The Hitchins-Kasser-Massie (HKM) Framework for Systems Engineering

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Abstract. George Friedman (Friedman, 2006) called for the development of a grand unified theory of systems engineering (GUTSE) echoing (Hill and Warfield, 1972) who wrote "*development of a theory of systems engineering that will be broadly accepted is much to be desired*." Taking up the spirit of the challenge, this paper applies systems thinking to systems engineering to propose a framework that can serve as a vital element in formalizing the discipline of systems engineering and potentially as a platform for developing such a theory.

This paper focuses on what systems engineers do, and builds on past research and success. Documenting research using an object-oriented approach in a creative and innovative manner it discusses the evolution of a proposed framework for systems engineering that meets or shows promise of meeting the following four requirements (Kasser, 2006):

1. The framework shall provide an understanding of why systems engineers can't agree on their roles and activities.
2. The framework shall provide an understanding of the reasons for the overlap between systems engineering and management.
3. The framework shall provide a way to cope with complexity.
4. The framework shall enable the lowering of the cost of doing work by at least an order of magnitude.

The framework is based on a combination of the Hitchins' five-layer representation of systems engineering (Hitchins, 2000) extended by Kasser and Massie over the systems lifecycle phases (Kasser and Massie, 2001) coupled with Shenhar and Bonen's taxonomy of systems based on technological uncertainty (risk) (Shenhar and Bonen, 1997).

Background

While the world is turning to systems engineering to solve the problems of developing and maintaining the systems underpinning our civilization, after 50 years of trying, development projects are still characterized by cost and schedule overruns as well as outright cancellations (CHAOS, 2004). Against this background,

- Systems engineering is struggling to be recognised as an engineering discipline in an environment in which it is perceived to overlap the activities of project management.
- While universities offer degrees in systems engineering and pursue research, systems engineering still lacks a framework for research and education.

- Systems engineers can't agree on what systems engineering is (activity).
- Systems engineers can't agree on what systems engineers do (role).
- Systems engineers can't agree on a definition of systems engineering.

This situation needs to be remedied. Research has shown that one reason for the lack of agreement is that systems engineers do many and different tasks in their work (Kasser and Palmer, 2005) and consequently have different perspectives on systems engineering. In addition performing systems engineering seems to be like solving wicked problems (Rittel and Webber, 1973) which have the following ten characteristics:

1. There is no definitive formulation of a wicked problem.
2. Wicked problems have no stopping rule.
3. Solutions to wicked problems are not true-or-false, but good-bad,
4. There is no immediate and no ultimate test of a wicked problem.
5. Every solution to a wicked problem is a "one-shot" operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible options that may be incorporated into the plan.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
10. The planner has no right to be wrong.

Many of the characteristics of wicked problems also seem to map into the first phase of the scientific method of solving problems, namely a life cycle consisting of:

1. Observation of the system without an understanding of the system.
2. Formulation of an hypothesis to explain the system.
3. Use of the hypothesis to predict the behaviour of the system in various situations.
4. Testing of the hypothesis to determine if the system behaves as predicted in those situations.

It is possible that wicked problems manifest themselves in the first step of the scientific method cycle even if nobody is using the scientific method to address the problem. That is the system or a part of it is under observation, but no working hypothesis to explain the system has yet been developed. For example, the state of the art of chemistry before the development of the periodic table of the elements could be considered as a wicked problem, as could the state of electrical engineering before the development of Ohm's Law.

If today's systems engineering is in a similar state, namely solving wicked problems, then a major step forward in the development of the discipline would be to apply the scientific method to postulate a hypothesis (namely a framework for systems engineering exists); prototype and test it; and eventually evolve a working framework for applying systems engineering in the manner of the application of the periodic table of elements in chemistry. The process of thinking about the observations, and applying the scientific method would be enlightening in itself. This paper takes the plunge and lists four requirements for a framework for systems engineering, then documents the evolution of one such a framework by viewing systems engineering from the perspective of problem solving.

Requirements for a framework

The proposed framework in the context of an engineering discipline was discussed in (Kasser, 2007b). A framework for systems engineering must provide an improvement on the current paradigm, or there is little point in developing one. Looking around at the state of systems engineering and its problems, the following four requirements for such a framework were defined (Kasser, 2006).

1. The framework shall provide an understanding of why systems engineers can't agree on their roles and activities.
2. The framework shall provide an understanding of the reasons for the overlap between systems engineering and management.
3. The framework shall provide a way to cope with complexity.
4. The framework shall enable the development of a way of working that lowers the cost of doing work by at least an order of magnitude.

Rationale for the requirements for the Framework

The rationale for these four requirements for the framework is explained below.

1. The framework shall provide an understanding of why systems engineers can't agree on their roles and activities

(Hill and Warfield, 1972) anticipated (Friedman, 2006) writing "*development of a theory of systems engineering that will be broadly accepted is much to be desired*." Without such an understanding, systems engineers will continue to discuss rather than develop and apply systems engineering, and not move onwards to the creation of a discipline. Until a framework for the broad range of activities known by the term 'systems engineering' is developed and systems engineers understand their location of their activity within the framework it will be impossible to develop a theory of systems engineering.

2. The Framework shall provide an understanding of the reasons for the overlap between systems engineering and management

We need this understanding to be able to reengineer organizations in order to remove the overlap. The overlap is expensive due to both the duplication of resources and the modern management paradigm which has separated the decision makers from the people who understand the implications of the decisions. This situation was recognized almost at the dawn of systems engineering by Goode and Machol who wrote "*The most difficult obstacle that may be encountered by an [systems] engineer is not the problem but a management which is unsympathetic or lacking in understanding*" (Goode and Machol, 1959) page 513). The optimal management method is said to be "Management by Walking Around" (MBWA) (Peters and Austin, 1985). Yet (Deming, 1986) page 22) wrote *"MBWA is hardly ever effective. The reason is that someone in management, walking around, has little idea about what questions to ask, and usually does not pause long enough at any spot to get the right answer"*. And the situation continues into the 21st century as satirized by Scott Adams in his Dilbert cartoons (Adams, 2006). Think of the cost of the waste and the work expended to implement and then correct the results of poor decisions. Once there is an understanding of the reasons for and the nature of the overlaps, we stand a chance of removing the overlap.

