

# A Proposed Framework for a Systems Engineering Discipline

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## Abstract

The paper discusses the rationale for, and describes a proposed framework for systems engineering in the context of a discipline. This framework, the Hitchins-Kasser-Massie (HKM) framework has already facilitated postgraduate teaching of systems engineering and has provided reasons why systems engineers have a plurality of views concerning the scope and nature of systems engineering. The contribution of this paper is to place the HKM framework in the context of Kline's definition of a discipline.

## Introduction

George Friedman called for the development of a grand unified theory of systems engineering (GUTSE) (Friedman, 2006) echoing the earlier lament by (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 those challenges, this paper proposes a framework for systems engineering that can serve as a vital element in formalizing the discipline of systems engineering and potentially as a platform for developing such a theory.

The paper begins with a discussion of the need for the framework, as a fundamental part of a discipline, observes that systems engineering shows the symptoms of being in the

early stages of a discipline. The paper then discusses the elements of a discipline and hypothesizes that a framework for systems engineering exists. Using the scientific method to build on an earlier two-dimensional framework, the paper then presents a candidate three-dimensional-framework based on the problem solving perspective. The paper then discusses some insights that the framework has already provided.

## The need for a framework

We need a framework because systems engineering has failed to fulfill 50 years of promises of providing solutions to the complex problems facing society. (Wymore, 1994) pointed out that it was necessary for systems engineering to become an engineering discipline if it was to fulfill its promises and thereby survive. Nothing has changed in that respect since then. (Wymore, 1994) also stated that

*“Systems engineering is the intellectual, academic, and professional discipline, the principal concern of which is to ensure that all requirements for bioware/hardware/software systems are satisfied throughout the lifecycles of the systems. This statement defines systems engineering as a discipline, not as a process. The currently accepted processes of systems engineering are only implementations of systems engineering.”*

Out of more than 50 definitions discovered

in the literature (Kasser and Massie, 2001; Kasser and Palmer, 2005), Wymore provided the only definition of systems engineering as a discipline.

### The elements of a discipline

Consider the elements that make up a discipline. One view was provided by (Kline, 1995) page 3) who states

*“a discipline possesses a specific area of study, a literature, and a working community of paid scholars and/or paid practitioners”.*

Systems engineering has a working community of paid scholars and paid practitioners. However, the area of study seems to be different in each academic institution but with various degrees of commonality. This situation can be explained by the recognition that

- (1) systems engineering has only been in existence since the middle of the 20<sup>th</sup> century (Johnson, 1997; Jackson and Keys, 1984; Hall, 1962), and
- (2) as an emerging discipline, systems engineering is displaying the same characteristics as did other now established disciplines in their formative years.

Thus, systems engineering may be considered as being in a similar situation to the state of chemistry before the development of the periodic table of the elements, or similar to the state of electrical engineering before the development of Ohm's Law. This is why various academic institutions focus on different areas of study but with some degree of commonality in the systems development life cycle. Nevertheless, to be recognized as a discipline, the degree of overlap of the various areas of study in the different institutions needs to be much, much greater.

### Moving towards a discipline

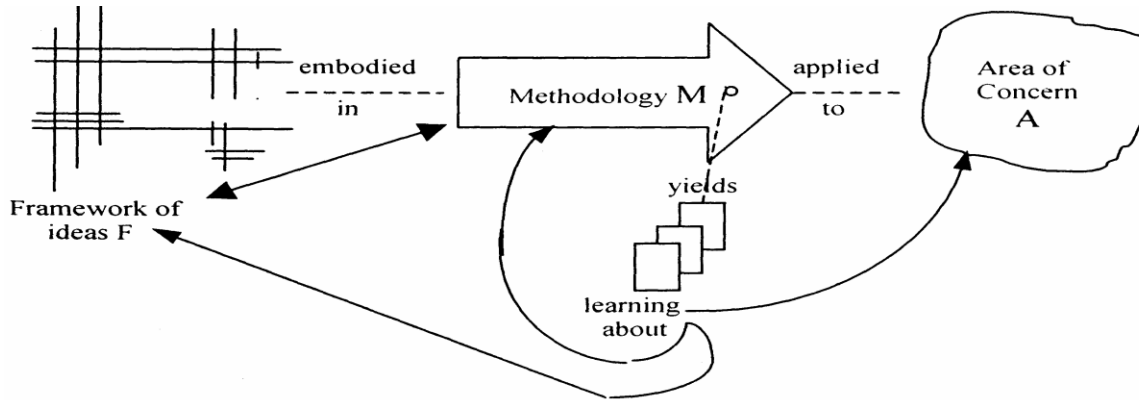
As today's systems engineering is in a similar state to chemistry and electrical engineering in their formative years, then a major step forward in the development of the discipline would be to apply the scientific method to postulate a hypothesis (namely a framework for systems engineering exists); identify and prototype a candidate framework, test it; modify it and eventually evolve a working framework for systems engineering. This framework would pull together systems engineering in an analogous manner to the application of the periodic table of elements in chemistry.

