# Assessing the competencies of systems engineers

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**Abstract:** This paper addresses the problem of assessing the competencies of systems engineers. The paper provides a number of sources of requirements for the competencies of systems engineers. The requirements are aggregated into three areas – knowledge, cognitive skills and individual traits. The paper then summarises and briefly evaluates the following published approaches to describing or assessing the competencies or characteristics of systems engineers against the requirements.

- Knowledge, Skills, and Abilities (KSA).
- INCOSE Certified Systems Engineer Professional (CSEP) Examination.
- INCOSE UK Systems Engineering Competencies Framework (SECF).
- Capacity for Engineering Systems Thinking (CEST).

The conclusion of the paper is that each of the ways of assessing competency are providing solutions to different problems and that none of them assesses the competencies of systems engineers against the set of requirements or provides a way of differentiating between the five different types of systems engineers (Kasser, et al., 2009).

## Requirements for the competencies of systems engineers

The then Assistant Secretary to the United States Navy, Robert A. Frosch wrote, "*Systems, even very large systems, are not developed by the tools of Systems Engineering, but only by the engineers using the tools.*" (Frosch, 1969). Recognition of the need to certify the competencies of systems engineers can be traced back at least as far as (Kasser, 2000). Subsequent research into developing the requirements for a 21st century introductory course on systems engineering, included a literature review of text books published between 1959 and 1999 starting with (Goode and Machol, 1959) as well as the proceedings of the international symposia of the INCOSE since 1991. The findings from this research resulted in the emergence of a number of requirements for the competencies of systems engineers (Arnold, 2006; Kasser, et al., 2008). These requirements included:

- Those extracted from a list of specifications or traits for an “Ideal Systems Engineer” (Hall, 1962), pages 16-18).
- Being able to define the problem (Wymore, 1993), page 2).
- Competent, skilled and knowledgeable systems engineers capable of effectively

Table 1 Types of Knowledge (Woolfolk, 1998)

| | |
|---|---|
| **Declarative knowledge** | Knowledge that can be declared in some manner. It is “knowing that” something is the case. Describing a process is declarative knowledge. |
| **Procedural knowledge** | Knowing how to do something. It must be demonstrated; performing the process demonstrates procedural knowledge. |
| **Conditional knowledge** | Knowing when and why to apply the declarative and procedural knowledge. |

working on various types of complex integrated multi-disciplinary systems in different application domains, in different portions of the system lifecycle, in teams, alone, and with cognizant personnel in application and tool domains.

- Important skills and knowledge to include in corporate systems engineering training programs (Watts and Mar, 1997).
- The ability to communicate systems engineering principles to others.
- In the acquisition portion of the system lifecycle, facilitate the effective acquisition of solution systems that meet the customer’s needs at the time the system is specified, at the time the solution system is actually acquired and during the full length of its operational life.
- Engineers who are effective at solving open-ended problems (Durward K. Sobek II and Jain, 2004).
- Ways of identifying the five different types of systems engineers (Kasser, et al., 2009).

The requirements were aggregated into the following three areas:

- **Knowledge** of systems engineering and the application domain in which the systems engineering is being applied. (Woolfolk, 1998) described the three types of knowledge shown in Table 1. The declarative and procedural knowledge of systems engineering can be found in the body of literature of systems engineering (e.g. (Blanchard and Fabrycky, 1981; Hitchins, 2007) and (Wasson, 2006), etc.) and much is summarized in (Haskins, 2006). Note that since systems engineers apply their skills to 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 domain knowledge at the same competency level as for systems engineering, namely declarative, procedural and conditional at the appropriate level of competence.
- **Cognitive characteristics** include systems thinking and critical thinking which provide the ability to think, identify and tackle problems by solving, resolving, dissolving or absolving problems (Ackoff, 1999) page 115) in both the conceptual and physical domains. Systems thinking, is a discipline for seeing wholes (Senge, 1990), whereas critical thinking is “a unique kind of purposeful thinking in which the thinker systemically and habitually imposes criteria and intellectual standards upon the thinking, taking charge of the construction of thinking; [continually] guiding the construction of the thinking according to standards; [deliberately] assessing the effectiveness of the thinking according to the purpose, the criteria and the standards (Paul and Willsen, 1995) page 21).
- **Individual traits**, namely the ability to communicate with, work with, lead and influence other people, integrity, etc.

