# A Maturity Model for the Competency of Systems Engineers

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**Abstract.** This paper proposes a maturity model for the competency of systems engineers that instead of measuring years of experience is based on an assessment of an individual's skill against ability in each of three broad dimensions – knowledge (systems engineering and domain), cognitive characteristics (systems thinking and critical thinking) and individual traits. The maturity model is designed in such a manner so as to be a generic maturity model for assessing competency in many practitioner professions simply by changing the knowledge requirements.

## Introduction

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). However, the literature on what constitutes a systems engineer contains little consensus on subject. (Hall, 1962), pages 16-18) provided specifications or traits for an "Ideal Systems Engineer". (Hitchins, 1998) states "[systems engineering] is a philosophy and a way of life". Later studies include (Frank, 2002) and (Frank, 2006) who consolidated and classified the characteristics of successful systems engineers into ten cognitive characteristics, eleven abilities, ten behavioural competences and fifteen dealing with knowledge. Research into developing the requirements for a 21st century introductory course on systems engineering, resulted in the emergence of a number of requirements for the competencies of systems engineers (Arnold, 2006; Kasser, et al., 2008). These requirements included:

- Competent, skilled and knowledgeable systems engineers capable of effectively 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.
- Being able to define the problem (Wymore, 1993), page 2).
- Important skills and knowledge to include in corporate systems engineering training programs (Watts and Mar, 1997).
- 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, 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 maturity model

A number of ways of measuring competencies were identified in the research including

- Knowledge, Skills, and Abilities (KSA);
- INCOSE Certified Systems Engineer Professional (CSEP) Examination;
- INCOSE UK Systems Engineering Competencies Framework (SECF) (Hudson, 2006);
- Capacity for Engineering Systems Thinking (CEST) (Frank, 2006);
- The JPL Systems Engineering Advancement **(**SEA**)** project (Jansma and Jones, 2006).

However, none of these ways seem to meet the requirements listed above (Kasser, et al., 2010) so an alternative approach was needed. Further research identified that at one point of time in the development of theories of motivation, Henry A. Murray identified separate kinds of behaviour and developed an exhaustive list of 39 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). On the other hand, Maslow's hierarchical classification of needs (Maslow, 1966, 1968, 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, yet the contents of those categories are an aggregation of Murray's list.

So the lesson learned from behavioural psychology indicates that the production of a long list is an important and necessary intermediate stage in the process, but once developed, the list should be aggregated to some small set of common generic characteristics. This maturity model follows Maslow's approach of aggregating lists into broad areas of generic characteristics and 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*

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

*performance criteria*". The vertical axis or dimension of this maturity model 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 the assessment of the individual's skill against the corresponding ability in each knowledge area (requirement).

# The vertical dimension

The vertical dimension covers the following three broad areas:

- **Knowledge** of systems engineering and the application domain in which the systems engineering is being applied.
- **Cognitive characteristics**, namely the ability to think, identify and tackle problems by solving, resolving, dissolving or absolving the problems (Ackoff, 1999) page 115) in both the conceptual and physical domains.
- **Individual traits**, namely the ability to communicate with, work with, lead and influence other people.

## *Knowledge*

This area covers the knowledge of systems engineering and the application domain in which the systems engineering is being applied. (Woolfolk, 1998) described the following three types of knowledge:

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

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; Jansma and Jones, 2006; Hitchins, 2007) and (Wasson, 2006)) and much of that knowledge is summarized in (Haskins, 2006). Note that since systems engineers work 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 domain knowledge at the same ability level as for systems engineering, namely declarative, procedural and conditional.

## *Cognitive characteristics*

The need for systems thinking is widely recognized as a critical ability in the role of systems engineering (Frank, 2007) as is the need for analysis and critical thinking. However, in a similar manner to the many definitions of systems engineering that have been proposed over the last 50 years, there are a number of different definitions of systems thinking and critical thinking in the literature, and sometimes the terms are even used interchangeably or as a generic synonym for cognitive characteristics. These cognitive characteristics are used in activities requiring insight, innovation and analysis such as:

- Understanding the whole system and seeing the big picture.
- Understanding interconnections between elements and subsystems.

- Understanding systems without getting bogged down in details.
- Having a tolerance for ambiguity and uncertainty.
- Understanding the implications of a proposed change.
- Understanding a new system/concept immediately upon presentation.
- Understanding analogies/parallelism between systems.
- Understanding and exploring synergy.
- Thinking creatively.

The problem of assessing the degree of cognitive characteristics was solved in the manner of the maturity model by separating the systems thinking and critical thinking abilities and assessing each skill independently. The definitions of systems thinking and critical thinking and their relationship selected for the maturity model are shown in Figure 1. Consider each of them one at a time.

