is Goode and Machol's '*System Engineering: An Introduction to the Design of Large-Scale Systems'* from 1957. As is typical of engineering, systems engineering had already been practiced by Bell Laboratories and others for more than a decade (Hall, 1962).

The term discipline derives from the Latin d*isciplina*[7], which were written instructions to pupils or disciples. The term is also associated with methods of training such as military drills. Within educational institutions, the term refers to a formal branch of learning, often associated with a school or department, such as a school of Medicine or a department of Mathematics. Liles et. al, (1995) distilled six basic characteristics that define a *discipline*:

1. a focus of study,
2. a world view or paradigm,
3. a set of reference disciplines used to establish the discipline,
4. principles and practices associated with the discipline,
5. an active research or theory development agenda, and
6. the deployment of education and promotion of professionalism.

These are discussed briefly in turn.

Systems Engineering Focus of Study. The discipline of engineering emerged from man's need to create tools. The basic role of the engineer is to take scientific theory and put it to practical use. Hence, a new engineering discipline must have a unique focus which addresses a human need. Systems engineering, is described as "an interdisciplinary approach and means to enable the realization of successful systems."[8]

This definition is provided by the International Council on Systems Engineering (INCOSE) and further elaborates the need to consider multiple dimensions of the problem in the areas of cost, schedule and performance, manufacturing and test, training and support, and disposal. The objective of systems engineering is to integrate all the contributing disciplines to create a systematic process that proceeds from concept to production to operation, and on to retirement or recycling. The desired end result is a quality system that meets the needs of all stakeholders.

This fundamental definition has led to the development of a body of knowledge, principles, and practices having to do with all phases of the system life cycle. Systems engineering appears to have a unique, if multidisciplinary, focus of study.

Systems Engineering World View. A discipline includes a world view or paradigm that defines the framework for further development of the discipline through practice and research.

Systems engineering adopts the world view of general systems theory in viewing all systems as 'wholes' that can not be properly designed as a collection of parts. This holistic view drives advances in both practice and research relevant to systems of systems[9] - one of the newest topics in the field at this writing. Systems engineering as a profession was motivated by the increasing complexity of man-made systems and uncertainty about their environment (Ferris, 2007). This has led to a basic viewpoint of systems engineering as the balance between "risk-taking and risk-mitigation." (Kossiakoff and Sweet, 2003, 15)

Systems Engineering Reference Disciplines. As a multidisciplinary field of focus, systems engineering, by definition, builds upon a large body of existing disciplines as the base for educating future systems engineers. Given the broad scope of the system life cycle, systems engineering is firmly rooted in organizational theory, economics, mechanical and electrical engineering, to name a few. Recently attention has been given to behavioural sciences to provide a better understanding of human needs and communication mechanisms.

Systems Engineering Principles and Practices. As an offshoot of engineering, systems engineering began as a loose collection of practices that were eventually written down, analysed and refined into a set of principles. Han (2004) analysed and compared nine lists of systems engineering principles found in various publications.

Principles. The principles that apply to systems engineering are often embedded with other disciplines. By way of example, a principle of software systems engineering is "What applies to small systems does not apply to large ones." (Endres and Rombach, 2003; 71) This principle essentially warns against trying to apply the practices that work in small systems to larger, more complex systems because of issues of scalability; methods that apply to craftsmen do not support industrialization.

Systems engineers should also be familiar with the 'laws' from cybernetics and general systems theory relevant to complex systems – a sampling is listed here (with initiating author) without further discussion:

- Requisite Variety (Ashby)
- Requisite Parsimony (Miller)
- Requisite Saliency (Boulding)
- Meaning and Wisdom (Pierce)
- Authenticity and Autonomy (Tsivacou)
- Unintended Consequences (Merton)

Practices are embedded in the variety of frameworks or process models that exist to define the systematic approach to "bringing a system into being"[10] that is espoused by systems engineering. Table 1 summarizes twelve of the most often cited systems engineering frameworks. As the distribution of checkmarks indicates, there is a great deal of consistency between these models, indicating a general consensus on the set of practices appropriate to systems engineering. It should be noted that an unchecked process in the table does not mean the author of the framework is not concerned about this activity, only that the activity is not specified in the model description. The reference model is based on the scientific method for problem solving. Table 2 contains a brief description of each of the frameworks and the source used to derive the comparison.

