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A Framework for Benchmarking Competency Assessment Models

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ABSTRACT

This paper discusses the need for competent systems engineers, the differences between nine current ways of assessing competencies (competency models) and the difficulty of comparing the competency models due to the different ways each model groups the competencies. The paper then introduces a competency model maturity framework (CMMF) for benchmarking competency models of systems engineers. The paper benchmarks the nine models using the CMMF and a surprising finding was an error of omission in all nine models. The paper shows that the CMMF can also be used as the basis for developing an original model for a specific organization in a specific time and place and concludes with suggestions for future research. © 2012 Wiley Periodicals, Inc. Syst Eng 16: 29–44, 2013

Key words: competency frameworks; competency assessment

1. INTRODUCTION

Current approaches for constructing and using competency models are based on observations of what systems engineers do in organizations, but there is no way to directly compare competency models or verify if indeed they are fit for the purpose. The purpose of this paper is to introduce a competency model maturity framework (CMMF) for comparing or benchmarking competency models of systems engineers. The literature review for the research documented in this paper covers both systems engineering and the domain of cognitive psychology. The paper begins with a discussion on the need for competent systems engineers, and then discusses the role of systems engineers in the workplace providing examples of a number of points of view as to what those roles are and alludes to the difficulty of gaining a generic consensus on the nature of the role of the systems engineer. At that point the focus of the paper changes to ways of assessing the competencies of systems engineers. The paper continues with a brief examination of nine different competency models and shows that each competency model seems to have been designed for a different purpose in different domains, times, and places. Since competency and competency models are widely discussed in the domain of cognitive psychology, the authors have found it both necessary and helpful to adopt language from the domain of cognitive psychology, avoiding the need to invent yet more systems engineering terminology for concepts already well-defined in the domain of cognitive psychology. Table I contains a glossary to assist in the comprehension of the paper.

The paper then introduces a 2-dimensional CMMF that can be used for comparing and enhancing existing competency models and as a competency model by those organizations that do not yet have a competency model and wish to develop one. The CMMF is based on assessing the competency needed to perform systems engineering in five monotonically

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Table I. Glossary

Word	Meaning	Source
ability	The required competence to perform the function successfully.	
analytical thinking	The abstract separation of a whole into its constituent parts in order to study the parts and their relations	TheFreedictionary.com
behavior	The way in which an animal or a person acts in response to a particular situation stimulus	American Dictionary
capability	Having the ability required for a specific task or accomplishment	TheFreedictionary.com
cognitive	of, relating to, being, or involving conscious intellectual activity (as thinking, reasoning, or remembering)	Merriam-Webster, 2011
competencies	Behaviors that encompass the knowledge, skills, and attributes required for successful performance	[LaRocca, 1999]
competency model	A descriptive tool that identifies the competencies needed to operate in a specific role within a(n) job, occupation, organization, or industry.	[Ennis, 2008]
	A collection of competencies that together define successful performance in a particular work setting.	[ETA, 2010]
competent	having requisite or adequate ability or qualities	Merriam-Webster, 2011
conditional knowledge	Knowing when and why to apply the declarative and procedural knowledge.	[Woolfolk, 1998]
critical thinking	Judicious reasoning about what to believe and therefore what to do	[Tittle, 2011]
declarative knowledge	Knowledge that can be declared in some manner. It is "knowing that" something is the case. Describing a process is declarative knowledge.	[Woolfolk, 1998]
holistic thinking	Art and science of handling interdependent sets of variables	[Gharajedaghi, 1999]
	The combination of thinking about something using the black box and white box perspectives and critical thinking	
knowledge	A body of information needed for the successful performance of the process, or set of processes, considered relevant to the discipline of interest.	
procedural knowledge	Knowing how to do something. It must be demonstrated; performing a process demonstrates procedural knowledge.	[Woolfolk, 1998]
proficiency	Levels of capability	[Metzger and Bender, 2007]
skill	The observable or measured competence in performing the function.	
systems thinking	Systems thinking seeks to address and solve complex problems by understanding the system parts and their interactions within the context of the whole system, rather than in isolation. C.f. Systems Approach	Hitchins, 2011
trait	a distinguishing quality (as of personal character)	Merriam-Webster, 2011

ascending levels. The paper then benchmarks the nine competency models studied using the CMMF and identifies an error of omission common to all models, and continues with suggestions for future research.

2. THE NEED FOR COMPETENT SYSTEMS ENGINEERS

Inadequate systems engineering is repeatedly cited as a major contributor to failed projects, particularly in the National Aeronautical and Space Administration and the US Department of Defense [Evans, 1989, Leveson, 2004, Wynne and Schaeffer, 2005, Welby, 2010]. A literature review reveals that many of the works on improving systems engineering have focused on improving and developing new systems engineering processes, and tend to ignore people (see Swarz and DeRosa [2006] and Goldberg and Assaraf [2010] for typical examples). To be fair, this is not unique to systems engineering [Microsoft, 2008]. For example, Peter Drucker wrote: "Throughout management science—in the literature as well as in the work in progress—the emphasis is on techniques rather than principles, on mechanics rather than decisions, on tools rather than on results, and, above all, on efficiency of the part rather than on performance of the whole" [Drucker, 1973: 509].

However, the literature on "excellence" focuses on people and ignores process [Peters and Waterman, 1982, Peters and Austin, 1985, Rodgers, Taylor, and Foreman, 1993]. In addition, Robert A. Frosch, when an Assistant Secretary to the US Navy, wrote, "[S]ystems, even very large systems, are not developed by the tools of systems engineering, but only by the engineers using the tools" [Frosch, 1969]. And out of the software realm comes the phrase attributed to Grady Booch: "A fool with a tool is still a fool."