3. The Framework shall provide a way to cope with complexity

Systems engineering has not delivered on its promise to meet the challenge of complexity as documented by Chestnut who wrote "*Characteristic of our times are the concepts of complexity, growth and change*" (Chestnut, 1965 page 1) and "*in a society which is producing more people, more materials, more things, and more information than ever before, systems engineering is indispensable in meeting the challenge of complexity*" (Chestnut, 1965 page vii). There is a growing dichotomy in the literature on the subject of complex systems. On one hand there is literature on the need to develop new tools and techniques to manage them, e.g. (Cook, 2000; Bar-Yam, 2003). On the other hand, there is literature on techniques such as aggregation which mask the underlying complexity to ensure that only the pertinent details for the particular situation to deal with the issues are considered e.g. (Hitchins, 1998; Kasser and Palmer, 2005; Maier and Rechtin, 2000; Hitchins, 1992 page 6). Perhaps the dichotomy is due to the observation that "*the classification of a system as complex or simple will depend upon the observer of the system and upon the purpose he has for considering the system*" (Jackson and Keys, 1984). For the framework to be useful, it must provide a way to cope with complexity.

4. The Framework shall enable the development of a way of working that lowers the cost of doing work by at least an order of magnitude

This is a grand target to aim at. Systems engineering overlaps project management and other organizational activities (Johnson, 1997; Roe, 1995), so it can adopt some of their tools and techniques. There should be no reason why the process architecting function (Kasser, 2005) could not improve processes, products and organizations to the point where the cost of developing projects is lowered by an order of magnitude. If the Framework only allows the achievement of 50% of this target, it will still be a significant improvement.

The role of the systems engineer

There have been many diverse opinions on the topic over the years concerning what systems engineers do (Allison and Cook, 1998; Hitchins, 2000; Sage, 1995; Badaway, 1995; Kasser, 1995). Three further opinions are:

1. "*Despite the difficulties of finding a universally accepted definition of systems engineering, it is fair to say that the systems engineer is the man who is generally responsible for the over-all planning, design, testing, and production of today's automatic and semi-automatic systems*" (Chapanis, 1960 page 357).
2. The principal functions of systems engineering are "*to develop statements of system problems comprehensively, without disastrous oversimplification, precisely without confusing ambiguities, without confusing ends and means, without eliminating the ideal in favour of the merely practical, without confounding the abstract and the concrete, without reference to any particular solutions or methods, to resolve top-level system problems into simpler problems that are solvable by technology: hardware, software, and bioware, to integrate the solutions*

to the simpler problems into systems to solve the top-level problem" (Wymore, 1993) page 2).
3. "*Systems engineering is a wide-range activity, and it should not be handled in the same form for all kinds of systems*" (Shenhar and Bonen, 1997).

Each opinion represents a viewpoint based on the experience of the writer[1]. In addition, the latest systems engineering standard ISO 15288 provides a list of the organizational processes or activities in which systems engineers are involved as shown in Figure 1 extracted from the Standard (Arnold, 2002) page 61). Thus, ISO 15288 could be considered as a framework for systems engineering based on the activities which systems engineers perform.

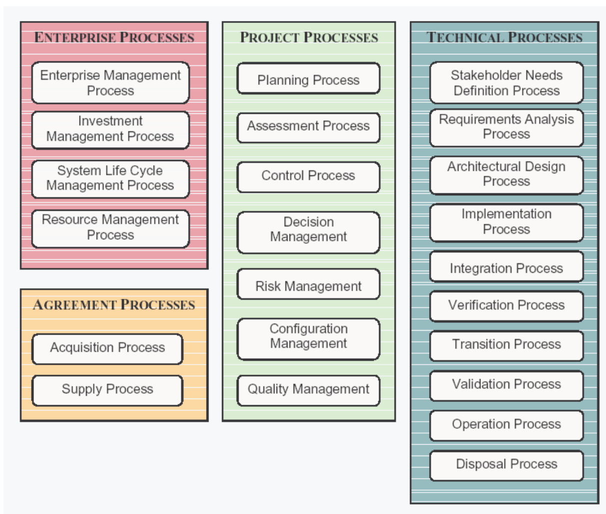

Figure 1 ISO 15288 Systems Engineering Processes

Systems engineering is performed in an organization with overlapping disciplines (Kasser, 1996; Friedman, 2006; Roe, 1995). Research into the origin of the disciplines found the following statement – "*driven by cold war pressures to develop new military systems rapidly, operations research, systems engineering, and project management resulted from a growing recognition by scientists, engineers and managers that technological systems had grown too complex for traditional methods of management and development*" (Johnson, 1997). (Kasser and Palmer, 2005) separated the activities (systems engineering, systems architecting, project management and process architecting) from the roles or job titles (systems engineers, systems architects, project managers and process architects). Since the common factor in all three disciplines is problem solving, the first attempt to formulate a proposed framework for systems engineering that meets the requirements stated above is based on problem solving.

Problem solving methodologies

(Flood and Jackson, 1991) developed a systemic meta-methodology called Total Systems

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[1] At least in the case of Kasser, J. E., *Applying Total Quality Management to Systems Engineering*, Artech House, Boston, 1995.

Intervention (TSI) that guides practitioners through a systemic process of choosing a methodology based on the problem situation. TSI is broadly summarized in Table 1 (Flood and Jackson, 1991) Figure 2.2, page 42). However, application of the Table is not as simple as it appears since not only are there a number of methodologies to consider but "*the classification of a system as complex or simple will depend upon the observer of the system and upon the purpose he has for considering the system*" (Jackson and Keys, 1984). This prompted the attempt to identify an alternative framework. Note if Table 1 is considered as showing the activities performed in the problem context, the location of operations research and systems engineering as methodologies to be used in a simple unitary problem context is supported by (Kasser, 2005) who stated that the role of systems engineers in a organization is more than performing the activity known as systems engineering.

Table 1 Methodologies in the Problem Context Map (Flood and Jackson, 1991)

	Unitary	Pluralist
Simple	Operations research Systems analysis Systems engineering Systems dynamics	Social systems design Strategic assumption surfacing and testing
Complex	Viable system diagnosis General system theory Socio-technical systems thinking Contingency theory	Interactive planning Soft systems methodology

A number of authors classify systems by levels of complexity and types of system. These approaches seem to be paralleling the development of theories of motivation in Psychology. For example, Murray identified separate kinds of behaviour and developed an exhaustive list of psychogenic or social needs (Murray, 1938). While this list has been very influential in the field of psychology, it has not been applied directly to the study of motivation in organizations. This is probably because the length of the list makes it impractical to use. One could expect that classifying systems by complexity and types would result in similar lengthy lists. Maslow's hierarchical classification of needs (Maslow, 1954; Maslow, 1968; Maslow, 1970) on the other hand, has been by far the most widely used classification system in the study of motivation in organizations. Maslow differs from Murray in two important ways, his list is hierarchical, commonly drawn as a pyramid, and is short, namely it only contains five categories. While levels of complexity and types of system can also be expected to be influential in systems engineering, the research focused on locating or developing a shorter broad-based classification based on problem solving.