Table 1 - One dozen Systems Engineering Frameworks

Activity	Ref.	#1	#2	#3	#4	#5	#6	#7	#8	#9	10	11	12
1. Identify stakeholders		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
2. Formulate the problem							✔	✔			✔	✔	
3. Define requirements	x	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
4. Investigate alternatives		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
5. Define performance	x	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
6. Requirements Analysis		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
7. Model the system		✔	✔		✔	✔	✔	✔	✔	✔	✔	✔	
8. Define functions	x	✔	✔		✔	✔	✔	✔	✔	✔	✔	✔	✔
9. Engineering design	x	✔		✔	✔		✔	✔	✔	✔	✔	✔	✔
10. Design Architecture		✔	✔	✔	✔	✔	✔	✔			✔		✔
11. Assess and manage risk		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔
12. Implementation		✔				✔	✔	✔	✔	✔	✔		✔
13. Manage interfaces		✔			✔		✔	✔		✔	✔		✔
14. Integration		✔	✔	✔	✔		✔	✔	✔	✔	✔	✔	✔
15. Define tests	x	✔	✔	✔	✔		✔	✔	✔	✔	✔		✔
16. Verification	x		✔	✔	✔	✔	✔	✔	✔	✔	✔		✔
17. User Training				✔				✔			✔		✔
18. Production support	x				✔		✔	✔	✔		✔		✔
19. Transition				✔		✔		✔	✔		✔		✔
20. Validation		✔		✔	✔	✔	✔	✔		✔	✔	✔	✔
21. Operational support				✔	✔	✔	✔	✔	✔				✔
22. Maintenance				✔	✔			✔	✔		✔		✔
23. Replacement, upgrade											✔		
24. Retirement, disposal				✔					✔				✔
25. Manage baselines		✔	✔	✔	✔		✔	✔	✔	✔	✔		✔
26. Manage project*		✔	✔	✔	✔	✔	✔	✔	✔		✔	✔	✔
27. Conduct reviews		✔	✔		✔		✔	✔	✔	✔	✔		✔
28. Maintain documentation			✔				✔	✔			✔		
29. Manage information	x	✔	✔		✔				✔		✔		✔
30. Address legacy systems			✔					✔			✔		
31. Manage complexity			✔		✔		✔	✔			✔		
32. Capture business plans				✔	✔		✔	✔			✔		✔
33. Manage quality				✔	✔		✔	✔			✔		✔
34. Integrate disciplines				✔	✔		✔		✔		✔	✔	✔
35. Acquisition						✔	✔	✔	✔		✔		✔
36. Supply						✔	✔		✔		✔		✔
37. Continuously re-evaluate		✔							✔		✔		✔
38. Environmental impact							✔				✔	✔	
Total number of checked activities	8	20	19	23	26	17	30	31	26	17	36	14	31

*Details concerning project management activities are suppressed.

Table 2 – key to frameworks described in Table 1

#	Name	Characteristics
	Reference	Based on the scientific problem solving process – mapping provided by (Chase, 1974)
1	SIMILAR	Parallel and iterative processes with re-evaluation to modify the system, the inputs, the product, or the process; purports to contain all elements of other models; based on functional analysis and a definable problem; requires extensive communication and coordination. (Bahill and Gissing, 1998)
2	Plowman	Cyclic and recursive model that is applied at different levels of rigor depending on the type of program or project involved; based on functional analysis and a definable problem; processes linked to standard military documentation artefacts; enhancing communication and system understanding. (Plowman, 2002)
3	Tufts	This model defines eight high-level activities that span from the front end marketing and business capture to operations and maintenance portion of the life cycle; linear and concurrent processes defined; based on CMMi and EIA 632. (Tufts, 2002)
4	Vee	The basis of models used by the USAF and NASA (Forsberg, Mooz, Cotterman, 2005).
5	INCOSE1	Model based on the EIA/IS 632 systems engineering standard; based on functional analysis; iterative processes; "effectively communicate a "shared vision" of the systems being developed and avoidance of omissions or confusion that often result from a lack of integration." (INCOSE SE Handbook, 2002, pp. 30-31)
6	AT&T	Part of a Process-Methods-Tools-Environment paradigm; extracted best current practice within AT&T. (Martin, 1997; Hall, 1962)
7	GERDC	Early synthesis of diverse practices; functional structure. (Chestnut, 1967)
8	SELC1	Comprehensive model; physical systems; focus on bringing a system into being. (Blanchard and Fabrycky, 1981)
9	Spiral	Risk-driven process for product or system development; iterative. (Boehm, 1986)
10	Planguage	Incremental deliveries provide constant feedback and control risk. (Gilb, 1988, and 2005)
11	NTNU	Linear model, with an iterative problem solving process; focus on bringing the system into being while recognizing useful life and disposal events. SE as a generic process for systematic problem solving. (Asbjørnsen, 1992) Additional modifications were made by Fet (1998).
12	INCOSE2	System lifecycle processes based on the standard ISO/IEC 15288 – Systems engineering – system lifecycle processes. (INCOSE SE Handbook, 2006)

Systems Engineering Research Agenda. The research agenda for systems engineering is as broad as the disciplines that contribute to its definition. Sahraoui, Buede and Sage (2004) proposed a set of issues essential to the growth and application of systems engineering. The Systems Engineering Vision (INCOSE, 2007) contains a list of topics considered critical to the advancement of the profession and the relevance of systems engineering to solving the problems of the future. These topics can be grouped into four primary areas:

- Insertion of systems engineering principles into an expanded curriculum
- Influence of systems engineering techniques in a technical society
- Innovative approaches toward systems engineering education delivery
- Increased collaboration between educational institutions, societies interested in systems engineering, and persons with interdisciplinary interests.