While the focus on improving process continues [Goldberg and Assaraf, 2010; West, 2010], the need to certify the competencies of systems engineers is now becoming widely recognized. For example, systems engineering competency models are becoming more widely developed and used in support of systems engineering workforce selection, development, education, and training [Burke et al., 2000, Jansma and Jones, 2006, Menrad and Larson, 2008, Verma, Larson, and Bromley, 2008, Squires et al., 2011]. In addition there is a growing international interest in a certified systems engineering professional (CSEP) qualification.[1]

3. ROLES AND ACTIVITIES OF SYSTEMS ENGINEERS

Research into developing the requirements for, and subsequently updating, a 21st century introductory immersion course on systems engineering [Kasser et al., 2008] included a literature review of textbooks published between 1959 and 2009 starting with Goode and Machol [1959] as well as the proceedings of the international symposia of the INCOSE since 1991. Findings from this research determined that:

- The role of the systems engineer in the workplace depends on the situation.
- Definitions and descriptions of systems engineering currently comprise different interpretations of the broad raft of activities that systems engineers might undertake according to their role in the workplace.

This multichotomy exists because different users of the term "systems engineering" for almost 60 years have chosen or perceived different meanings. For example, one comment from 1960 was: "Despite the difficulties of finding a universally accepted definition of systems engineering,[2] 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: 357]. Jenkins expanded that comment into 12 roles of a systems engineer, and seven of those roles (activities performed by a person with the title systems engineer) overlapped the role of the project manager (activities performed by a person with the title project manager) [Jenkins, 1969: 164].

Some of the evolution of the role of the systems engineer can be seen in the very little overlap between the 12 roles documented by Jenkins and Sheard's 12 systems engineering roles [Sheard, 1996]. Jenkins' roles relate to the activities in conceiving and planning the solution system while, almost 30 years later, Sheard's set of roles relate to interpersonal relationships between the practitioners of disparate skills and disciplines implementing the solution system.

Furthermore, the role of the systems engineer (the activities performed by a person with the title systems engineer) overlaps the roles of people from other professions according to both Jenkins [1969] and Sheard [1996]. The research found several other sources of lists of activities performed by systems engineers including:

- A few examples of the different overlaps between systems engineering and project management [Brekka, Picardal, and Vlay, 1994, Roe, 1995, DSMC, 1996, Kasser, 1996, Sheard, 1996, Johnson, 1997, Watts and Mar, 1997, Bottomly et al., 1998].[3] In addition, the Defense Systems Management College definition of systems engineering is: "The management function which controls the total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimise the overall system effectiveness" [DSMC, 1996]. Notice the use of the term "management function."
- A discussion on the overlaps between systems engineering and other disciplines [Emes, Smith, and Cowper, 2005].
- An example of the activities performed in new product design that overlaps those of systems engineering [Hari, Weiss, and Zonnenshain, 2004].
- A general set of 28 tasks and activities that were normally performed within the overall context of large-scale systems engineering [Eisner, 1988]. Eisner called the range of activities "specialty skills" because some people spend their careers working in these specialties. Thus according to Eisner [the role of][4] the systems engineer overlaps at least 28 engineering specialties.
- Thirty tasks that form the central core of systems engineering [Eisner, 1997: 156]. The whole area of systems engineering management is covered in just one of the tasks. Eisner states that "not only must a Chief Systems Engineer understand all 30 tasks; he or she must also understand the relationships between them, which is an enormously challenging undertaking that requires both a broad and deep commitment to this discipline as well as the supporting knowledge base."

4. ASSESSING SYSTEMS ENGINEERING COMPETENCY

Competency assessment tends to be performed using competency models which form the foundation for developing curriculum and selecting training materials, and for licensure and certification requirements, job descriptions, recruiting and hiring, and performance reviews [CareerOneStop, 2011]. "These models have competency domains broken down into competency groups and further sub-categorized into sub-competencies. As one continues to the next[5] levels in the hierarchy, the competencies become further focused and specific to the industry, job or occupation, and position" [Ennis, 2008]. A multilevel assessment approach to assessing proficiencies of systems engineers groups the knowledge, traits, abilities, and other characteristics of successful systems engineers into a 2-dimensional maturity model[6] in accordance with Arnold, who wrote: "[A]t its simplest, competence may be viewed in terms of two dimensions or axes. One axis

[1]There are independent national qualifications in Korea and Singapore.
[2]Fifty years later, nothing has changed in that respect.
[3]A different set of overlaps, as seen across the years.
[4]Author's interpretation.
[5]Next level down, or lower levels.
[6]Due to space limitations, where prior work covers a topic in detail, the work is cited and summarized.

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defines the process, or set of processes, considered relevant to the discipline of interest. The other axis establishes the level of proficiency attained typically using a progression of increasing-value cardinal points that are defined in terms of attainment or performance criteria" [Arnold, 2000].

The activities performed by a systems engineer in one organization are different from those performed by a systems engineer in another organization and sometimes even in different parts of the same organization. It could thus be expected that different ways of assessing the competency of systems engineers would assess different characteristics. The following four competency models were studied to determine their coverage:

1. Knowledge, Skills, and Abilities (KSA)
2. INCOSE Certified Systems Engineer Professional (CSEP) Examination [INCOSE, 2008]
3. INCOSE UK Systems Engineering Competencies Framework (SECF) [INCOSE UK, 2010]
4. Capacity for Engineering Systems Thinking (CEST) [Frank, 2006].