The Hitchins-Kasser-Massie Framework

This section introduces a three dimensional framework for systems engineering. The vertical and horizontal dimensions of the framework are based on the work of (Kasser and Massie, 2001) who, in conceptualizing a framework for a systems engineering body of knowledge based on the roles of systems engineers, created the following two-dimensional framework.

The vertical dimension is based on the work of (Hitchins, 2000) who proposed the following five-layer model for systems engineering:

- **Layer 5 -** Socioeconomic, the stuff of regulation and government control.

- **Layer 4** - Industrial Systems Engineering, or engineering of complete supply chains/circles. Many industries make a socio-economic system. A global wealth creation philosophy. Japan seems to operate most effectively at this level.
- **Layer 3** - Business Systems Engineering - many businesses make an industry. At this level, systems engineering seeks to optimize performance somewhat independent of other businesses
- **Layer 2**- Project or System Level. Many projects make a Business. Western engineer-managers operate at this level, principally making complex artifacts.
- **Layer 1**- Product Level. Many products make a system. The tangible artifact level. Many [systems] engineers and their institutions consider this to be the only "real" systems engineering.

Hitchins states that the five layers form a "nesting" model, i.e. many products make a project, many projects make a business, many businesses make an industry and many industries make a socio-economic system. Clearly, these statements are only approximate since-

- A socioeconomic system has more in it than just industries.
- A business has more in it than just projects, and so on.
- Actual organizations may divide the work in different ways resulting in either sub-layers, or different logical break points.

The horizontal dimension of the framework is based on the work of (Kasser and Massie, 2001) who, in developing a framework for a systems engineering body of knowledge based on the roles of systems engineers, extended the five layers of systems engineering discussed by (Hitchins, 2000) to explicitly cover the phases of the systems engineering life cycle. The phases have been stated in various ways in various standards, conference papers and books, but for this framework they are defined in generic terms as:

A. Identifying the need.
B. Requirements analysis.
C. Design of the system.
D. Construction of the system.
E. Testing of the system components.
F. Integration and testing of the system.
G. Operations, maintenance and upgrading the system.
H. Disposal of the system.

The resulting two dimensional framework is shown in Figure 2.

Adding the third dimension (Kasser and Massie, 2001)'s vertical and horizontal dimensions provide a map for the location of the activities performed by systems engineers. This paper now goes beyond (Kasser and Massie, 2001) and discusses the development of the candidate for the third dimension. The third dimension of the HKM Framework is the difficult one since there are many ways to classify the types of problems posed in each area of the network. One immediately obvious approach is by the domain (aerospace, military, commercial etc.) however, it was felt that

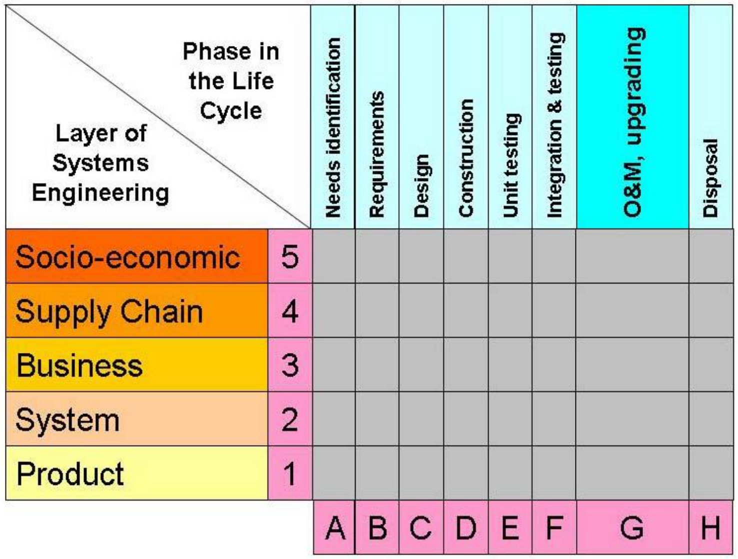

Figure 2 The HKM Framework[2]

- this situation was analogous to the development of theories of motivation in Psychology, and
- if the analogy holds true then applying lessons learned from Psychology to systems engineering, should provide a workable framework.

At one point of time in the development of theories of motivation, Henry A. Murray identified separate kinds of behaviour and developed an exhaustive list of psychogenic or social needs (Murray, 1938). However, the list is so long that there is almost a separate need for each kind of behaviour that people demonstrate (Hall and Lindzey, 1957). While this list has been very influential in the field of psychology, it has not been applied directly to the study of motivation in organizations. This is probably because the length of the list makes it impractical to use. On the other hand, Maslow's hierarchical classification of needs (Maslow, 1954; Maslow, 1968; Maslow, 1970) has been by far the most widely used classification system in the study of motivation in organizations. Maslow differs from Murray in two important ways; his list is:

- **Arranged in a hierarchy** -commonly drawn as a pyramid, and contains a set of hypotheses about the satisfaction of these needs.
- **Short** -- Only five categories.

Clayton P. Alderfer subsequently proposed modifying Maslow's theory by reducing the number of categories to three (Alderfer, 1972). Murray's and early theories defined needs or instincts, Maslow's shows interdependencies and relationships between those needs and Alderfer proposed further reductions in the number of categories. Applying this situation to systems engineering, it was felt that using system domains as the third dimension would be analogous to using Murray's list of needs and a Maslow/Alderfer more generic-type classification was needed. Consider Maslow as having identified common categories and then grouped Murray's needs into

[2] Xuan-Linh Tran reformatted the orginal drawing into this format.

those categories as well as adding the interdependencies and relationships between those needs. In any domain of systems engineering systems engineers deal with problems (Wymore, 1994).

Problem stating and problem solving may be considered as two sides of the same coin depending on the perspective from which one views the coin. For example, a set of requirements may be considered as:

- **a solution** – the specification of a system that will meet a need.
- **A problem** – a description of something that needs to be designed.