The Systems Engineering Advancement Research Initiative at MIT states, "In order to be effective research must be performed and then transitioned to practice which relates to the realm of complex systems with expanded system of systems scope, complex context requiring a socio-technical approach, and methods to take a value-driven perspective where value propositions involve synthesis of many stakeholder needs."[11]

In comparison, The Systems Engineering Doctorate Centre at Loughborough University[12] lists their research agenda, developed with industry partners, to address current and future challenges in systems engineering associated with exploiting systems of systems, managing systems complexity, maximising system performance, capacity and capability of affordable systems, and understanding humans in the system.

The four lists indicate agreement about the new challenges facing the profession, and where research can increase the body of knowledge while enhancing the practice of systems engineering.

Systems Engineering Education and Professionalism. In 1990 a group of educators and leaders in the profession of systems engineering met to discuss the future. The result was the formation of INCOSE, and the subsequent growth of the organization to over 7000 members from six continents, representing practitioners, educators and researchers. In 2004, INCOSE established a certification for systems engineering professionals (CSEP) and over 150 people have been certified to-date. Recognition of the value added by systems engineers has been slow, but recently governmental bodies in both the Netherlands and Norway have established investments in systems engineering. In Norway, the Norwegian Center of Expertise in Systems Engineering is established with committed funding from the state for the next ten years to enhance the competitive advantage of this cluster of firms through the use of systems engineering.

INCOSE tracks the programs offering degrees or courses on systems engineering worldwide on their website.[13] The reporting is voluntary and the list is continuously updated. At this writing there were 63 institutions reported in the USA, eleven in China, seven in the UK, six in Canada, two each in Australia and France, and one each in Germany, India, Israel, the Netherlands, Korea, Saudi Arabia, Singapore, and Turkey.

Systems engineering curricula are typified by combined technical depth and breadth in the course of study. Within the USA, efforts are underway to achieve recognition for a systems engineering course of study from the Accreditation Board for Engineering and Technology.

Sage (2000) has also looked at the question of the future directions for systems engineering education. He recommends and expanded curriculum that includes

• team skills, and collaborative, active learning;
• communication skills;
• a systems perspective;
• an understanding and appreciation of diversity; different cultures, business practices;
• 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 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." (Ibid; 171)

This means that there is a lot to learn, and as multi-disciplinarians, systems engineers need more than ever to be generalists who understand underlying principles without being able to solve a given problem alone (Goode and Machol, 1957). This has serious implications for educational institutions. For example, NTNU is looking into the establishment of a 5 year Master's level degree program in 'systems engineering' to give the student a chance to assimilate a broad range of learning. This activity is still in early investigation stages, but hints at an approach that may alleviate the time constraints.

Summary. Given this discussion of the criteria for a discipline and the corresponding attributes of systems engineering across academia and industry, it should be safe to conclude that systems engineering can correctly be referred to as a discipline. Figure 1 replicates the Biglan classification of educational disciplines.[14]

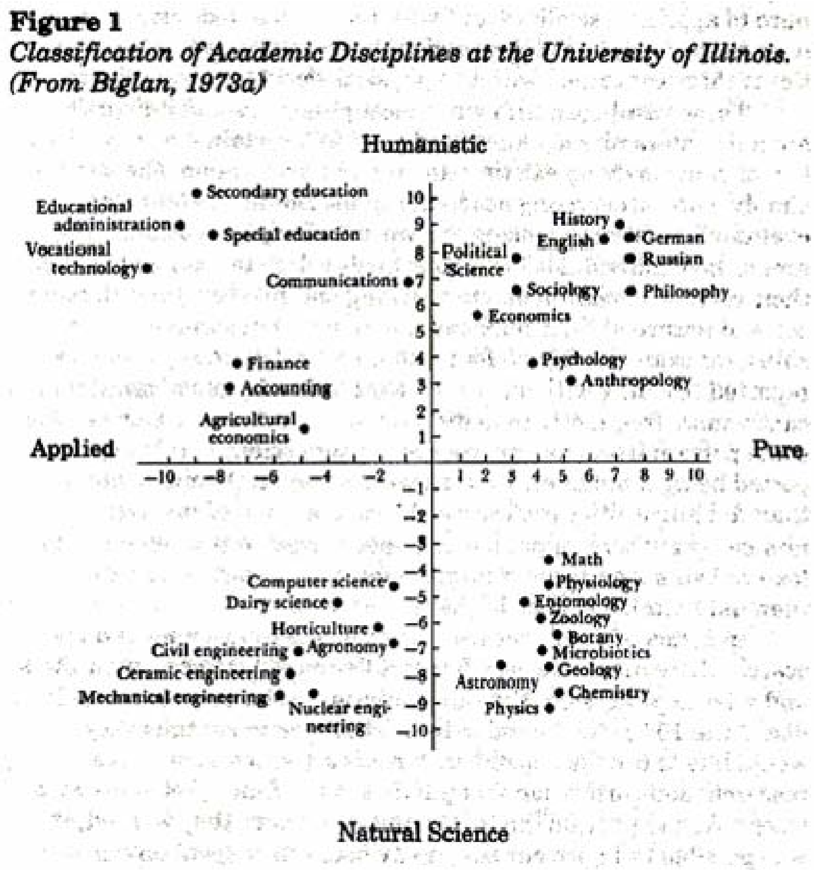

Figure 1 – Classification of academic disciplines from the University of Illinois, 1973