The findings showed that each of the competency models had different goals and objectives [Kasser, Frank, and Zhao, 2010]. Sometime later in the research, the following competency models were also studied with similar findings:

1. A systems engineering competency taxonomy (SECT) [Squires et al., 2011]
2. NASA 2010 Systems Engineering Competencies [NASA, 2010]
3. The JPL Systems Engineering Advancement (SEA) project [Jansma and Jones, 2006]
4. MITRE 2007 Systems Engineering Competency Model [Metzger and Bender, 2007]
5. National Defense Industrial Association (NDIA) proposed systems engineering competency model [Gelosh, 2008].

Consider each of these competency models. Descriptions of each competency model are brief and where details of the content are given, the intent of each summary is to enable the differences between the competency models to be seen, not to highlight the contents of the competency model.

4.1. Knowledge, Skills, and Abilities

Knowledge, Skills, and Abilities (KSA) are one way of assessing the suitability of candidates for job positions according to qualification standards published by the US Office of Personnel Management (OPM). These standards are intended to identify applicants who are likely to perform successfully on the job, and to screen out those who are unlikely to do so [OPM, 2009]. In practice, KSAs tend to be lists of statements written by, or on behalf of, candidates. These statements are targeted to specific positions and describe a number of situational challenges faced by the candidate and outcomes achieved in previous jobs that are to be used by evaluators in a pass–fail mode when looking for qualified candidates for the specific position.

KSAs are an improvement over resumes written as job descriptions citing years of experience that state nothing about the achievements of the person. Moreover, being descriptive, KSAs do not seem to be generally suitable for assessing the difference between a person who does not understand the underlying fundamentals and just follows a process to reach a successful conclusion and a person who understands what needs to be done and can create and implement a process to do it successfully. Lastly, while KSAs can provide a multilevel assessment of the proficiency of a systems engineer, there is no standard definition for any such levels.

4.2. INCOSE CSEP Exam

The International Council on Systems Engineering (INCOSE) Certified Systems Engineering Professional (CSEP) examination [INCOSE, 2008] is only a part of the three-tier INCOSE approach to certifying the competency of a systems engineer and should not be considered a stand-alone certification of competency. The INCOSE CSEP examination is designed to test the applicant's knowledge of the contents of the INCOSE Systems Engineering Handbook [Haskins, 2006, 2011]. Consequently, the handbook focuses on processes according to ISO/IEC 15288, only addresses a limited body of declarative and procedural knowledge, and does not address the cognitive skills and the individual traits in an objective manner. These skills and traits are addressed in a subjective manner in the follow-up evaluation of the career experience of the candidate. The CSEP examination may be considered as a minimal measurement of systems engineering competency.

4.3. INCOSE UK Systems Engineering Competencies Framework

The Systems Engineering Competency Framework (SECF) [INCOSE UK, 2010] was initially developed in response to an issue identified by the INCOSE UK Advisory Board (UKAB) [Hudson, 2006]. The objective determined by the INCOSE UKAB was "to have a measurable set of competencies for systems engineering which will achieve national recognition and will be useful to the enterprises represented by the UKAB" [INCOSE UK, 2010]. The focus of the SECF is on the competencies of systems engineering rather than the competencies of a systems engineer.

The SECF competencies are grouped into three themes: Systems Thinking, Holistic Lifecycle View, and Systems Engineering Management.

1. **Systems Thinking** contains the underpinning systems concepts and the system/supersystem skills including the enterprise and technology environment.
2. **Holistic Lifecycle View** contains all the skills associated the systems lifecycle from need identification, requirements through to operation and ultimately disposal.
3. **Systems Engineering Management** deals with the skills of choosing the appropriate lifecycle and the

planning, monitoring and control of the systems engineering process.

According to the SECF, each competency should be assessed in terms of four levels of comprehension and experience defined by "Awareness" through to "Expert":

- **Awareness:** The person is able to understand the key issues and their implications. The person is able to ask relevant and constructive questions on the subject. This level is aimed at enterprise roles that interface with Systems Engineering and therefore require an understanding of the Systems Engineering role within the enterprise.
- **Supervised Practitioner:** The person displays an understanding of the subject but requires guidance and supervision. This proficiency level defines those engineers who are "in-training" or are inexperienced in that particular competency.
- **Practitioner:** The person displays detailed knowledge of the subject and is capable of providing guidance and advice to others.
- **Expert:** The person displays extensive and substantial practical experience and applied knowledge of the subject.

While the SECF is a worthwhile effort, there seem to be a number of inconsistencies in the document including:

- The four levels of proficiency are not in the same dimension: While the last three levels are attributable to increasing levels of proficiency of systems engineers, the "awareness" level is applicable to people who work with systems engineers at high levels in an organization and as such there is an assumption that these people should have some knowledge of systems engineering.
- The allocation of knowledge to the systems thinking competency theme does not match the way the term cognitive skills is used in the systems thinking and critical thinking professions (domains). This is a potential cause of confusion.
- While lists of abilities within the competencies make it easy to assess compliance by checking off experience against the items on the list, the method has the same intrinsic defect as the use of KSAs. Namely, it does not seem to be generally suitable for assessing the difference between a person who does not understand the underlying fundamentals and just follows a process to reach a successful conclusion and a person who understands what needs to be done and can create and implement a process to do it successfully.

The SECF does however provide a way of setting the systems engineering role proficiency requirements for jobs in a process-oriented work environment, namely, meeting one of the purposes for competency models produced by human resource professionals. Nevertheless, it should be used with care for assessing the competencies of individuals due to:

- Its lack of an objective way of assessing cognitive skills and individual traits
- Its being based on the observed role of a systems engineer in a number of UK organizations, namely, the knowledge that systems engineers in the UK have, rather than the knowledge systems engineers need to have.