The hypothesis behind this research is that if the activities performed by systems engineers can be plotted in a framework it may be able to bring about a revision of the *a priori* understanding of systems engineering. This means a change in the understanding of its current paradigm (Churchman, 1979) page 105) or Weltanschauung (Checkland and Scholes, 1990), and its emergence as a true engineering discipline. (Kasser, 2006) discussed the evolution of a proposed framework for systems engineering. This paper places that framework in the context of Kline's definition of a discipline.

### Elements relevant to research in a discipline

According to (Checkland and Holwell, 1998) research into a discipline needs the following three items:

- **An Area of Concern (A)**, which might be a particular problem in a discipline (area of study), a real-world problem situation, or a system of interest.
- **A particular linked Framework of Ideas (F)** in which the knowledge about the area of concern is expressed. It includes current theories, bodies of knowledge, heuristics, etc as documented in the literature as well as tacit knowledge.



**Figure 1 Elements relevant to any piece of research (Checkland and Holwell, 1998) page 23)**

- **The Methodology (M)** in which the framework is embodied that incorporates methods, tools, and techniques in a manner appropriate to the discipline that uses them to investigate the area of concern.

Figure 1 extracted from (Checkland and Holwell, 1998) page 23) illustrates the relationship between these elements. Given that there is a working community of paid scholars and/or practitioners (Kline, 1995) page 3), these same three elements can also be used to characterise a discipline because they expand (Kline, 1995)'s specification and encompass the key aspects of a discipline (Cook, Kasser and Ferris, 2003). Consider each of these elements in turn, as they apply to systems engineering.

**An Area of Concern (A).** Pragmatically, the Area of Concern (A) should be both what systems engineers do and where they do it. There have been many diverse opinions on these topics over the years, typical examples are (Allison and Cook, 1998; Hitchins, 2000; Sage, 1995; Badaway, 1995; Kasser, 1995; Chapanis, 1960; Shenhar and Bonen, 1997; Wymore, 1993) hence the difficulty in defining systems engineering. Three sample opinions are:

*“Despite the difficulties of finding a universally accepted definition of systems engineering, it is fair to say that*

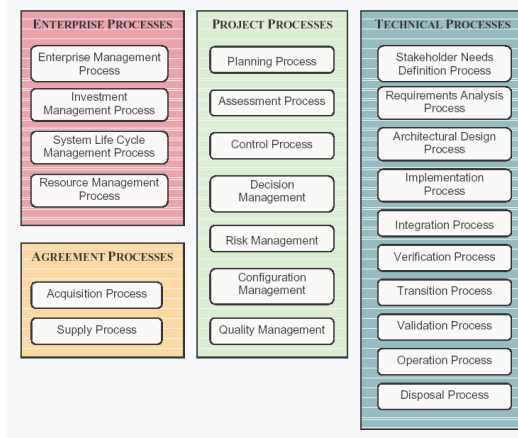
*the systems engineer is the man who is generally responsible for the over-all planning, design, testing, and production of today’s automatic and semi-automatic systems” (Chapanis, 1960) page 357).*

*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).*

*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).*

In addition, the latest systems engineering

standard ISO 1528 provides a list of the organizational processes or activities in which systems engineers are involved as shown in Figure 2 extracted from the standard (Arnold, 2002) page 61). Note the use of the word “management” in eight of the process boxes.