As can be seen, the upper right quadrant deals with disciplines that characteristically have been termed the humanities, together with a smattering of social sciences. The lower right quadrant contains the sciences and mathematics, with specific disciplines ranging from physiology to physics. The lower left quadrant contains applied disciplines that deal largely with the physical world whereas the upper left quadrant contains applied disciplines that deal with the social world, primarily education and business.

It could be argued that since 1990, Systems Engineering has matured from a set of practices informally documented to a discipline with a body of knowledge that recognizes the contributions of non-engineering disciplines. Banathy (1999) believed that "A disciplined approach to engaging our creative energy calls for a level of understanding that crosses the boundaries between the humanities, the arts, the sciences, and technologies." An open question for future investigation is where should systems engineering appear in this matrix?

Comparison of the Systems Engineering Frameworks

This section returns attention to the systems engineering frameworks presented above. A number of observations can be drawn from Table 1. First, consider the number of activities checked for each framework, as provided in the final line of the table. If one considers 38 to be a 'perfect score', then one observes that only frameworks AT&T, GERDC, Planguage and INCOSE2 score 30 or more. Checking the dates of the sources, the first two predate 1970, and the fourth is an extrapolation from the ISO standard for systems engineering issued in 2002. This could suggest that as a profession, as we began to 'solidify' our practices, we also simplified them, at the risk of leaving out certain activities. However, it should be noted, that no two of these frameworks has an identical pattern of checked activities, and some of the frameworks are intended to focus on the development phase, versus the entire life cycle, viz., INCOSE1, SELC1 and Spiral. This substantiates critical advice given in all versions of the INCOSE Systems Engineering Handbook about the importance of tailoring any adopted practices before using them.

Next, consider the set of activities presented. The reader already familiar with some or all of these frameworks recognizes immediately that certain liberty has been taken by the author in categorizing the activities that appear in Table 1. For example, activity 5, Define Performance, appears in every framework, but is expressed in many different ways. Table 3 provides a sampling of the ways in which this activity is described in some of the frameworks, where the term 'define performance' is not explicitly used. However, the phase is found in the Vee, Planguage, NTNU, and INCOSE2 sources.

Table 3 – Expressions categorized as 'define performance'

Framework	Expression
Reference	In the problem solving process, the hypothesis ("If *[I do X]*, then *[Y]* will happen.") must be constructed in such a way that it can be measured to support a subsequent test and conclusion.
SIMILAR	The 'A' in the acronym SIMILAR stands for Assess Performance. It is only logical that if performance will be measured, then the criteria have been defined.
Plowman	While never explicitly stated at the model level, the activities include conducting trade studies as a basis for informed decision making, which in turn suggests that performance criteria have been defined.
Tufts	Another framework that only hints at the definition activity by indicating an activity called 'Manage Performance.'
INCOSE1	The list of essential steps includes 'Establish Performance Requirements.'
AT&T	Hall states, "*Selecting objectives is the logical end of problem definition*." (p. 9) The word 'performance' does not even appear in the index.
GERDC	Desired performance is initially referred to as "*… criteria on which the remaining work may be based*." (p. 27)
SELC1	Under the heading 'Definition of Operational Requirements' is the category 'performance and related parameters.'

Finally, Table 1 notes that the broad range of activities associated with managing a project have not been itemized as the author has categorized them outside of the scope of systems engineering activities, notwithstanding the plethora of literature on systems engineering management.

Systems Engineering Meta-model

This careful collection of frameworks and their comparison has been conducted with the intention of teasing out common attributes that might provide some insight into the real work of systems engineering. The author has distilled this into a meta-framework she calls the 6C's of systems engineering, so named for the following characteristics: Comprehension, Communication, Coordination, Collaboration, Cooperation, and Continuity.

Comprehension. This word was originally 'understanding,' which really ruined a fine pattern of words beginning with the letter 'c.' Many of the activities listed in Table 1 require the systems engineer to be knowledgeable in a domain, and otherwise able to understand, in a complete way, the information shared by the stakeholders. Jack Ring has stated, "As systems engineers our value is manifested in our ability to comprehend 'the problem' …" (Ring, 2002; 19). Chestnut writes, "The approach one uses in solving a problem is greatly influenced by his understanding of it." (Chestnut, 1967; 104). Kossiakoff and Sweet (2003) talk of the power of multidisciplinary knowledge, and Banathy (1996) calls social systems design a multidimensional human activity of disciplined inquiry. All of which adds up to a person who listens well, can empathize with underlying value systems, and brings a broad personal knowledgebase to the work of systems engineering.