# Assessing systems engineering competency

A multi-level assessment approach groups the knowledge, traits, abilities and other characteristics of successful systems engineers into a two-dimensional maturity model[1] in accordance with (Arnold, 2000) who wrote "*at its simplest, competence may be viewed in terms of two dimensions or axes. One axis 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*". The vertical axis or dimension defines the knowledge and the horizontal axis or dimension defines five increasing levels of ability needed to perform work successfully. The measurement of the competency of an individual is can then be done in five ascending levels based on the following five types of systems engineers described in (Kasser, et al., 2009):

- **Type I**. This type is an "apprentice" who can be told "how" to implement the solution and can then implement it.
- **Type II**. This type is the most common type of systems engineer. This type has the ability to figure out how to use the systems engineering process to implement a physical solution once told what conceptual solution to implement.
- **Type III**. Once given a statement of the problem, this type has the necessary know-how to conceptualize the solution and to plan the implementation of the solution.
- **Type IV.** This type has the ability to examine the situation and define the problem (Wymore, 1993), page 2) but unlike the Type IIIs they cannot conceptualise the solution.
- **Type V.** This type combines the abilities of the Types III and IV, namely has the ability to examine the situation, define the problem, conceptualise the solution, plan and carry through the implementation of the physical solution.

Research identified a number of published ways of assessing systems engineering competency, including:

- Knowledge, Skills, and Abilities (KSA).
- INCOSE Certified Systems Engineer Professional (CSEP) Examination.
- INCOSE UK Systems Engineering Competencies Framework (Hudson, 2006).
- Capacity for Engineering Systems Thinking (CEST) (Frank, 2006).

Consider each of them.

## *Knowledge, Skills, and Abilities*

**Description:** Knowledge, Skills, and Abilities (KSA) are one way of assessing the suitability of candidates for job positions. The United States Office of Personnel Management (OPM) has published qualification standards that 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). However, according to the OPM, the standards are not designed to rank candidates, identify the best qualified applicants for particular positions, or otherwise substitute for a careful analysis of the applicant's knowledge, skills, and abilities. OPM's standards are based on Knowledge, Skills, and Abilities which are the attributes required to perform a job and are generally demonstrated through qualifying experience, education, or training. These attributes can be defined as

- **Knowledge** is a body of information needed for the successful performance of a function.

[1] Due to space limitations, where prior work covers a topic in detail, the work is cited and summarized.

- **Ability** is the required competence to perform the function successfully.
- **Skill** is the observable or measured competence in performing the function.

**Discussion:** 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 as applicable a number of (lists) situational challenges and outcomes in a prior position 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 which 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 multi-level assessment of the capabilities of a systems engineer, there is no standard definition for any such levels.

## *INCOSE CSEP Exam*

**Description.** The International Council on Systems Engineering (INCOSE) Certified Systems Engineering Professional (CSEP) examination is but a part of the INCOSE approach to certifying the competency of a systems engineer. The exam tests the applicant's declarative knowledge or ability to retain and declare the knowledge in the INCOSE Systems Engineering Handbook edited by (Haskins, 2006). The focus is on process-based systems engineering. The exam does not test the cognitive skills nor does it test the individual traits. Once having passed the exam, the applicant has to demonstrate procedural knowledge by providing a detailed curriculum vitae containing KSAs (see above) documenting years of experience in the workplace and the use of individual traits.

**Discussion:** The INCOSE CSEP qualification seems to be designed to test the applicant's knowledge of the contents of the INCOSE Systems Engineering Handbook. Consequently it addresses a limited body of declarative and procedural knowledge and does not address the cognitive skills and the individual traits in an objective manner. It may be considered as a very minimal measurement of systems engineering competency.