**Figure 2 ISO 52888 Systems Engineering Processes**

There have also been many discussions in the literature about the overlapping of, and differences in, the roles of systems engineering, systems architecting, and project management, e.g. (Brekka, Picardal and Vlay, 1994; Roe, 1995; Sheard, 1996; Kasser, 1996; Mooz and Forsberg, 1997; Kasser, 2002; Eisner, 2002; Kasser and Palmer, 2005; Kasser, 2005; Falconbridge and Ryan, 2003; Maier and Rehtin, 2000) and (Alleman, 2005) who recasts project management as systems management using systems engineering. In addition, there have also been many discussions in the literature about the depth of specialty knowledge required for each of the roles in the development of systems, typical examples are (Kasser and Schermerhorn, 1994; Roe, 1995; Bottomly, Brook, Morris and Stevens, 1998; Maier and Rehtin, 2000; Kasser, 2000; Kasser, 2002). 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, techni-

cal 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 reason for the overlapping of the disciplines turned up information as to how the overlap originated. 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)*

and the argument in the rest of the paper seem to provide a definitive answer. (Kasser, 2005) showed how the roles evolved into overlapping functions due to the differences in the activities assigned to the roles in different organisations. The (A) of systems engineering thus needs to span the activities performed by the roles of the systems engineer, operations researcher and project manager.

**The framework of ideas (F).** (Checkland and Holwell, 1998) pages 23-25) discuss the importance of a “declared-in-advance” epistemological framework (F) when undertaking

interpretive research. Thus establishing an (F) is fundamental to the definition of a research topic or a discipline. As systems engineering focuses on problems (Wymore, 1994), the (F) for systems engineering can be considered as being documented in the literature on systems thinking, problem solving and the activities that take place in the (A).

**The methodology (M).** Since the activity known as systems engineering overlaps other organisational activities, systems engineering may be considered as a meta-methodology incorporating the methodologies, tools and techniques used in the (A) by both systems engineers and practitioners of the other organisational 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);
- the process-oriented, blended, object-oriented, rapid development, people oriented, and organisational-oriented methodologies discussed in (Avison and Fitzgerald, 2003);
- a whole suite of problem solving tools for requirements elicitation and elucidation discussed in (Hari, Kasser and Weiss, 2007); these include interviews (Alexander and Stevens, 2002), Joint Applications Development (JAD) (Wood and Silver, 1995), Analytical Hierarchical Process (AHP) (Saaty, 1990), Nominal Group Technique (NGT) (Memory Jogger, 1985) scenario building, user/customer interviews, questionnaires, customer visits, observation, customer value analysis, use cases, contextual inquiry, focus groups, viewpoint modelling (Darke and Shanks, 1997), and Quality Function Deployment (QFD) (Hauser and Clausing, 1988; Clausing and Cohen, 1994);
- the more commonly used hard systems methodologies discussed in (Blanchard

and Fabrycky, 1981; Buede, 2000) and other treatments of the systems engineering process.

## The Hitchins-Kasser-Massie Framework

The vertical and horizontal dimensions of the framework are based on the work of (Kasser and Massie, 2001) who, in conceptualising 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 of the framework** 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 artefacts.
- **Layer 1** - Product Level. Many products make a system. The tangible artefact 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. Hitchins also states that these statements are only ap-

proximate 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 covers the phases of the systems engineering life cycle. (Kasser and Massie, 2001) did not define explicit phases. The phases have been stated in various ways in various standards, conference papers and books, but for this framework, they are now defined in generic terms as:

- Identifying the need.
- Requirements analysis.
- Design of the system.
- Construction of the system.
- Testing of the system components.
- Integration and testing of the system.
- Operations, maintenance and upgrading the system.
- Disposal of the system.