Communication. All of systems engineering activities require good communication skills. Chase describes this facilitation in this way, "In fact, it must be stressed that a participant in an integrated system design effort… must, therefore, be able to use a commonly understood system-oriented language, and not just his specialist-oriented jargon, which when employed by any number of specialists in relation to a systems-oriented context, and result only in a babel of tongues." (Chase, 1974; 21) Kossiakoff and Sweet also use the 'Tower of Babel' analogy. This powerful influence on the outcome of an endeavour has also been recognized in other disciplines, for example, Conway's Law. Endres and Rombach emphasize this point by observing, "Conway's law is valid since system development is more a communication problem than a technical problem. It is more important to think about communication barriers and enablers than about tools that enhance the clerical or intellectual capabilities of the individual." (Endres and Rombach, 2003; 82) Try to find a job description today that does not include the catch phrase, 'good oral and written communication skills.'

The next three characteristic may seem very similar, but each deserves to be included on its own merits. Consider athletic endeavors, such as a soccer team. Each team member needs to maintain their own balance – or coordination of their body parts. As an entire group, the team cooperates toward the objective of scoring goals, and this is often achieved by executing well rehearsed sequences of plays in collaboration with team-mates.

Coordination. Coordination focuses on a harmonious functioning of parts for effective results.[15] This attribute was recognized by Sheard (1996) as the Coordinator Role of systems engineers. Hall begins his book by stating that "… effective systems engineering calls for careful coordination of process, people and tools. Such coordination cannot be learned from a book or set of books." (Hall, 1962; v) Chestnut goes further; "The interplay between the system engineer and engineering design specialist requires the closest coordination …" (Chestnut, 1967; 36) The Systems Engineering Handbook (INCOSE, 2006) agrees that coordination and communication create the biggest challenges for large projects, especially when the teams are distributed and can not meet face-to-face.

Cooperation. By cooperation is meant a group of persons working together toward a single defined objective, such as a soccer team, or a project organization. Kossiakoff and Sweet are very clear, "It is the systems engineers who provide the linkages that enable these disparate groups *[engineering specialists]* to function as a team. The systems engineers accomplish this feat through the power of multidisciplinary knowledge. … Through the ability to understand different languages comes the capability to obtain cooperative effort from people who otherwise would never be able to achieve a common goal." (Kossiakoff and Sweet, 2003; 25)

Collaboration. Collaboration is cooperation on a smaller scale. The term means working together with others, very often people or agencies with which one is not directly connected. This may be especially important when involving the stakeholders in a process. They may have a vested interest, but they exist, most often, outside the boundaries of the defined project team. Likewise, systems interfaces may require two or more separate firms to work together, facilitated by systems engineering oversight.

Continuity. System life cycles can be very long. One contribution that systems engineering can provide to a system is that of continuity. As an example, the Systems Engineering Handbook (INCOSE, 2006) lists continuity in configuration and traceability. In products, such as automobiles, systems engineers are called upon to continuously upgrade the capabilities of a product to take advantage of technological advances, or to modify components in response to changing legislation regarding safety or pollution control, to name two examples. Sage (2000) refers to this as 'knowledge brokering.'

This characteristic is also tightly connected to the need for good decision-making throughout the life cycle. Kossiakoff and Sweet express it this way, "The systems engineer is always the advocate of the total system in any contest with a subordinate objective." (Kossiakoff and Sweet, 2003; 14)

Code of Ethics. It should be stated explicitly that the 6C's sit in a context of a code of ethics. Systems engineering practitioners have a moral obligation to serve the higher needs of society. The INCOSE Code of Ethics for systems engineers states, "The practice of Systems Engineering can result in significant social and environmental benefits, but only if unintended and undesired effects are considered and mitigated. … [Systems engineers] guard the public interest and protect the environment, safety and welfare of those affected by engineering activities and technological artifacts." [16]

Framework mapping. Table 4 maps the activities of Table 1 onto the attributes of this meta-framework of systems engineering. Some of the activities map to more than one attribute. While the attributes appear in no predetermined sequence, the order may reflect the author's bias for which attributes are most needed or exercised by an activity. Table 4 represents a first attempt to consider the activities of systems engineering in terms of abstract human activity rather than concrete artifacts of the process or methodology employed (Friedman and Sage, 2004).