Consequently, the first attempt to formulate a framework for systems engineering in this research (Kasser, 2006) based the third dimension of the framework on problem solving (risk mitigation). One context of categories for risk mitigation was found in the literature in (Shenhar and Bonen, 1997) who presented a taxonomy in which systems were classified according to three levels of system scope and four levels of technological uncertainty (risk). Their three levels of system scope correspond roughly to the three lower layers of the Hitchins five layer model (Hitchins, 2000) and their four levels of technological uncertainty (risk) are:

- **Type a** — Low-Technology Projects which rely on existing and well-established technologies to which all industry players have equal access. The system requirements of Low-Tech Projects are usually set by the customer prior to signing the contract and before the formal initiation of the project execution phase.
- **Type b** — Medium-Technology Projects which rest mainly on existing technologies; however, such systems incorporate a new technology or a new feature of limited scale. Their requirements are mainly set in advance; however, some changes may be introduced during the product development phase. This process often involves a joint effort of the contractor and customer. It may also require the involvement of potential customers in the process.
- **Type c** — High-Technology Projects which are defined as projects in which most of the technologies employed are new, but existent — having been developed prior to the project's initiation. System requirements are derived interactively with a strong involvement by customers or potential users, and many changes are introduced during the development phase.
- **Type d** — Super-High-Technology Projects which are based primarily on new, not entirely existent, technologies. Some of these technologies are emerging; others are even unknown at the time of the project's initiation. System requirements are hard to determine; they undergo enormous changes and involve extensive interaction with the customer.

As the development progresses through the systems development lifecycle the work takes place in different areas of the HKM Framework. The nature of the problems faced by systems engineers in each area of the framework will be different because the problems will depend on the level of technological uncertainty of the specific system (Shenhar and Bonen, 1997). Thus, that systems engineer could be working in Area '2Ba' if it is a low technical risk system or Area '2Bd' if it is a Super-High-Technology Project. Shenhar and Bonen stated that [the role of] systems engineering was a wide-ranging activity, and should not be performed in the same manner for all kinds of systems. Shenhar and Bonen also claim that adopting the wrong system and management style may cause major difficulties during the process of system creation. Namely what works in Area '2Ba' may not work in Area '2Bd'.

Meeting the Requirements for the Framework

For the HKM framework to offer a serious competitive advantage over the current paradigm it must meet all of the four requirements for the framework stated above. Consider ways in which the HKM framework meets or can meet the requirements.

1. The framework shall provide an understanding of why systems engineers can't agree on their roles and activities

(Sheard, 1996) discussed two perspectives on twelve roles of systems engineers some of which were life-cycle roles, some program management, and some which belonged in both. The framework places that discussion in context of the areas in which the activities are performed, because systems engineers work in different layers and in different phases of each layer. (Cook, 2003) demonstrates this in the classroom by positioning the areas in which systems engineers work in the framework as summarized below.

- Traditional systems engineering covers Layer 2 completely as shown in Figure 3 (Cook, Kasser and Ferris, 2003).
- Contemporary test and evaluation is shown in Figure 4. The "V" model can be seen in the figure.
- Military platforms lie mostly in Layer 2 with some activities in Layers 3 and 1 as shown in Figure 5.
- Information systems overlap several layers as shown in Figure 6. They comprise traditional systems integrated out of products interacting with the business and supply chain layers.
- Capability Development lies as shown in Figure 7. These roughly correspond to the investment management and resource management processes shown in Figure 1 (Arnold, 2002). The positioning of Capability Development in the figure indicates that this activity is focussed in the front of the business-layer lifecycle. Capability Development also interacts with the supply chain level because there is a need to ensure enduring support to future Defence capabilities. Lastly, it interfaces to Layer 2 through the acquisition projects it generates[3].

When activities which were plotted in the framework are overlapped, the result is shown in Figure 8. It shows that systems engineers working in the different parts of the framework do different tasks. Figure 8 does not show, but other evidence indicates that the systems engineers working in the different areas of the framework use the same words but with different meanings. For example the word "capability" has different meanings in areas '3A' and '2C'. Consequently, no wonder they can't agree on what systems engineering is and on what systems engineers do.

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[3] According to Cook, S. C., *Principles of Systems Engineering - Course Notes*, Systems Engineering and Evaluation Centre, University of South Australia, Adelaide, 2003., such a representation is, of course, overly simplistic because aspects of the capability development processes also occur further down the life-cycle, thus a more accurate representation would be an overlay whose colour saturation represents the degree of effort applied at each point in the two-dimensional space.