4.4. Capacity for Engineering Systems Thinking (CEST)

The capacity for engineering system thinking (CEST) is a proposed set of high-order thinking skills that enable individuals to successfully perform systems engineering tasks [Frank, 2006]. A study aimed at identifying the characteristics of successful systems engineers identified 83, which were aggregated into four sets of characteristics as follows:

- cognitive characteristics related to systems thinking
- systems engineering skills
- individual traits
- multidisciplinary knowledge and experience.

CEST focuses on the cognitive skills, individual traits, capabilities and knowledge, and background characteristics of a systems engineer who can examine system failures and identify and remedy system problems [Frank and Waks, 2001]. As such, it may be useful for assessing these aspects of the competency of systems engineers. However, at this time, CEST is still in its research stages.

4.5. A Systems Engineering Competency Taxonomy (SECT)

Squires, Wade, Dominick, and Gelosh [2011] have built a systems engineering competency taxonomy (SECT) from a selected set of existing competency models combined with some systems thinking research. The authors combined the following three models into single Experience Accelerator (ExpAcc) competency taxonomy:

- The Systems Planning, Research, Development, and Engineering (SPRDE) Systems Engineering (SE) and Program Systems Engineer (PSE) competency model, known as the SPRDE-ESE [DAU, 2010]
- The Systems Engineering Research Center (SERC) Technical Lead Competency Model [Gavito et al., 2010]
- A Critical/Systems Thinking Competency Model [Squires, 2007].

The final SECT competency taxonomy which covers 87 unique competencies is based on the following three-pronged approach:

- Systems and critical thinking is the backbone of the model.
- Technical expertise which comprises technical leadership, technical management, and technical/analytical skills.

- Project management and other broad-based professional competencies.

Unlike the other competency models studied, SECT evaluates the ability to deal with complexity in several levels of proficiency.

4.6. NASA 2010 Systems Engineering Competencies

NASA identifies 49 systems engineering competencies which are grouped by competency areas, competencies, and competency elements and assessed in four proficiency levels [NASA, 2010].

- The 10 competency areas are concepts and architecture, system design, production and operations, technical management, project management, internal and external environments, human capital management, security and safety, professional and leadership development.
- The 35 systems engineering element competencies express the overall knowledge, skills, and behaviors that systems engineers are expected to possess and/or perform as a part of their jobs.
- The four proficiency levels are technical engineer, project team member, subsystem lead, project systems engineer, and program systems engineer.

The model is tailored to the NASA needs. It does not include any overt reference to systems thinking, cognitive competencies, and behavioral traits.

4.7. The JPL Systems Engineering Advancement (SEA) project

Jansma and Jones [2006] developed a systems engineering competency model along three axes; processes, personal behaviors and technical knowledge as part of a project to improve systems engineering at the Jet Propulsion Laboratory (JPL). The SEA Project utilized a rigorous process to identify a list of highly valued personal behaviors of systems engineers.

The *processes* axis encompasses 10 systems engineering functions. The identified *personal behaviors* fall into five clusters:

1. leadership skills
2. attitudes and attributes
3. communication
4. problem solving and systems thinking
5. technical acumen.

The *technical knowledge* axis encompasses 21 systems engineering disciplines and fields.

4.8. MITRE 2007 Systems Engineering Competency Model

The MITRE Systems Engineering competency model [Metzger and Bender, 2007] is based on criteria for successful MITRE systems engineers. The MITRE model has three cumulative levels of proficiency (i.e., levels of proficiency) and consists of 36 competencies organized into five sections:

1. Enterprise Perspectives
2. Systems Engineering Life Cycle
3. Systems Engineering Planning and Management
4. Systems Engineering Technical Specialties
5. Collaboration and Individual Characteristics.

The authors of this model do not claim that their model is a general competency model. They explicitly state that the model is tailored to the MITRE needs. The model was not "scientifically" validated. The authors generally claim that "the original draft competencies were based upon information from standards bodies, the MITRE Institute, commercial companies, and Government sources. … The model went through numerous revisions with input from many people across MITRE before it reached this form. It will continue to evolve and be upgraded. …" [Metzger and Bender, 2007].

The MITRE systems engineering competency model has three increasing levels of proficiency, Foundational, Intermediate, and Expert. MITRE assumes that a person's competence at a specific proficiency level is generally the result of education, work experience, job tasks, and specific job roles. A MITRE systems engineer is likely to be expert in some competencies, intermediate in others, and foundational in others. It is not expected, and it would be highly unlikely, that any one person would be expert in all the behaviors and competencies in this model.

4.9. National Defense Industrial Association (NDIA) Proposed Systems Engineering Competency Model

According to a presentation by Gelosh, the National Defense Industrial Association (NDIA) proposed systems engineering competency model groups 50 competencies in the following four areas [Gelosh, 2008]:

1. **Analytical** containing 20 competencies covering systems engineering tools and techniques design considerations.
2. **Technical management** containing 15 competencies in the technical management process.
3. **General** containing five competencies pertaining to a total systems view.
4. **Professional competencies** containing 10 competencies covering thinking, problem solving, and interpersonal skills.

The planned approach, according to the presentation, was to develop the competencies based on the roles of systems engineers. Two years later, the model was still a work in progress [NDIA E&T, 2010]; for example, the first of the proposed 2011 tasks was to survey existing, freely available systems engineering competency models for entry-level systems engineers to develop the minimum requirements for an individual to be called a systems engineer. Reasons for this lack of progress may include:

- The difficulty of defining a role-based systems engieering body of knowledge (SEBoK) due to the broad range of non-systems engineering activities performed by systems engineers in their role in the workplace that require knowledge from other disciplines [Kasser and Massie, 2001, Kasser and Hitchins, 2009] as discussed above
- The different opinions on the nature of systems engineering [Kasser and Hitchins, 2011] that preclude obtaining consensus with respect to a SEBoK for systems engineering.