Table 4 – Mapping of activities onto meta-framework attributes

Activity	**Attributes of Systems Engineering ***
Identify stakeholders	Collaboration, Comprehension
Formulate the problem	Collaboration, Comprehension, Continuity
Define requirements	All
Investigate alternatives	Collaboration, Comprehension, Continuity
Define performance	Collaboration, Comprehension, Continuity
Requirements Analysis	Collaboration, Comprehension, Continuity
Model the system	Comprehension, Coordination, Cooperation
Define functions	Comprehension, Coordination
Engineering design	Coordination, Continuity
Design Architecture	Coordination, Continuity
Assess and manage risk	Collaboration, Comprehension, Cooperation, Continuity
Implementation	Collaboration, Cooperation

Activity	Attributes of Systems Engineering *
Manage interfaces	Coordination, Collaboration, Cooperation
Integration	Coordination, Collaboration, Cooperation
Define tests	Coordination, Collaboration, Cooperation
Verification	Coordination, Collaboration, Cooperation
User Training	Collaboration, Cooperation
Production support	Coordination, Collaboration, Cooperation, Continuity
Transition	Collaboration, Cooperation
Validation	Coordination, Collaboration, Cooperation, Collaboration
Operational support	Coordination, Continuity
Maintenance	Coordination, Collaboration, Cooperation, Continuity
Replacement, upgrade	All
Retirement, disposal	Coordination, Collaboration, Cooperation, Continuity
Manage baselines	Coordination, Collaboration, Cooperation, Continuity
Manage project	All
Conduct reviews	All
Maintain documentation	Continuity
Manage information	All
Address legacy systems	Comprehension, Collaboration, Coordination
Manage complexity	All
Capture business plans	Comprehension, Collaboration, Continuity
Manage quality	Coordination, Collaboration, Cooperation, Continuity
Integrate disciplines	All
Acquisition	All
Supply	All
Continuously re-evaluate	All
Environmental impact	Comprehension, Continuity

* Note: Communication maps onto all activities

Figure 2 illustrates a relative weighting of the 6C's based on their frequency of appearance in Table 4. The radar diagram indicates that Communication is the most frequently exercised attribute, followed closely by Collaboration.

Coordination, Cooperation and Continuity are very similarly weighted. Comprehension is listed least often – but this does not mean the brain is not engaged for every activity, just that certain activities require more concentration to achieve understanding.

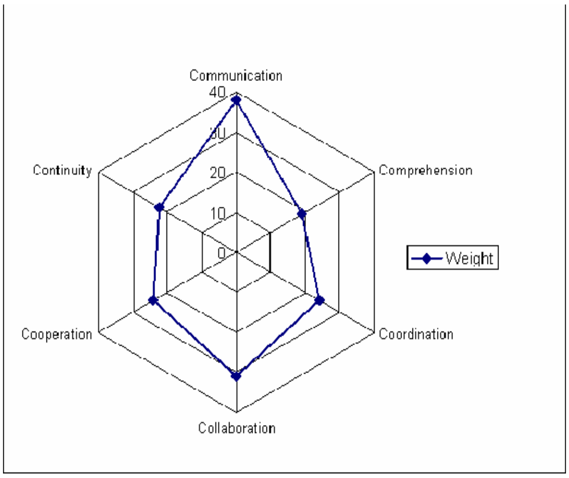

Figure 2 – Radar Diagram of the 6C's Framework of Systems Engineering

The intention of creating a meta-framework of systems engineering activities is to address the contention that there are classes of problems to which systems engineering does not apply, and that this includes systems with exclusively social objectives (Checkland, 1999).

Systems Engineering Practices

At issue is the question, is there a class of problems to which systems engineering does not apply? The quick answer is, probably. The aforementioned principle of scalability suggests that projects of a certain size, specification and complexity do not require full-scale systems engineering. This is not the same as saying that such projects do not benefit from a systematic approach to design or construction, but only that many of the 38 activities listed in Table 1 would not be necessary, and tailoring a systems engineering process could result in using only a handful of activities. But to-date there is no formal definition that indicates the tipping point at which systems engineering should be applied to solving a problem.

This question is further complicated by the existence of numerous brands of systems engineering in the literature. Hard, soft, cognitive, industrial, information, and software are adjectives often appended to the front of systems engineering. And it does not stop there, it is possible to find literature on applied, aero, control and ocean systems engineering, just to name a few that will not be discussed here. The adjective 'hard' generally applies to using systems engineering as a systematic approach to solving problems using model building and simulations and many of the activities listed in Table 1. Soft systems methodology is the term adopted by Checkland to differentiate his approach from the former to address perceived deficiencies in problem formulation. This method exercises soft skills, such as the ability to engage in negotiation or dialogue, to establish an environment of trust, to network, and to facilitate process or change management. Cognitive systems engineering focuses on how man interacts with the environment and draws from experience and research in both cognitive psychology and hard systems engineering. Industrial engineering is often found in academic settings in departments of systems and industrial engineering. This may be explained by the fact that both disciplines are concerned with the development, improvement, implementation and evaluation of integrated systems of people, money, knowledge, information, equipment, energy, material and process.[17] Information systems engineering applies computer science and human cognition theories to the management and design of computer-based information systems. Software systems engineering has close parallels to hard systems engineering with a focus on software systems – which also suggests some overlap with information systems engineering.

DeRosa (2005) introduces Enterprise Systems Engineering to focus on some the difficulties of "beginning with a specification" by presenting approaches for creating initial specifications and thereby addressing one of Checkland's primary objections to hard systems engineering. These early efforts to produce a specification also have been described by some as the 'dark side of systems engineering' because, until recently, it was rarely discussed (Fossnes, 2007).