## *INCOSE UK Systems Engineering Competencies Framework*

**Description:** The Systems Engineering Competency Framework (SECF) was developed in response to an issue identified by the INCOSE UK Advisory Board (UKAB). 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*'. The focus of the SECF is on the Competencies of Systems Engineering rather than the Competencies of a Systems Engineer (Hudson, 2006). The SECF primarily covers the knowledge requirements being based on the following sources which would tend to make it process oriented:

- International Standards Organisation ISO15288 (Arnold, 2002).
- Maturity Model Integration.
- EIA731 (EIA 731-1, 1997).
- INCOSE Systems Engineering Body of Knowledge & Handbook (Haskins, 2006).
- NASA [Systems Engineering] Handbook.
- IEE/BCS Safety Competency Guidelines.

The SECF competencies are grouped into three themes; Systems Thinking, Holistic Lifecycle

View, and Systems Engineering Management.

- **Systems Thinking** contains the underpinning systems concepts and the system/super-system skills including the enterprise and technology environment.
- **Holistic Lifecycle View** contains all the skills associated the systems lifecycle from need identification, requirements through to operation and ultimately disposal.
- **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. They are 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 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.

**Discussion:** the SECF (Hudson, 2006) is a work in progress and appears to be a document that is still out for review and comment. While being a worthwhile effort, there seem to be a number of inconsistencies in the document including:

- The four levels of competency are not in the same dimension. while the last three levels are attributable to increasing levels of competencies 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. In addition, the ‘awareness’ level addresses both knowledge and cognitive characteristics.
- The allocation of knowledge to the systems thinking competency theme does not match the cognitive skills used in the systems thinking and critical thinking professions. This is a potential cause of confusion.
- While lists of abilities of 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 provides a way of setting the systems engineering knowledge requirements for jobs in a process-oriented work environment. However, it should be used with care for assessing the competencies of individuals due to

- its lack of coverage;
- 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 organisations; namely the knowledge systems engineers in the UK have, rather than the knowledge systems engineers need.

### *Capacity for Engineering Systems Thinking (CEST)*

**Description:** The capability 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 fourteen cognitive characteristics, twelve capabilities, nine behavioural competences and three knowledge and experience characteristics (38 characteristics in total). The research hypothesized that successful systems engineers could be characterized by high levels of CEST. Future research proposes to use CEST as a basis for psychological testing to assess a person's interest for systems engineering positions and other engineering positions that require systems thinking with a goal of identifying those individuals that have a greater probability of becoming successful systems engineers.

**Discussion:** CEST focuses on the cognitive skills, individual traits, capabilities and knowledge and background characteristics of a systems engineer.

## Discussion

Each of the ways of assessing competences described in the paper has been developed as a result of a different need. The INCOSE CSEP and UK SECF focus mainly on the [systems engineering] knowledge domain. CEST focuses on the cognitive skills, individual traits, capabilities and knowledge and background characteristics of a systems engineer. CEST was developed based on a survey of what people thought were characteristics of successful systems engineers.

The CSEP and SECF focus on assessing declarative and procedural knowledge and tend to produce Type II systems engineers. This reflects the current mainstream systems engineering paradigm since much of systems engineering is now taught as declarative and procedural knowledge. 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) page 509.) Today's need is for Type IV and V systems engineers and managers (engineer leaders) with the cognitive skills, individual traits and declarative, procedural and conditional knowledge to tackle problems to realize solutions.

The research showed that there does not seem to be a published method for differentiating between the five types of systems engineers. However, CEST might be a way to identify people with the potential to become Type IV's and V's early in their careers. These people could then be provided with fast track training to enable their organization to obtain the best use of their capabilities in the future.

## Summary

This paper addressed the problem of assessing the competencies of systems engineers. The paper provided a number of sources of requirements for the competencies of systems engineers. The requirements were aggregated into three areas – knowledge, cognitive skills and individual traits. The paper then summarised and briefly evaluated several published approaches to describing or assessing the competencies or characteristics of systems engineers against the requirements.