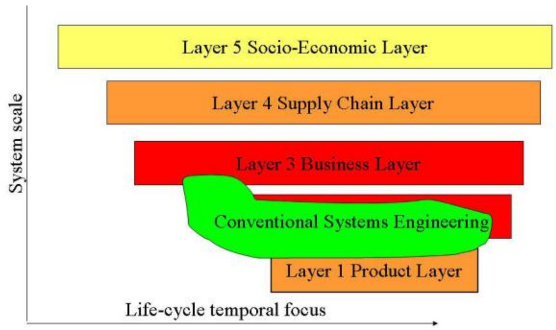

Figure 3 Traditional Systems Engineering

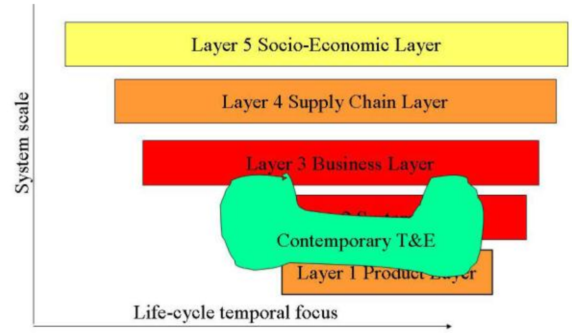

Figure 4 Contemporary Test and Evaluation

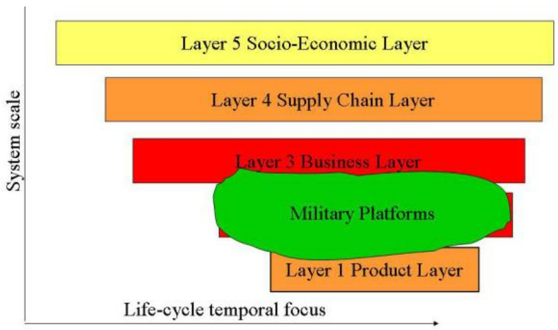

Figure 5 Military Platforms

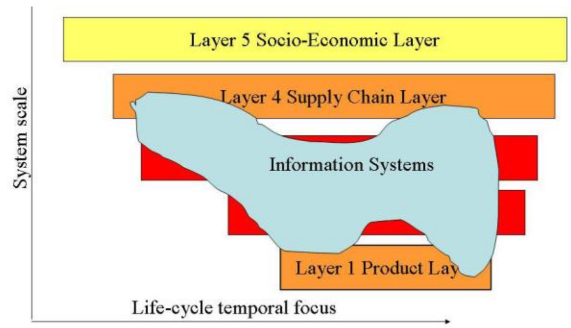

Figure 6 Information Systems

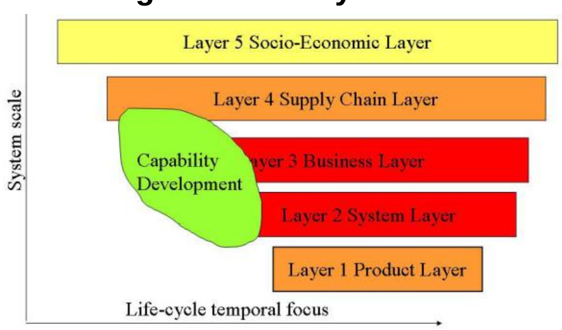

Figure 7 Capability Development

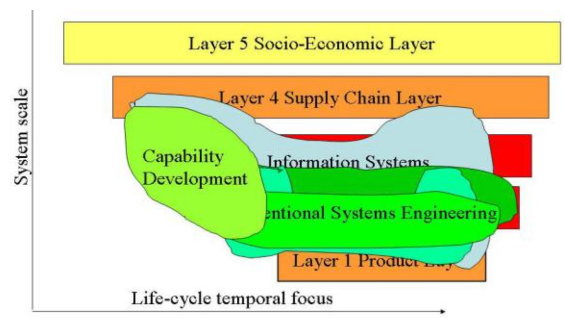

Figure 8 Overlay of areas

As if this isn't enough, consider the role of the systems engineer in Layer 2 which was examined and discussed in (Kasser and Palmer, 2005). Systems engineers working in that layer do different things in different organizations due to the overlap of roles and activities, and there is no reason to think that systems engineers working in other layers also do different things in those layers than do systems engineers working in different organizations. Again it should not come as a surprise that systems engineers working in the same layer but in different organizations can't agree on what systems engineers do and what systems engineering is without this external perspective provided by the framework. Thus it can be said that the framework meets the requirement to provide an understanding of why systems engineers can't agree on roles and activities.

2. The Framework shall provide an understanding of the reasons for the overlap between systems engineering and management.

According to (Sillitto, 2005) when examining a system of interest common advice given to systems engineers is to first look out from the system. However, this only provides one perspective. Systems engineers need to step out of the system and look back into it from a number of perspectives as stated in (Kasser and Palmer, 2005).

Stepping outside the system and looking back into it, it can be seen that (Chestnut, 1965) page 8) stated that systems engineering had a large number of definitions referencing (Churchman, Ackoff and Arnoff, 1957; Goode and Machol, 1959; Morton, 1959; Eckman, 1961; Williams, 1961; Hall, 1962; Gosling, 1962; Bender, 1962; Feigenbaum, 1963) and (Mesarovic, 1964).

The overlap between management and engineering was recognized as early as 1959 by (Goode and Machol, 1959) who wrote *"Management has a design and operation function, as does engineering"*. Later perspectives on the overlapping of, and differences in, the roles of systems engineering, systems architecting, and project management have also been discussed in the literature, e.g. (Brekka, Picardal and Vlay, 1994), (Roe, 1995), (Sheard, 1996) (Kasser, 1996), (Mooz and Forsberg, 1997), (Kasser, 2002b), (Kasser and Palmer, 2005) and (Kasser, 2005) as well as the depth of specialty knowledge required for each of the three roles in the development of systems (Kasser and Schermerhorn, 1994), (Roe, 1995),(Maier and Rechtin, 2000), (Kasser, 2000), and (Kasser, 2002b). For example, according to (Roe, 1995) the knowledge and skills of systems engineers are the same as those of project management in the areas of management expertise, technical breadth and technical depth. Roe adds that the difference in application is that the system engineer has more technical breadth, while the project manager has more management expertise. (Bottomly, Brook, Morris and Stevens, 1998) studied the roles of the systems engineer and the project manager and identified 185 activities and their competencies (experience and knowledge). Their findings included:

- No competency was assessed as being purely the province of systems engineering.
- There is no sharp division between the two disciplines (systems engineer and the project manager) even at the level of individuals.

Further research into the origin of the disciplines found the following statement – "*driven by cold war pressures to develop new military systems rapidly, operations research, systems engineering, and project management resulted from a growing recognition by scientists, engineers and managers that technological systems had grown too complex for traditional methods of management and development*" (Johnson, 1997). Thus systems engineering, project management and operations research can be seen as three solutions to the problems of the Cold War by three different communities of practice (Johnson, 1997) that have continued to evolve and overlap. In specific organisations, practitioners of one of the disciplines would perform activities that were not being performed in that organisation, but were being performed by a practitioner of a different discipline in a different organisation (Kasser, 2005). As a result,

- Today's organisational paradigm contains three overlapping evolving disciplines (project management, systems engineering and operations research) attempting to solve the same problems from three different perspectives (Johnson, 1997).
- Each discipline is using its own tools and techniques and adopting others as and when

needed.

- Each discipline has instances of poor implementation leaving a vacuum which another discipline fills. This has created a large degree of overlap of activities. These boundaries are artificial and often detrimental (Friedman, 2006).
- The evolution and overlap is continuing. Note the eight boxes containing the word "management" in Figure 1.
- Operations research was defined as "*how to make sure that the whole system works with maximum effectiveness and least cost*" (Johnson, 1954) page xix) a goal that many modern systems engineers would apply to systems engineering. The overlap between operations research and systems engineering was noted as early as 1954 when Johnson wrote "*Operations research is concerned with the heart of this control problem – how to make sure that the whole systems works with maximum effectiveness and least cost*" (Johnson, 1954) page xi). Goode and Machol wrote that the steps of the operations research and systems engineering processes have much in common however there is a fundamental difference in approach. According to (Goode and Machol, 1959) page 130) "*the operations analyst is primarily interested in making procedural changes whilst the systems engineer is primarily interested in making equipment changes*." A lasting difference was noted by Roy as "*Operations research is more likely to be concerned with systems in being than with operations in prospect*" (Roy, 1960) Page 22).

By mapping the activities performed by the three disciplines involved in acquiring and maintaining systems into a two-dimensional map (Kasser and Palmer, 2005), the framework has shown that organisational activities do overlap and has initiated research into the history of the disciplines which has provided further information as to how the overlaps began and evolved (Johnson, 1997). The framework can thus be said to have met this requirement.