And without consensus on a SEBoK, the committee cannot produce even a minimal objective traceable set of generic requirements for the competency of a systems engineer.

5. COMPARING THE DIFFERENT COMPETENCY MODELS

As expected, each of the competency models described above was developed to provide a solution to a different problem and contains different bodies of knowledge. This is in accordance with general industry practice for the design and use of competency models [Ennis, 2008]. However, none of the competency models discussed above was presented in a format compatible with the nine-tier US Employment and Training Administration (ETA) Competency Model Clearinghouse's General Competency Model Framework [ETA, 2010]. Each of these competency models identified a large number of competencies and then grouped the competencies into smaller manageable *but different* groups that, while meeting the need of the time and place, make comparing the assessment approaches difficult, as shown in the summary in Table II.

At the detailed level, NDIA aggregates "requirements management" into "technical competencies" [Gelosh, 2008] while MITRE groups the same function into a "systems engineering life cycle" [Metzger and Bender, 2007]. SECT allocates "requirements analysis" to "Technical/Analytical Competencies" [Squires et al., 2011] while MITRE incorporates the function into "requirements engineering" which is allocated to "systems lifecycle." Thus, a common framework that could encompass all the assessment approaches is needed to compare the different competency models. This framework would allow owners and users of each of the competency models to benchmark their competency model against the others, perhaps identify gaps, and upgrade their approach.

Some of the competencies being assessed fall into the category of cognitive characteristics. The traditional aca-

Table II. Arrangement of Competencies in the Nine Competency Models

KSAs	INCOSE CSEP Exam	SECF	CEST	SECT	NASA 2010	JPL SEA	MITRE	NDIA
N/A	Systems Engineering Overview	Systems Thinking	Cognitive Characteristics	Systems and Critical Thinking	Concepts and Architecture	Processes	Enterprise Perspectives	Analytical
	General Lifecycle Stages	Holistic Lifecycle View	Systems Engineering Skills	Technical Expertise	System Design	Personal Behaviors	Systems Engineering Life Cycle	Technical Management
	Technical Processes	Systems Engineering Management	Individual Traits	Project Management	Production and Operations	Technical Knowledge	Systems Engineering Planning and Management	General
	Project Processes		Multidisciplinary Knowledge		Technical Management		Systems Engineering Technical Specialties	Professional Competencies
	Agreement Processes				Project Management		Collaboration and Individual Characteristics	
	Organizational Project Enabling Processes				Internal and External Environments			
	Tailoring Processes				Human Capital Management			
	Specialty Engineering Activities				Security and Safety			
					Professional and Leadership Development			

Table III. Comparison of Proficiency Levels in the Competency Models

KSAs	INCOSE CSEP Exam	SECF	CEST	SECT	NASA 2010	JPL SEA	MITRE	NDIA
N/A	N/A	Awareness	N/A	None or Aware Only	Technical Engineer/Project Team Member	N/A	Foundational	N/A
		Supervised Practitioner		Apply with Guidance	Subsystem Lead		Intermediate	
		Practitioner		Apply	Project Systems Engineer		Expert	
		Expert		Manage or Lead	Program Systems Engineer			
				Advance State of Art				

demic approach to measuring cognitive characteristics is based on the revised Bloom's taxonomy which combines systems thinking and critical thinking [Anderson et al., 2000]. Research into the psychology domain identified an alternative approach which, unlike Bloom's taxonomy, allows for the systems thinking and critical thinking skills to be assessed separately as discussed in Section 6.1.2 [Kasser, 2010].

The levels of ability in each in each of the nine competency models studied are also different, some models only recognize one level, some models assess skill proficiencies and some assess necessary proficiencies for job positions (roles) at specific levels in the organizational hierarchy as shown in Table III. Note that the SECT evaluates proficiency in dealing with complexity, a different scale with respect to the evaluation of proficiency in the other competency models.

6. A 2-DIMENSIONAL COMPETENCY MATURITY MODEL FRAMEWORK FOR BENCHMARKING THE COMPETENCY MODELS OF SYSTEMS ENGINEERS

This section introduces a CMMF for benchmarking the different competency models.

6.1. The Vertical Dimension

The vertical dimension is based on three categories:

1. Knowledge
2. Cognitive characteristics
3. Individual traits.

6.1.1. Category 1: Knowledge

Knowledge covers:

- Systems engineering
- The problem domain
- The implementation domain in which the system is being realized
- The solution domain in which the systems engineering is being applied to realize the solution system.

Opinions vary on what constitutes systems engineering; each opinion will have a different vision of the knowledge content. This was reflected in the different ways of assessing systems engineering proficiency discussed above. In addition, since systems engineers apply their skills in different domains (e.g., aerospace, land and marine transportation, information technology, defence, etc.), there is an assumption that, to work in any specific domain, the systems engineer will need the appropriate problem, solution, and implementation domain knowledge.

Knowledge of "systems engineering process" and systems engineering tools is considered as part of systems engineering rather than the implementation domain. The implementation domain sets the constraints on both the process and solution system. For example, the development system for a software system is in the implementation domain. Implementation domain knowledge relates to the properties of the compiler as well as the characteristics (especially limitations) of the development hardware. In another environment, the implementation domain might include thermal vacuum chambers and other equipment used to partially or fully develop and test the solution system.

It is tempting to assume that the problem domain and the solution domain are the same, but they are not necessarily so. For example, the problem domain may be urban social congestion, while the solution domain may be a form of underground transport to relieve that congestion. Lack of problem domain competency may lead to the identification of the wrong problem and lack of solution domain competency may lead to selection of a less than optimal or even an unachievable solution system. Risk management is an activity (process) that requires competency in the problem, solution, and implementation domains. Similarly, a "system failure" needs to be distinguished from a "system problem."