The horizontal dimension is also nested but in time. For example, the initial acquisition of a system might flow linearly through the system development life cycle from Area 2B through Areas 2C, 2D, 2E, 2F to delivery and operations and maintenance in Area 2G. However, the activities that take place during the operations and maintenance phase (Area 2G) are the same as those that take place in requirements analysis (of change requests) (2B), design (2C), construction (2D) testing (2E) and integration (2F) of the configurations of the various system upgrades.

The vertical and horizontal axes produce a two-dimensional map containing 40 areas as shown in Figure 3. Thus, a systems engineer performing requirements analysis for a new system is working in Area '2B'. Another systems engineer performing integration and testing on the same or a different new system is

working in Area '2F.' Note, while the axes of the framework are shown in a linear manner, this is just for the convenience of drawing. The operations and maintenance phase of the system life cycle generally lasts much longer than the initial acquisition phases, hence column G is drawn wider than the other columns.

Layer of Systems Engineering \ Phase in the Life Cycle	Needs identification	Requirements	Design	Construction	Unit testing	Integration & testing	O&M, upgrading	Disposal
	A	B	C	D	E	F	G	H
Socio-economic	5							
Supply Chain	4							
Business	3							
System	2							
Product	1							

Figure 3 The HKM Framework for Systems Engineering

### 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

1. this situation was analogous to the development of theories of motivation in Psychology, and
2. 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 iden-

tified 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 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 devel-

oped 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.

Thus, Shenhar and Bonen's work forms the basis for the risk dimension of the HKM Framework at least in the lower layers of traditional systems engineering.

As the development of a system progresses through the system development life-cycle 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). Shenhar and Bonen also support (Martin, 1994)'s 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'. Thus, a systems engineer working in Area '2B' should be using methodologies appropriate to Area '2Ba' if it is a low technical risk system or Area '2Bd' if it is a Super-High-Technology Project.

### Insights from the HKM Framework

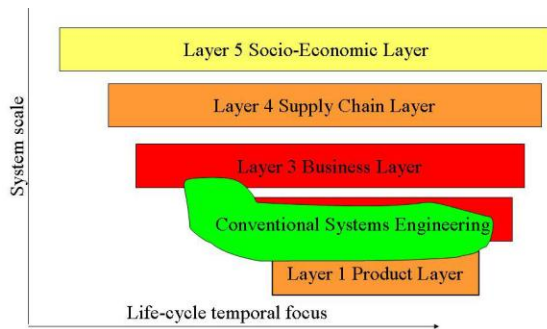
The effort spent to provide the first attempt at a map of the (A) of the discipline of systems engineering by applying lessons learned from Psychology to systems engineering, seems to be providing a useable frame-

work. The following are some of the insights already afforded by the framework.

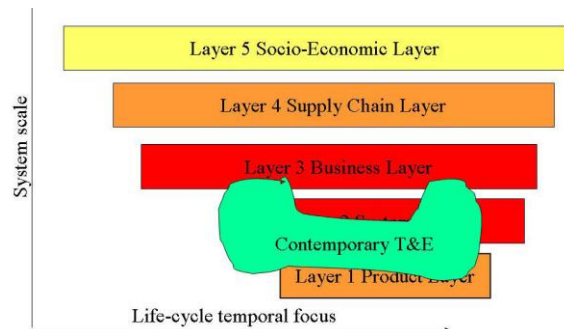
1. Reasons why systems engineers do not agree on the roles of systems engineers and the different definitions of systems engineering.
2. A roadmap for a more complete set of system requirements.
3. The place of operations research in the framework.
4. The similarity between new product development and systems engineering.
5. An explanation of the iterative nature of systems engineering.

**1. Reasons why systems engineers do not agree on the roles of systems engineers and the different definitions of systems engineering.** The HKM Framework illustrates one reason why systems engineers have not been able to agree on roles and activities is that systems engineers work in different layers and in different phases of each layer (Areas of the framework). (Cook, 2003) demonstrates this in the classroom by positioning a number of areas in which systems engineers work as summarized below.