3. The Framework shall provide a way to cope with complexity.

Systems engineering has been the promised approach to solving the problems of complexity for at least 50 years. For example, Chestnut wrote in 1965 "*In a society which is producing more people, more materials, more things, and more information than ever before, systems engineering is indispensable in meeting the challenge of complexity*" (Chestnut, 1965) page vii). A few years later, Wymore wrote "*Systems engineering is the professional, intellectual and academic discipline the primary concerns of which are the analysis and design of large-scale, complex, man/machine systems*" (Wymore, 1976). Yet instead of solving problems, systems engineering seems to be making things more and more complex.

As stated above, according to (Sillitto, 2005) when examining a system of interest it is common advice to first look out from the system. Consider the systems acquisition process from this perspective. The top half of Figure 9 represents a reference model for the activities performed in the acquisition process in the top three layers of the framework. The cycle begins when a high level need for additional enterprise wide Defence Capability is identified. It is compared with the Capability that exists or is in the process of being acquired and due to be phased into service, and a gap analysis is made to identify missing Capability. Once identified, the missing Capability is slated to be acquired. To guide the acquisition process, evaluation criteria are also developed to influence the acquisition decision. Ideally the gap analysis generally identifies a number of implementation choices or possible solutions to the problem posed by the missing Capability. These choices include not only the procurement of new materiel but changes to doctrine and/or operations and reuse of spares located somewhere else in the enterprise. Recent changes to the acquisition process perform the gap analysis to not only identify current Capability gaps, but project into the future to identify the most probable gaps, five, ten and even twenty years into the future producing a lot of PowerPoint engineering products and science fiction. Thus what has been termed as Enterprise Systems Engineering and the Engineering of Systems applies across many systems. It:

- Converts capability needs to requirements.
- Identifies problems.
- Mostly uses soft systems methodologies.
- Tends to be political rather than technical.
- Employs an enterprise wide architecture framework.
- Comprises the top three layers of the framework.

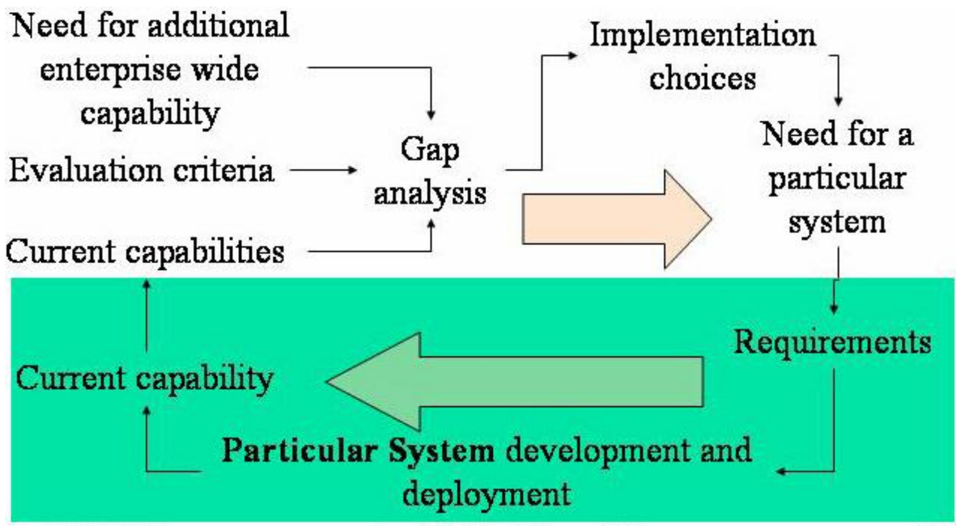

Figure 9 The process for the engineering of complex systems

Glossing over how the decision of which specific choice to implement, a decision is made and a specific system is defined and enters the acquisition process, namely:

- Contract(s) are awarded for development of the Capability the system is to provide;
- Changes are managed throughout the System Development Life Cycle of the Capability being acquired[4].

The lower half of Figure 9 represents one instance, namely the particular system of many such instances of Capability being acquired and upgraded asynchronously (Kasser, 2002a) in such a manner as to ensure the entire available Capability meets the need(s) all the time. Thus what has been termed as traditional Systems Engineering:

[4] This is a description of a reference model; the real world is somewhat different.

- Applies to particular or single systems.
- Converts requirements to Capability.
- Implements solutions.
- Mostly uses hard systems methodologies.
- Tends to be technical rather than political.
- Shows how a particular system fits into the Enterprise-wide architecture framework.
- Comprises the lower two layers of the framework.

If the outward looking perspective shown in Figure 9 is replaced by an external perspective, the situation can be represented in the form of the reference model shown in Figure 10. When drawn in this way several things become apparent, namely:

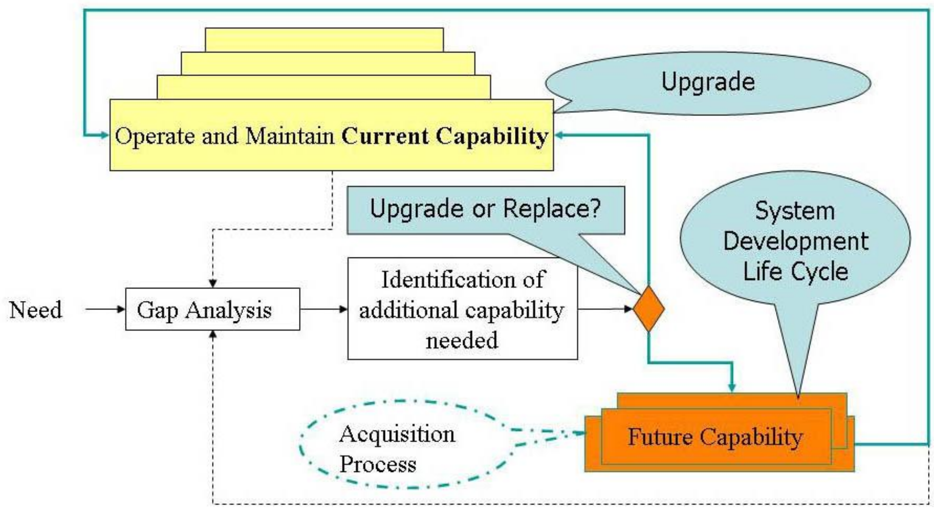

Figure 10 A Service and Support system

- Figure 10 is a representation of a very complicated system.
- The purpose of drawing the system boundaries for the reference model shown in Figure 10 can be stated as a high level representation of a system that provides Capability as and when needed. When a need for Capability arises, a gap analysis is made between the Capabilities that are available and those planned to go into service (within their individual System Development Life Cycle) and a decision is made to fill the gap by upgrading existing Capability, replacing Capability or providing new Capability.
- The box marked "gap analysis" could also be labelled "strategic planning", the box marked "identification of additional capability needed" could be labelled "capability development" and the box marked "future capability" could be labelled as "produce future capability". In this context, Figure 10 is a functional representation of a system.
- System architecting and systems engineering activities can be seen taking place in three parts of Figure 10 (Upgrade, Upgrade or Replace, and the System Development Life Cycle).
- The methodologies used in various parts (subsystems) of Figure 10 are different in accordance with (Flood and Jackson, 1991), (Shenhar and Bonen, 1997) and (Martin, 1994). Strategic planning, capability development and requirements elicitation tend to be performed