The large number of implementation, problem, and solution domains in which systems engineering takes place also requires a corresponding large SEBoK, which is not necessarily applicable to all systems engineers. Consequently, the knowledge must be tailored to the specific problem, solution, and implementation domains and the phase of the system lifecycle. For example:

- **Requirements analysis.** Systems engineers performing requirements analysis will need to know how to develop a matching set of specifications that describe the mission and support functions of the solution system in its fielded operational context, a different subset of systems engineering knowledge to that needed by systems engineers performing test and evaluation.
- **Control or operations and maintenance environment.** Systems engineers working in a control or operations and maintenance environment will need knowledge of the software development process and the tools, and the properties of the underlying development hardware platforms as well as the solution domain in which the system is to be fielded.
- **Electrooptical engineering.** Systems engineers working in an electrooptical engineering factory will need knowledge of how the various components can be configured without disturbing the performance of the system.
- **Sociotechnical systems.** Systems engineers working on sociotechnical systems will need the appropriate knowledge of human behavior and how humans interact with technology and each other.
- And so on.

6.1.2. Category 2: Cognitive Characteristics

Cognitive characteristics namely systems thinking and critical thinking provide the problem identification and solving skills[7] to think, identify, and tackle problems by solving, resolving, dissolving, or absolving problems [Ackoff, 1999: 115], in both the conceptual and physical domains. Problem identification and solving competency is not the same thing as problem domain competency.

6.1.2.1. Systems thinking. The approach to the assessment of systems thinking was developed from the only systematic and systemic approach to applying systems thinking discovered in the literature [Richmond, 1993]. Further research[8] based on Richmond's work produced a set of nine viewpoints called System Thinking Perspectives (STP) [Kasser and Mackley, 2008], which have been used in teaching holistic thinking in postgraduate classes and workshops in Israel, Japan, Singapore, Taiwan, and the UK. The STPs are operational, functional, big picture, structural, generic, continuum, temporal, quantitative, and scientific. Of these nine perspectives, the first eight are descriptive and the ninth is prescriptive. The eight discriptive perspectives are used to view or describe the situation, while the prescriptive perspective is the one which contains the statements of the problem and candidate solutions.

6.1.2.2. Critical thinking. A literature review showed that the problem of assessing the degree of critical thinking in students seemed to have already been solved [Eichhorn, 2002, Wolcott and Gray, 2003, Allen, 2004, Paul and Elder, 2006]. Wolcott and Gray aggregated lists of critical thinking abilities by defining five levels of critical thinking [Wolcott and Gray, 2003]. In addition, Wolcott's method for assessing a critical thinking level was very similar to that used by Biggs for assessing deep learning in the education domain [Biggs, 1999]. Since a tailored version of the Biggs criteria had been used successfully at the University of South Australia for assessing student's work in postgraduate classes on systems engineering [Kasser et al., 2005], Wolcott's method was adopted for the CMMF. Wolcott's five levels (from lowest to highest) are:

0. Confused fact finder
1. Biased jumper
2. Perpetual analyzer
3. Pragmatic performer
4. Strategic re-visioner.

6.1.3. Category 3: Individual Traits

These are the traits providing the skills to communicate with, work with, lead and influence other people, ethics, integrity, etc. These traits include communications, personal relationships, team playing, influencing, negotiating, self-learning, establishing trust, managing, leading, emotional intelligence [Goleman, 1995], and more [Covey, 1989, ETA, 2010, Frank, 2010]. These traits may be selected to suit the role of the systems engineer in the organization and assessed in the way that the ETA industry standard competency models assess those traits [ETA, 2010]. There is no need to reinvent an assessment approach.

6.2. The Horizontal Dimension

The horizontal dimension provides a way to assess the competence of a person in each broad area of the vertical dimension against the levels of increasing ability. The nine competency models discussed above defined proficiency in different ways and in different ranges as shown in Table III. For example, Dreyfus and Dreyfus [1986], quoted by Ennis [2008], describe levels of proficiency that include novice, experienced beginner, practitioner, knowledgeable practitioner, expert, virtuoso, and maestro. From the novice who is focused on rules and limited or inflexible in their behavior to the individual who is willing to break rules to provide creative and innovative solutions to business problems, a way to encompass the existing approaches of assessing systems engineers needed to be developed.

Systems engineers are innovators, problem formulators, and solvers. Gordon et al. provided a way to identify the difference in cognitive skills between innovators, problem formulators, problem solvers and imitators [Gordon et al., 1974]. The difference is based on:

[7]Problem solving and identification skills have been listed separately to map into Types IV and V as discussed below.

[8]Funded by a grant from the Leverhulme Trust to Cranfield University in 2007.

Table IV. Factors Conducive to Innovation

Ability to find **similarities** among objects which seem to be **different**	HIGH	Problem solvers	Innovators
	LOW	Imitators/Doers	Problem Formulators
		LOW	HIGH
		Ability to find **differences** among objects which seem to be **similar**	

- Ability to find differences among objects which seem to be similar
- Ability to find similarities among objects which seem to be different.

The differences in the "ability to find …" leads to the different type of persons shown in Table IV [Gordon et al., 1974]. For example, problem formulators score high in ability to find differences among objects which seem to be similar, and problem solvers score high in ability to find similarities among objects which seem to be different.