# Conclusions

The conclusions of the paper are:

1. Eeach of the ways of assessing competency discussed in this paper are providing solutions to different problems as follows.
    - Knowledge, Skills, and Abilities (KSAs) are designed to be used to assess the suitability of applicants for job positions.
    - The INCOSE Certified Systems Engineer Professional (CSEP) Examination seems to be designed to be used to assess the applicant's knowledge of the contents of the INCOSE Systems Engineering Handbook.
    - The INCOSE UK Systems Engineering Competencies Framework (SECF) is designed to be used to assess the systems engineering knowledge capability of organisations and individuals.
    - The Capacity for Engineering Systems Thinking (CEST) is a proposed set of high order thinking skills that may allow early detection of a person's suitability to become a Type V systems engineer.
2. None of ways of assessing competency discussed in this paper provides a way of differentiating between the five types of systems engineers (Kasser, et al., 2009).
3. A maturity model for distinguishing between the five types of systems engineers should be developed.

# Afterword

Subsequent research resulted in the development of a maturity model for assessing the competencies of systems engineers, to be published in (Kasser and Frank, 2010).

# Biographies

**Joseph Kasser** combines knowledge of systems engineering, technology, management and educational pedagogy. Having been a practicing systems engineer and engineering manager since 1970 in the USA, Israel, and Australia he brought a wealth of experience and a unique perspective to academia in 1997. He has since become internationally recognised as one of the top systems engineering academics in the world. He is an INCOSE Fellow, the author of "A Framework for Understanding Systems Engineering", "Applying Total Quality Management to Systems Engineering" and many INCOSE symposia papers. 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 the recipient of many other awards, plaques and letters of commendation and appreciation. He holds a Doctor of Science in Engineering Management from The George Washington University, is a Certified Manager and a certified member of the Association for Learning Technology. He gave up his positions as a Deputy Director and DSTO Associate Research Professor at the Systems Engineering and Evaluation Centre at the University of South Australia in early 2007 to move back to the UK to develop the world's first immersion course in systems engineering as a Leverhulme Visiting Professor at Cranfield University. He is an INCOSE Ambassador and also served as the initial president of INCOSE Australia and as a Region VI Representative to the INCOSE Member Board. He is currently a principal at the Right Requirement Ltd. in the UK and a Visiting Associate Professor at the National University of Singapore.

**Moti Frank** earned his B.Sc. in Electrical Engineering in 1981 from the *Technion* – Israel Institute of Technology - and worked for more than 20 years as an electronics and systems engineer in the hi-tech industry and Israeli Air Force. After he was released as a Lt. Colonel, he earned his M.Sc. in 1996, and Ph.D. in Industrial Engineering and Management and Education in Technology and Science in 1999, both from the *Technion*. Currently, he is professor and the chair of the Department of Technology Management in HIT, Holon Institute of Technology. His research interests are Systems Engineering, Systems Thinking and Project Management.

**Yang Yang ZHAO** is currently a PHD student at the National University of Singapore (NUS). She earned her Master's degree in System Design and Management from NUS in July 2009. After her receiving first Master's degree in Engineering Management from City University of Hong Kong (CTU), she worked as a research assistant for one year at the Department of Manufacturing and Engineering Management in CTU. Her research interests include system engineering, technological and innovation management.

## References

Ackoff, R. L., *Ackoff's Best. His Classic Writings on Management*, John Wiley & Sons, Inc., New York, 1999.

Arnold, E. P., "*Defining, Finding, and Hiring REAL Systems Engineers"*, proceedings of 16th Annual Symposium of the International Council on Systems Engineering, INCOSE, Orlando FL, 2006.

Arnold, S., "*Systems Engineering: From Process towards Profession"*, proceedings of The 10th Annual Symposium of the INCOSE, Minneapolis, MN, 2000.