Contributions from socio-technical systems theory[18] advise that humans in organizations should have roles that are complementary to machines as opposed to humans being extensions to machines – such as a clerk who inputs data all day long but has no connection to how the data is used. Likewise, the design of such systems should reflect an optimization of both the social and the technical elements of the system – for example, the same or different people should not be feeding the same information into different computer-based systems.

Kossiakoff and Sweet (2003) describe two different sources for engineering activities in the automotive industry. One is described as socio-driven need or new constraints on the product that are placed on the manufacturer by the environment. An example of this is new rules from regulatory or legislative bodies that determine the demand for fuel economy, safety, pollution control, and after-life reclamation of parts. On the other hand are the techno-driven needs, which are usually self-imposed changes to integrate technological advancements that make the product more interesting, safer or less expensive to produce. An example of this type of change is the recent explosion of computer technology found in modern automobiles.

Most systems will benefit from a combination of hard systems engineering with extensions that incorporate the intentions of soft systems methods as illustrated in Rees (2000). The reason for this is that the problems to which systems engineering is applied can be classified as 'wicked' problems. Kasser (2007) provides a summary of what is meant by wicked problems. He reports on an informal survey against the themes of the published papers of the INCOSE annual symposium and finds also that despite increasing attention, socio-economic systems was the least addressed theme. This result is consistent with Haskins (2008) and can easily be explained by the demographics of the INCOSE membership, which is primarily employed in the making of 'well-defined' systems. However, this indicates a potential to improve our membership profile by attracting more systems engineers with an interest and concern in social challenges.

Empirical applications of systems approaches to social challenges

Checkland (1999) maintained the distinction between 'hard' and 'soft' systems thinking with the former being more appropriate for technical well-defined problems. This view is not well aligned with the bulk of systems engineering literature, whose authors would love to return to the days of non-trivial technical systems that could be defined well, if those days ever existed.

While he was president of the International Society for the Systems Sciences, Banathy (1999) observed, "Unique to our age is the massive scale at which we are applying science and technology to the construction of our physical, social, and cultural reality."

In his newly released book, 'An introduction to systems science,' Warfield opens with a list of bad practices that his book intends to remedy, including a criticism of much of systems literature, "It offers either theory with no empirical evidence, or (less commonly) empirical evidence with no supporting theory, or now and then, sheer fantasy with neither theory nor evidence; thereby at least giving some relief from monotonous bifurcation." (Warfield, 2006; vii) He attempts to compensate for the dearth of empirical evidence with contributions from other authors about their experiences applying systems science. "It was my intention in inviting these authors to try to obtain a sufficient variety in both locale and subject matter to help show that the idea of systems science as a neutral science was a valid concept…" (Ibid; xi) He dedicates a chapter each to contributions from four sectors, which he labels private, government, social, and education. Each of the three stories that appear under the chapter for the social sector relate a history of the use of the Interactive Management method in a social setting, from peace-building efforts in Cyprus to citizen involvement in local planning in Mexico and Latin America. From the latter account, Professor Moreno asserts that the structured participation of individual citizens is one of the most relevant challenges for development today.

Haskins (2007) has reported on case work conducted in Verdal, Norway in which she applied a systems engineering framework called iFACE to help residents of an industrial park establish a vision for their further development.

Fet (2004) conducted a project in Klaipeda, Lithuania, to map and evaluate the environmental performances of 10 industrial companies and the local community by using systems engineering methodology.

Karl-Henrik Robèrt founded the Natural Step to help others achieve their sustainability goals. His implementation methodology is called Strategic Sustainable Development and contains many activities found in Table 1 (Robèrt, et. al, 2002). Thesis projects demonstrating this approach are available online.[19]

Pat Hale, in describing the INCOSE participation in the GEOSS consortium, reported that GEOSS is typical of problems that systems engineers will face in the future, "in addition to technical complexity, GEOSS has disciplinary and domain complexity. GEOSS is an 'engineered system,' but no solutions exist without politics, economics and sociology, etc."[20]

Implications for educating systems engineers

Dörner provides a comprehensive exposition of the "inadequacies of human thought in dealing with complex systems." (Dörner, 1996; 185) He recounts many examples of exercises in which traditional problem solving approaches do not yield the desired results. He proposes that faced with complexity, humans simplify, focus on what we think we understand, and proceed with full speed to a conclusion, all in an effort to use our scarce 'thinking' capabilities as efficiently as possible. Another reason he offers is the amount of time it takes to assimilate new material. This has also been expressed as the Librarians Law: "The more knowledge that is available, the more effort has to be spent on the processes to use it." (Endres and Rombach, 2003; 228) It should come as no surprise that we are trounced by the Law of Unintended Consequences when we know so little at the time of decision-making.