Anecdotal evidence (observation and experience) indicated that within the multichotomy of systems engineering there appeared to be five types of systems engineers [Kasser, Hitchins, and Huynh, 2009][9] which may be mapped into Table IV. These five types are (from lowest to highest level of competency):

- **Type I.** This type is an apprentice who has to be told "how" to implement the solution system.
- **Type II.** Type IIs are imitator/doers. This type is the most common type of systems engineer. Type IIs have the ability to follow a systems engineering process to implement a physical solution system once told what to do.
- **Type III.** Type IIIs are problem solvers. Once given a statement of the problem, this type has the expertise to conceptualize the solution system and to plan the implementation of the solution, namely create the process to realize the solution.
- **Type IV.** Type IVs are problem formulators. This type has the ability to examine the situation and define the problem [Wymore, 1993: 2], but cannot conceptualize a solution.
- **Type V.** This type is rare and combines the abilities of the Types III and IV; namely, it has the ability to examine the situation, define the problem, conceptualize the solution system, and plan and manage the implementation of the physical solution.

A person grows through the types with education and experience. It is important to identify people with the potential to become Type Vs as early as possible in their careers[10] and then to provide them with fast track training to enable their organization to obtain the best use of their capabilities in the future. Categorization by type is also situational because a Type V when moving to a different domain can drop down to a lower level, and then, as they learn more about the domain, rise back to Type V.

The authors have not attempted to map the types into roles or job titles because roles and titles vary with organizations. For example, a "lead systems engineer" in one organization may be performing the same role as a person with the title "senior systems engineer" or an "engineering specialist" in another organization. Moreover, these five types exist in other disciplines which would allow for the application of the framework in those disciplines by changing the knowledge components.

A 2-dimensional CMMF showing the assessment of the competency in increasing levels of competency (Type I to V) in the three categories discussed in Section 6.1 is summarized in Table V. Assessment of knowledge, cognitive skills and individual traits is made in ways already practiced in the psychology domain and do not need to reinvented by systems engineers. Where knowledge is required at the conditional level, it includes procedural and declarative. Similarly, where knowledge is required at the procedural level, it includes declarative knowledge.

7. BENCHMARKING THE NINE COMPETENCY MODELS

Each of the three categories contain some competencies that are common to all systems engineers and some competencies that apply to specific roles in specific domains in specific phases of the system life cycle in specific organizations. Each competency model thus contains information which can be allocated into these three categories and allows them to be subjectively compared or benchmarked as shown in Table VI. Findings from this comparison, based on the published literature, include:

- The number of levels of proficiency differs between competency models.
- The definition of the ability for a level of proficiency differs between competency models.

[9]The terminology of the "types" once explained seems to resonate with the audience. The terminology has been adopted into common usage in the systems engineering vocabulary in Singapore and in Israel after it was introduced in a workshop in 2010.

[10]These are the potential future leaders.

Table V. A Competency Model Maturity Framework (CMMF) for Systems Engineers

	Type I	Type II	Type III	Type IV	Type V
Category 1: Knowledge areas					
Systems engineering	Declarative	Procedural	Conditional	Conditional	Conditional
Problem domain	Declarative	Declarative	Conditional	Conditional	Conditional
Implementation domain	Declarative	Declarative	Conditional	Conditional	Conditional
Solution domain	Declarative	Declarative	Conditional	Conditional	Conditional
Category 2: Cognitive characteristics					
Systems Thinking					
Descriptive (8)	Declarative	Procedural	Conditional	Conditional	Conditional
Prescriptive (1)	No	No	Procedural	No	Conditional
Critical Thinking	Confused fact finder	Perpetual analyser	Pragmatic performer	Pragmatic performer	Strategic re-visioner
Category 3: Individual traits (sample)					
Communications	Needed	Needed	Needed	Needed	Needed
Management	Not needed	Needed	Needed	Needed	Needed
Leadership	Not needed	Not needed	Needed	Needed	Needed
Others (specific to situation)	Organization specific	Organization specific	Organization specific	Organization specific	Organization specific

Table VI. Comparison of Competency Models

Assessment approach	**KSA's**	**INCOSE CSEP Exam**	**SECF**	**CEST**	**SECT**	**NASA 2010**	**JPL SEA**	**MITRE**	**NDIA**
Category 1: Knowledge									
Systems Engineering	Yes [1]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Solution domain	Implied	No	No	No	Yes	Yes	Yes	Yes	No
Implementation domain [3]	Implied	No	Partial [4]	No	No	Partial [4]	Partial [4]	Partial [4]	No
Problem domain	Implied	No	No	Yes	Yes	Yes	Implied	Yes	Yes
Category 2: Cognitive skills	Yes	No	Yes	Yes	Yes	Implied	Yes	Yes	Yes
Category 3: Individual Traits	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Increasing levels of proficiency	No	No (Pass/Fail)	Partial [2]	No	Yes	Yes	No	Yes	No

In several instances, the various ways in which the competency models describe the competencies made populating this table a subjective excerise.
The use of the word "Yes" should be read with the understanding that each competency model identifies a different set of knowledge in each of the knowledge area rows in the table.
[1] Subjective approach, knowledge seems to be dependent on the situation, and no objective reference for validating characteristics.
[2] Lowest level is in a different dimension to remaining levels.
[3] Systems engineering tools have been allocated to the systems engineering knowledge area rather than to implementation domain.
[4] Does contain knowledge about the culture of the organization is which the systems engineering is taking place.

- The lack of competencies in the implementation domain in all nine competency models examined. However, it is fair to say that some of the models do consider the culture in which the systems engineering is taking place.

8. FUTURE RESEARCH

This section discusses the following future research opportunities:

- Identifying gaps in existing competency models
- Using the CMMF as a competency model.