Arnold, S. (Editor), *ISO 15288 Systems engineering — System life cycle processes*, International Standards Organisation, 2002.

Blanchard, B. B. and Fabrycky, W., *Systems Engineering and Analysis*, Prentice Hall, 1981.

Drucker, P. F., *Management: Tasks, Responsibilities, Practices*, Harper & Roe, New York, 1973.

Durward K. Sobek II and Jain, V. K., "*The Engineering Problem-Solving Process: Good for Students?"* proceedings of 2004 American Society for Engineering Education Annual Conference & Exposition, American Society for Engineering Education, 2004.

EIA 731-1, *Systems Engineering Capability*, Electronic Industries Association, 1997.

Frank, M., "*Knowledge, Abilities, Cognitive Characteristics and Behavioral Competences of Engineers with High Capacity for Engineering Systems Thinking (CEST)"*, The INCOSE Journal of Systems Engineering, Vol. 9 (2006), no. 2, 91-103.

Frosch, R. A., "*A new look at systems engineering"*, IEEE Spectrum, Vol. (1969), no. September, 25.

Goode, H. H. and Machol, R. E., *Systems Engineering*, McGraw-Hill, 1959.

Hall, A. D., *A Methodology for Systems Engineering*, D. Van Nostrand Company Inc., Princeton, NJ, 1962.

Haskins, C. (Editor), *Systems Engineering Handbook: A Guide for Life Cycle Processes and Activities, Version 3*, The International Council on Systems Engineering, 2006.

Hitchins, D. K., *Systems Engineering. A 21st Century Systems Methodology*, John Wiley & Sons Ltd., Chichester, England, 2007.

Hudson, S., "Systems Engineering Competencies Framework," INCOSE UK, 2006.

Kasser, J. E., "*The Certified Systems Engineer - It's About Time!"* proceedings of The 10th Annual Symposium of the INCOSE, Minneapolis, MN, 2000.

Kasser, J. E. and Frank, M., "*A Maturity Model for the Competency of Systems Engineers"*, proceedings of, 2010.

Kasser, J. E., Hitchins, D. and Huynh, T. V., "*Reengineering Systems Engineering"*, proceedings of the 3rd Annual Asia-Pacific Conference on Systems Engineering (APCOSE), Singapore, 2009.

Kasser, J. E., John, P., Tipping, K. and Yeoh, L. W., "*Systems engineering a 21st century introductory course on systems engineering: the Seraswati Project"*, proceedings of the 2nd Asia Pacific Conference on Systems Engineering, Yokohama, Japan, 2008.

Microsoft, Transforming Education: Assessing and Teaching 21st Century Skills,, 2008, http://download.microsoft.com/download/6/E/9/6E9A7CA7-0DC4-4823-993E-A54D18C19F2E/Transformative%20Assessment.pdf, last accessed 20 March 2009

OPM, Policies and instructions, 2009, http://www.opm.gov/qualifications/policy/index.asp, last accessed 29 October 2009

Paul, R. W. and Willsen, J., "Critical Thinking: Identifying the Targets," in *Critical Thinking: How to Prepare Students for a Rapidly Changing World*, J. Willsen and A. J. A. Binker (Editors), Foundation for Criical Thinking, Santa Rosa, CA, 1995.

Senge, P. M., *The Fifth Discipline: The Art & Practice of the Learning Organization*, Doubleday, New York, 1990.

Wasson, C. S., *System Analysis, Design, and Development concepts, principles and practices*, Wiley-Interscience, Hoboken, New Jersey, 2006.

Watts, J. G. and Mar, B. W., "*Important Skills and Knowledge to Include in Corporate Systems Engineering Training Programs"*, proceedings of The 7th Annual International Symposium of the INCOSE, Los Angeles, CA, 1997.

Woolfolk, A. E., "Chapter 7 Cognitive views of learning," in *Educational Psychology*, Allyn and Bacon, Boston, 1998, pp. 244-283.

Wymore, A. W., *Model-Based Systems Engineering*, CRC Press, Boca Raton, 1993.