This suggests that it is time to look more closely at the teachings of the thought leaders who have for decades straddled both the systems and software engineering divide. Both Tom Gilb, the inventor of Planguage, and Barry Boehm, the author of the spiral model, have long understood the value of combined iterative and incremental processes as a way to reduce risk in the face of uncertainty, and to learn by doing in the face of unclear objectives. Asbjørnsen (1992) describes the iterative nature of the problem solving process. When faced with an 'unsolvable problem' the next step in the process is to redefine the problem, presumably with the blessing and participation of our stakeholders.

Sage (2000) itemizes 12 deadly systems engineering transgressions. Two of them are particularly relevant to this discussion.

> *#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.*
>
> *#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 associated failure of not properly designing the system for effective user interaction. (Ibid; 168)*

Banathy (1999) believed that "A disciplined approach to engaging our creative energy calls for a level of understanding that crosses the boundaries between the humanities, the arts, the sciences, and technologies." Van Berkel (2000) makes a case for integrating environmental and sustainable development agendas into multidisciplinary education.

Reconsidering the librarian's law, this means that there is a lot to learn, and as multi-disciplinarians, systems engineers need more than ever to be generalists who understand underlying principles without being able to solve a given problem alone. This has serious implications for educational institutions. For example, NTNU is looking into the establishment of a 5 year Master's level degree program in 'systems engineering' to give the student a chance to assimilate a broad range of learning. This activity is still in the investigation stages, but hints at an approach that may alleviate the time constraints.

Another approach has been advocated by MIT where a new field of Engineering Systems has been defined as a superset of disciplines incorporating both engineering and management sciences and including Systems Engineering as an underlying discipline. The new field of Engineering Systems addresses some of the criticisms levied against systems engineering and expands the vision to encompass developing "sustainable engineering systems with optimised value to society as a whole." (Rhodes and Hastings, 2004: 4)

So where does this leave us? Empirical evidence does not give us any indication that systems engineering can not be applied to any class of complex problems. The evidence does suggest that our 'tool box' may need to expand to include tools not normally taught in engineering courses of study, such as in the disciplines of psychology and economics, to name two.

Conclusions

There has been a paradigm shift in modern science. Pulm (2005) summarizes it succinctly as follows, "… from Newton to Bergson, i.e., from mechanistic universe to intuition and creativity, from atomistic to holistic, from observation to participation, from one best solution to many good solutions, from prognoses to scenarios, from representations to constructivism, or from destructive to creative chaos."

When one considers how long systems thinking has been recognized – both Warfield (2006) and Checkland (1999) trace works back to the early Greeks for Western Civilization – the question emerges "Are we any nearer to using systems concepts to make the really important decisions?" such as those made by national and local governments. Notwithstanding periodic articles with optimistic titles like "Systems thinking is back on the agenda," (Hauck, 2005), this author agrees with Wolstenholme (2000) that there is still a long way to go.

The primary contribution of this paper is the summary and comparison of twelve modes of systems engineering as taken from the current literature, and the subsequent abstraction of a systems engineering metamodel. This paper also provided a critical assessment of the status of systems engineering as a discipline. Using examples from the literature, the author has demonstrated that there have been both successes and failures in the application of systems approaches to the solution of social and socio-technical problems. This suggests the need for extensions to the current curricula for engineers and systems engineers in particular. Future research should consider whether working with a definition of systems engineering from a more abstract set of perspective, such as the 6C's, will expand the flexibility of both the practitioners and the range of problems tackled, opening the way for the acceptance of systems engineering as a valid approach to addressing environmental issues and global challenges.

A propos, Dörner (1996) reported on a study of decision-making under crisis conditions. In this study, the participants acted under the principle of 'the ends justify the means' rather than their personal moral standards. Under such circumstances, redefining the problem will give less than just results. If the 'unsolvable problem' at hand concerns a product with a negative environmental effect and the only 'affordable' option is continuing without correcting the flaw in order not to loose the estimated product income then redefining the problem to eliminate concern for the environment should not be an option.

One could wonder whether new understanding about the impact of man-made systems on the planet combined with new technologies will be enough to halt the inevitable cataclysms currently forecast. As a body of educators, researchers, and professionals we need to step back and consider our potential contributions. The time has come to define '*principled' systems engineering* for the 21st Century.

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Biography

Cecilia is an American living and working in Norway and blending the best of both cultures into her daily life as a part-time teacher, consultant, author and volunteer. Her career includes commercial and government projects, with large and small firms, as both employee and entrepreneur. Technically, she has worked in every phase of the software lifecycle and has been a Certified Computer Professional since 1979. Her educational background includes a B.Sc. in Chemistry from Chestnut Hill College, and an MBA in Operations Management from Wharton, University of Pennsylvania. Within INCOSE, she has been an active volunteer, serving as editor of the Systems Engineering Handbook, version 3, and the INCOSE Systems Engineering Vision 2020. She is recognized as a Certified Systems Engineering Professional since 2004, and currently she is finishing work on her doctoral thesis on the application of Systems Engineering to sustainable development.

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