8.1. Identifying Gaps in Existing Competency Models

The existing competency models seem to have been populated based on observing the role of the systems engineer, namely, what systems engineers do in the workplace, and researching the literature for additional requirements. These competency models may suffer from errors of omission because the development methodology does not include a validation function to determine if something that should be done is not being done (and the effect of that lack may not show up for some months or even years). Indeed, this research has identified an error of omission in all of the nine competency models studied, namely, the lack of competencies in the implementation domain. In addition, benchmarking used alone produces followers, not leaders. Benchmarking should be used only as a check to make sure your competency model[11] is not lacking some necessary competency.

A useful tool for identifying both errors of commission and errors of omission is work flow analysis. Work flow analysis is a methodology that can be used to observe existing work flows and also to develop a conceptual reference model. The conceptual reference competency model activities can then be compared to those being observed, and any missing functions can be identified and initiated. A useful conceptual reference model is the Generic Reference Model [Hitchins, 2007], with its mission management, resource management, viability management, behavior management, and form management submodels.

A useful tool for mapping the activities in the workflow and hence the competencies needed to perform those activities in an objective manner is the Hitchins-Kasser-Massie (HKM) framework for understanding systems engineering[12] [Kasser, 2007b, 2007a] shown in Figure 1. The activities that need to be performed in each area of the framework are identified in the form of descriptions, scenarios, use cases, vignettes, concepts of operations,[13] etc. For example, consider the requirements engineering activities in Layer 2 Area 2B of the HKMF, these activities include requirements elicitation and elucidation. The appropriate competencies and proficien-

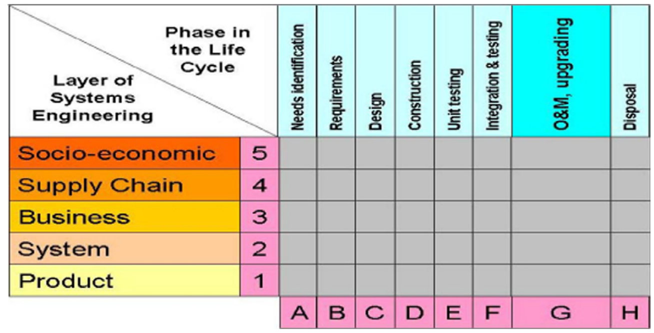

Figure 1. The HKM Framework for understanding systems engineering. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

cies for the type of person performing the activity in each of the scenarios can then be determined via any one of the many methods used in the human resources domain.

8.2. Using the CMMF as a Competency Model

In order for an organization to use the CMMF, the contents of each of the three categories must be determined and the CMMF populated. If the organization already has a competency model, then the competencies need to be transferred from the organizations' competency model into the appropriate areas in the CMMF. If the organization does not have a competency model and wishes to develop one, then the CMMF allows standardization of groupings, which helps identify both errors of commission and errors of omission. However, before developing a compentency model, a cost–benefit tradeoff should be performed since the amount of effort will depend on the level of detail required. The development effort should be for a model that will be useful, not something that will keep the human resource department busy.

Candidates must qualify at the appropriate proficiency level in all three categories to be recognized as being competent that competency level. While examination questions can require the respondent to use conditional knowledge, the successful application of conditional knowledge in the real world must be directly demonstrated by results documented in the form of KSAs supported by awards, letters, and certificates of appreciation from third parties (e.g., employers, customers, etc.). The assessment could thus be in two parts, one part by examination for the lower levels and the second by a portfolio demonstrating successful experience for the higher levels. This model is followed by the INCOSE Certification Program, in which the ESEP is awarded on the basis of a portfolio. Other higher level qualifications based on portfolios are awarded by the Association for Learning Technology (ALT) and the Institution of Engineering and Technology (IET) in the UK, namely, Certified Member of the ALT (CMALT) and Fellow of the IET (FIET).

Assessment of a candidate is simple in concept as follows.

[11] Or anything else you are creating and wish to benchmark.
[12] Credit is due to Ms. Xuan-Linh Tran at the University of South Australia for drawing the framework in this format.
[13] The terminology varies, but the concept is the same.

8.2.1. The Cognitive Skills and Individual Traits

Knowledge of the systems thinking perspectives is assesed as declarative, procedural, and conditional [Woolfolk, 1998]. Examination questions may be written to require the respondent to demonstrate the different types of knowledge. Ways of assessing the degree of critical thinking have been described by Wolcott and Gray [2003] and are used herein. The appropriate individual traits are assessed as being "needed" or "not needed" at a specific level of ability.

8.2.2. The Systems Engineering, Implementation, Problem and Solution Domain Knowledge

The knowledge is also assessed as being declarative, procedural, and conditional [Woolfolk, 1998]. The question then arises as what is the knowledge to be? As stated above, consensus on the contents of a "standard" SEBoK would be difficult to achieve across organizations and domains if it were to be based on the role of the systems engineer. That the knowledge competency is situational rather than generic does not stop the CMMF being populated by organizations needing competency assessments for their personnel working in their environment on their projects.

9. SUMMARY AND CONCLUSIONS

The paper began with a discussion on the need for competent systems engineers. The paper then discussed the role of systems engineers in the workplace, providing examples of a number of points of view as to what those roles are and alluding to the difficulty of gaining a generic consensus on the nature of the role of the systems engineer. At that point, focus of the paper changed to ways of assessing the competency of systems engineers using teminology from the domain of cognitve psychology rather than inventing new systems engineering terminology for existing concepts. The paper continued with a brief examination and discussion of nine different competency models and showed that each competency model seems to have been designed for a different purpose in different domains, times, and places.

The paper then introduced a 2-dimensional CMMF that can be used for both benchmarking existing competency models and as a competency model by those organizations that do not yet have a competency model and wish to develop one. The nine competency models were benchmarked using the CMMF, and one significant finding from this comparison is the lack of competencies in the implementation domain in all nine competency models studied. The paper concluded with suggestions for future research.

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