in a pluralist context, while once the requirements for a system are known, the context generally shifts to unitary and traditional systems engineering takes place. Once the context of the problem is known the appropriate methodology can be determined by the process architect (Kasser, 2005).

After thousands of years of performing physical decompositions of systems we have a good understanding of the process and can do it very well to simplify physical systems. We need to develop ways of performing non-physical decompositions of systems in a similar manner to simplify problems instead of introducing additional complexity. The framework has helped identify the problem and methodologies, but much more research needs to be done to convert complexity to simplicity (Kasser and Palmer, 2005).

4. The Framework shall enable the development of a way of working that lowers the cost of doing work by at least an order of magnitude.

Meeting this requirement will take a real reengineering effort (Hammer and Champy, 1993). It will need a fundamental change in the structure of the organisation and the partition of work. Understanding the reasons for the overlapping of roles in the organization allows the roles to be redefined to minimize the overlaps in the future. Redrawing the boundaries can be implemented as part of an object-oriented approach to building organizations.

It is tempting to state that systems engineering is the methodology to use to reduce the cost of doing work. However, as Maslow wrote, "*I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail*" (Maslow, 1966) pages 15 and 16). Thus applying systems thinking tells us to use the various tools and techniques used by any of the overlapping activities of systems engineering, project management, Total Quality Management, and others in the area of activity covered by the framework. The challenge is to build a new paradigm for doing work at a lower cost (the system) by mixing components from:

- Systems engineering (roles and activities) (Beer, Hall, Jackson, Checkland etc.);
- Management (Taylor, Ford, Drucker, Peters, Hammer and Champy etc.);
- Quality (Deming, Juran and Crosby etc.);
- Other appropriate sources;
- Some original twists

Early activities using an object-oriented approach to redraw boundaries and include prevention into the work process was described as an Anticipatory Testing approach (Kasser, 1995) and achieved promising results as shown by these examples of the difference between the current way of working in general, and the Anticipatory Testing approach. In the period September – December 1995, the Anticipatory Testing Corporation took part in three proposal efforts which provided a comparison of the cost of preparing proposals using the conventional and Anticipatory Testing methodologies, these were the:

- **PK proposal** - A 75 page technical proposal (+ other volumes) which was written both in Maryland and in Florida. The Anticipatory Testing Corporation led the proposal preparation effort which lost by being $10,000 more expensive than the winning offer.
- **NOVA proposal** - A 100 page technical proposal (+ other volumes) which was written in Maryland. The Anticipatory Testing Corporation was a small sub-contractor, had no say in

the proposal preparation effort.

- **NSF proposal** - A 147 page technical proposal (+ other volumes) which was written both in Maryland and Virginia in December 1995. The Anticipatory Testing Corporation led the proposal preparation effort.

The estimated total costs for each proposal are the costs for labour and materials assuming everyone who worked on the proposal were paid for all the hours they put in to preparing the proposal. A comparison of the PK and NOVA proposals is shown as part of Table 2. The 10 to 1 difference in cost is mostly the result of the Anticipatory Testing management approach rather than the size or type of the proposals. The NSF proposal provided another data point which correlates to the PK proposal.

Table 2 Comparison of September – December 1995 Proposals

Factor	NOVA	PK	NSF
Technical pages	100	75	147
Companies on team	4	2	3
Location	MD/DC	MD/FL	MD/VA
Management approach	Conventional	Anticipatory testing	Anticipatory testing
Estimated total equivalent costs ($US)	$100,000	$10,000	$20,000

The same Anticipatory Testing approach was later used in 2003 in the Systems Engineering and Evaluation Centre (SEEC) at the University of South Australia to write the main 32 pages of a proposal[5] to provide the Australian Defence Materiel Organisation (DMO) with a U.S. style coursework Master of Project Management degree with flexible delivery options. SEEC had no prior contracts with the DMO, so it was a cold proposal. The proposal effort began half way into the six week tendering period and was mostly written by one person. It was evaluated by the DMO customer as providing the best value, coming ahead of eight competing Australian universities, and the contract was worth more than AUD $1,500,000 over three years.

Redrawing boundaries has introduced the concept of the process architect (Kasser, 2005) and has also identified defects in the systems engineering process (Kasser, 2006; Kasser, 2007a), which if fixed can substantially contribute to lowering the cost of doing work. These defects include:

- The selection of independent alternative solutions may not provide the optimal solution. The optimal solution may be a combination of parts of the individual alternatives.
- The V Model lacks a feed forward or prevention component.
- The lack of a standard process for planning a project even though systems engineering (at least at Layers 1 and 2) is highly process oriented.
- The lack of a metric for the goodness of requirements even though there is consensus that

[5] The remaining pages were enclosures containing mostly pre-existing materials.

poor requirements are a major contributor to cost and schedule overruns (Kasser, Scott, Tran and Nesterov, 2006).
- A focus on technological solutions instead of the real need. This was recognized as early as 1959 by Goode and Machol who wrote "*the systems engineer is primarily interested in making equipment changes*" (Goode and Machol, 1959) page 130).

Thus while it cannot be claimed that the framework has met this requirement, it has certainly enabled the understanding of ways in which to do so.