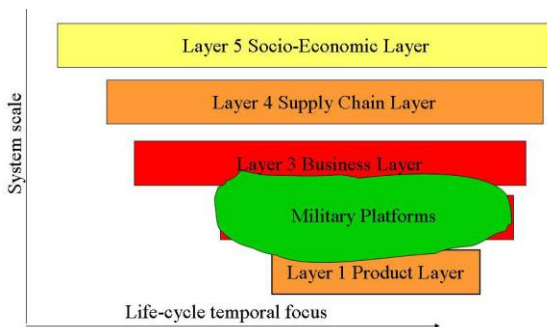
- "Traditional systems engineering covers Layer 2 as shown in Figure 9.
- Contemporary test and evaluation is shown in Figure 9. The "V" model can be seen in the figure.
- Military platforms lie mostly in Layer 2 with some activities in Layers 1 and 3 as shown in Figure 9
- Information systems overlap several layers as shown in Figure 9. They comprise traditional systems integrated out of [commercial] products interacting with the business and supply chain layers.
- Capability Development lies as shown in Figure 9. This roughly corresponds to the investment management and resource management processes shown in Figure 2 (Arnold, 2002). The posi-



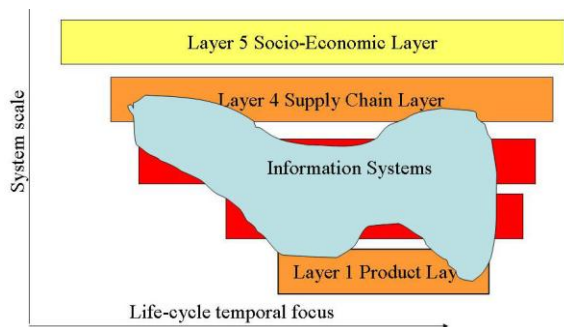
**Figure 4 Traditional Systems Engineering**



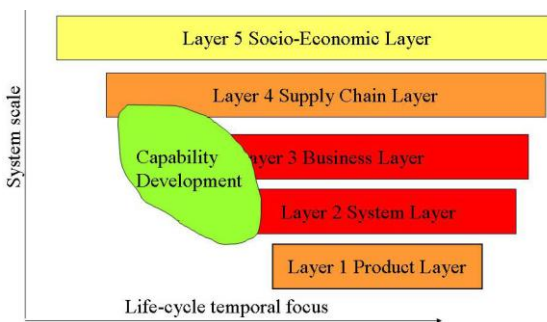
**Figure 5 Contemporary Test and Evaluation**



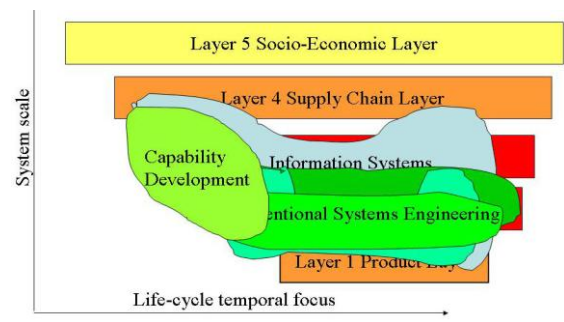
**Figure 6 Military Platforms**



**Figure 7 Information Systems**



**Figure 8 Capability Development**



**Figure 9 Overlay of areas**

tioning of Capability Development in the figure indicates that this activity is focused 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<sup>1</sup>.”

<sup>1</sup> According to Cook, S. C., *Principles of Systems Engineering - Course Notes*, Systems Engineering and

If the positions of activities in the framework are overlapped, the result is as shown in Figure 9. It shows that systems engineers working in the different parts of the framework do different tasks. Figure 9 does not

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.

show, but anecdotal evidence indicates that 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, it is no wonder they cannot agree on what systems engineering is and on what systems engineers do.

**2. A roadmap for a more complete set of system requirements.** The traditional requirements definition process focuses on the functional and performance of the system in its operations and maintenance phase. Treat the HKM framework as a road map, where the road begins in columns A or B, and ends in columns G or H. This gives an explicit assumption that the system will pass through other areas during its development lifecycle. During the requirements definition phase (Area 2B) determine if any of these areas lay requirements on the system (e.g. supply chain requirements such as installation, storage, and transport), and if so include them in the system requirements.

**3. The place of operations research in the framework.** 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). 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

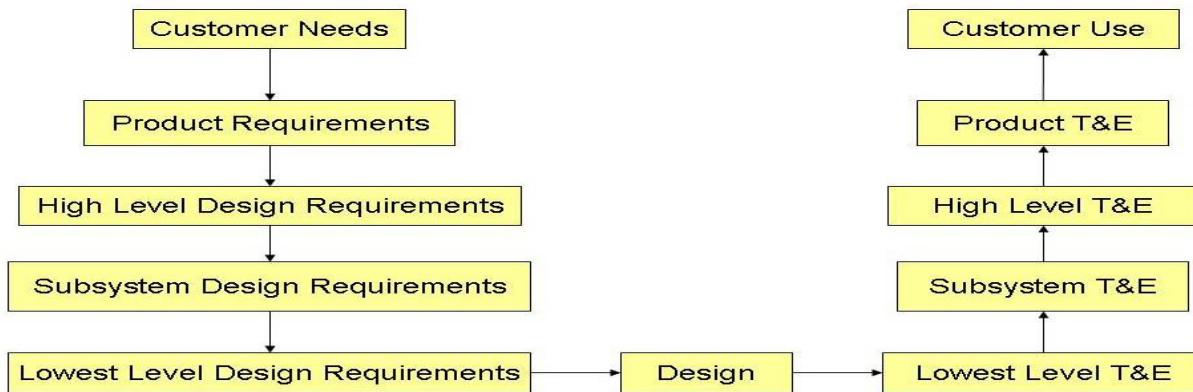
noted by Roy as “*Operations research is more likely to be concerned with systems in being than with operations in prospect*” (Roy, 1960) Page 22). Thus, operations research seems to focus on the areas in column G of the framework.

**4. The similarity between new product development and systems engineering.** (Priest and Sánchez, 2001) provide a description of the product development process as follows:

1. Requirements definition.
2. Conceptual design.
3. Detailed design.
4. Test and evaluation.
5. Manufacturing.
6. Logistics, supply chain, and environment.

The description of each step in the product development process maps into the HKM framework Layer 2 systems engineering life cycle yet the words systems engineering do not appear in the book. For example, the U-diagram on (Priest and Sánchez, 2001) page 64) shown in Figure 10 is equivalent to systems engineering’s V-diagram. This is hardly surprising as the product development process takes place in Layer 1 while traditional systems engineering takes place in Layer 2 of the framework as shown in Figure 9.

**5. An explanation of the iterative nature of systems engineering.** Students have had trouble grasping the concept that systems engineering is iterative. The Egg diagram (ANSI/EIA-632, 1999) shows iterative activities but does not clearly show how the emphasis changes over the life cycle. The FRAT cycle (Mar, 1994) on the other hand provides a clearer perspective in the context of the HKM Framework. For example, the answer to the question of “when do we do functional analysis?” is “several times”. We use it in the ‘F’ step of the FRAT cycle in each Area of the framework



**Figure 10 U-Shape development: flow down of design requirements and flow up of testing (Priest and Sánchez, 2001)**

## Summary

This paper takes up the spirit of the challenges for the development of a theory of systems engineering (Hill and Warfield, 1972; Friedman, 2006) and describes a candidate three-dimensional framework for systems engineering viewed from problem-solving and decision-making perspective that provides Kline's elements of a discipline namely an (A), (F), and (M). The paper has shown that the framework has already provided insight as to reasons why systems engineers have a plurality of views concerning the scope and nature of systems engineering. Research into this framework continues.

## Conclusions

The conclusions from the research discussed in this paper are:

- While the HKM Framework does not provide a theory of systems engineering, it does provide a platform for further research into the nature of systems engineering.
- The HKM Framework embodies the (A), (F) and (M) of systems engineering and hence can be considered as a candidate for the first formal representation of the discipline.

- By virtue of the HKM Framework, systems engineering can fulfil (Wymore, 1994)'s requirement to become a discipline since systems engineering now meets Kline's definition of a discipline, namely it has "a specific area of study, a literature, and a working community of paid scholars and/or paid practitioners" (Kline, 1995) page 3).

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