Further Research

The framework has helped to develop an understanding of the overlap of organisational activities in the workplace and from there it should be possible to use tools and techniques from all the disciplines in an interdependent manner to design effective organisations and reduce the cost of doing work. Early research into redrawing work boundaries has already produced some significant reductions in the cost of doing work. Examples of further research using this framework planned and in process at the present time are:

- Mapping tools used for systems engineering into the areas of the framework. (Johnson, 1997) showed how and why the activity known as systems engineering overlaps other organizational activities. Thus, a multi-methodology for systems engineering can be the methodologies, tools and techniques used in systems engineering as well as any of the overlapping activities. This puts a considerable number of tools into the toolbox of the systems engineer. These tools include Total Systems Intervention (Flood and Jackson, 1991), Soft Systems Methodology (Checkland and Holwell, 1998), those provided by (Avison and Fitzgerald, 2003) and (Checkland, 1993), as well as the more commonly used hard systems methodologies discussed in (Blanchard and Fabrycky, 1981) and other treatments of the systems engineering process. However, just reusing those tools from the other overlapping areas of activity is as fraught as the reuse of software without investigating the context from where the proposed reusable module was taken from and its suitability for use in the new context. The danger of such software reuse was demonstrated in the failure of the maiden flight of the Arianne 5 launcher on 4 June 1996. Once the context of the problem is known the appropriate methodology to be investigated for suitability needs to be determined by the process architect. This research maps systems engineering tools into the HKM framework based on the nature of the problems for which they are used to help provide solutions. This will be followed by mapping tools used in the other overlapping disciplines into the framework and developing requirements for an integrated digital environment or network centric commercial management information system (Tran and Kasser, 2007).
- Plotting the papers published at the annual INCOSE Symposia and regional conferences in the HKM framework. In some preliminary research, the topics covered by papers in the Annual International Symposia of the INCOSE published in 1994, 1997, 2000, 2003 and 2006 were plotted into the appropriate areas of the HKM framework (Tran and Kasser, 2007). When a paper covered more than one area it was counted in all the areas it covered. Papers that covered topics such as education or theory of systems engineering were excluded. The preliminary findings in Figure 11 show that the papers mostly cover Layer 2 with growing interest in Layer 3. This corresponds to growing awareness of the last few years of the need to consider integrating what used to be considered as separate systems.

- Identifying common types of project lifecycles other than the classic Defence Systems Development Life cycle by plotting the path taken by various projects in the framework. One wonders if the paths would be linear or more like the route taken by a player in the 'snakes and ladders' board game.
- Plotting the ANSI/EIE 632, IEEE 1220, ISO 15288, MIL STD 499C standards and the CMMI into the HKM framework.
- Determination if the (Shenhar and Bonen, 1997) taxonomy applies in the upper levels of the framework, or if a different type of risk should be considered. The lower two levels apply to the implementation phase and technical risk is a logical candidate for this dimension. However, for the upper levels the dimension might be based on contextual risk rather than technical risk.

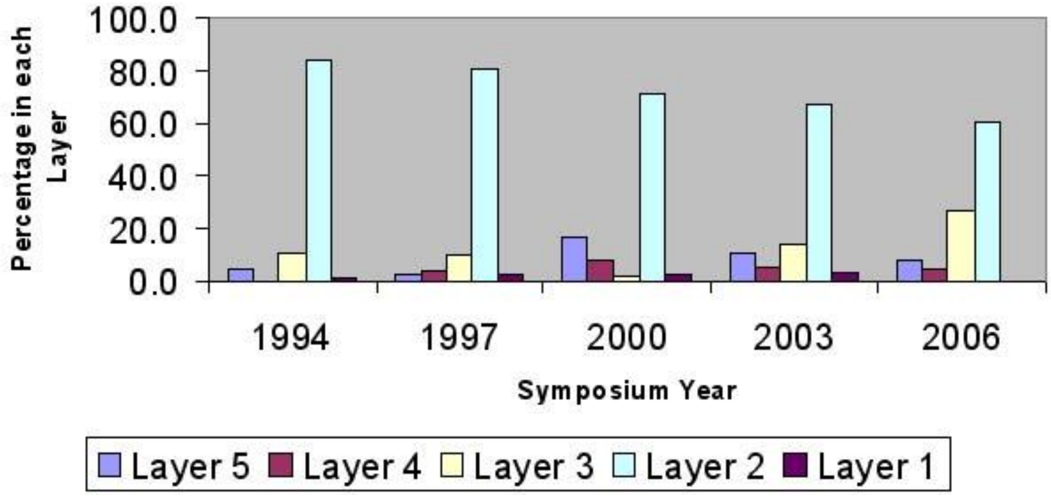

Figure 11 Focus of INCOSE Symposia Papers

Summary

This paper applied systems thinking to systems engineering. This paper focused on what systems engineers do. It documented past research and success, and the application of an object-oriented approach in a creative and innovative manner. It listed four requirements for a framework for systems engineering and discussed the evolution of the HKM framework that met or shows promise of meeting the four requirements. In its early days, the HKM framework has:

- Provided an understanding of why systems engineers can't agree on their roles and activities (Kasser and Palmer, 2005).
- Provided an understanding of the reasons for the overlap between systems engineering and management from the origin of the situation discussed by (Johnson, 1997).
- Shown a relationship between Enterprise Systems Engineering and the Engineering of Systems.

Conclusion

Although the HKM framework does not currently meet all four requirements for a framework for systems engineering, it has been able to provide explanations for some of the problems with today's systems engineering paradigm. It is thus a useful educational tool and provides a baseline stepping stone for future research.

Postscript

The benefits from the HKM framework problem-based paradigm not previously discussed should include:

- Moving organisations away from activities (industrial age) and towards problem solving and the knowledge needed to make informed decisions (information age).
- Requiring the education of a generation of people who will understand the consequences of their decisions. This could be the most tangible benefit and the real change.

The body of knowledge that we have today is not the sum of all knowledge. For example, McCloskey wrote "*In the present century, physical scientists, aided by powerful mathematical tools, have reduced to principle many phenomena little known and less well understood by the predecessors*" (McCloskey, 1954) page 258. One could argue that these scientists have solved what appeared at the time to be wicked problems? What are we going to learn in the future and how will it change our way of thinking?

Biography

Dr. Joseph Kasser has been a practising systems engineer for more than 35 years. He is an INCOSE Fellow and the author of "Applying Total Quality Management to Systems Engineering" and many INCOSE symposia papers. He holds a Doctor of Science in Engineering Management from The George Washington University, and is a Certified Manager. He is Deputy Director and an Associate Research Professor at the Systems Engineering and Evaluation Centre at the University of South Australia. He teaches online and in the classroom as well as performing research into the nature of systems engineering and the properties of object-oriented requirements. He is a recipient of NASA's Manned Space Flight Awareness Award (Silver Snoopy) for quality and technical excellence for performing and directing systems engineering and many other awards and commendations.

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