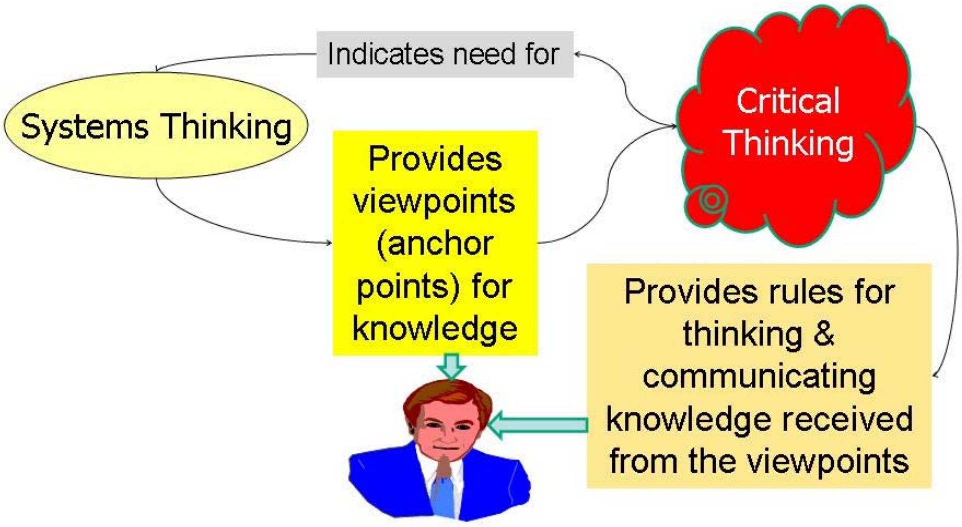


Figure 1 Relationship between Systems Thinking and Critical Thinking

## *Systems thinking*

Systems thinking is a discipline for seeing wholes (Senge, 1990), and indeed systems thinking is practiced much of the time by systems engineers but in an ad-hoc manner. Figuring out how to apply (and measure) systems thinking in a widely recognised and accepted systemic and systematic manner constitutes a problem yet to be solved (Kasser and Mackley, 2008). The literature abounds with:

- publications advocating the use of systems thinking, e.g. (Flood and Jackson, 1991),
- philosophical and academic theories of systems thinking, e.g. (Flood and Jackson, 1991),
- the need to view problems from various perspectives, e.g. (Morgan, 1997).
- one or two publications describing how an understanding of the way things are connected together provides one with a competitive advantage over those who do not share the same understanding (Morgan, 1997; Luzatto, circa 1735),
- descriptions of the application of feedback loops (e.g. casual loops) and the claim that the use of such loops constitutes systems thinking (Senge, 1990), and

- similar descriptions of the application of systems dynamics and the claim that systems dynamics constitutes systems thinking.

The approach to the application of systems thinking in a holistic manner used in this maturity model provides a basis for distinguishing competency levels of systems engineers. The approach was developed from the only systematic and systemic approach to applying systems thinking discovered in the literature (Richmond, 1993). Further research 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 systems thinking in postgraduate classes and workshops in Japan, Singapore, Taiwan and the UK. Holistic systems thinking is a systemic and systematic way of viewing a system from each of the following nine viewpoints.

1. Big picture
2. Operational
3. Functional
4. Structural
5. Generic
6. Continuum
7. Temporal
8. Quantitative
9. Scientific

The first eight perspectives are descriptive, while the scientific perspective is prescriptive. Consider each perspective in turn.

**Big picture perspective.** The big picture perspective allows the systems engineer to understand the whole system and provides a view of the forest rather than the trees. The perspective is from the meta-level in the hierarchy of systems containing the system and views the system within the context of its containing system – its environment, the closely coupled adjacent systems with which it interacts and any loosely coupled more distant systems. Thus the perspective contains information about the external boundary of the system and the assumptions behind the location of the boundary.

**Operational perspective.** The operational perspective allows systems engineers to understand the operation of systems without getting bogged down in details. The perspective is the manner in which the system operates or will operate (in the case of a new system). The system is viewed as a black box. The perspective shows the inputs and outputs and their relationships. This corresponds to the traditional 'open system' view. The black box perspective abstracts out (filters) the details of the internal nature of the system providing a view of the forest rather than the individual trees. The perspective is documented in the form of Use Cases, concept of operations, and other appropriate formats and produces operational requirements.

**Functional perspective.** The functional perspective allows systems engineers to understand the functions performed by a system. The perspective describes the functions or activities performed by the system without reference to which of the elements of the system perform those functions. This corresponds to the traditional 'closed system' view of the cause and effect feedback loops. The system is viewed as a white box. Depending on the level of system decomposition, this can be a view of what is being done or how it is being done. System dynamics is but one application of this perspective.

**Structural perspective.** The structural perspective provides an understanding of the interconnections between elements and subsystems. The perspective views the systems' architecture and the internal subsystem partition boundaries and any effects on the system due to its internal structure. This perspective incorporates the traditional physical, technical and architectural framework views.

**Generic perspective.** The generic perspective looks for similarities between the system and other systems in the same or other domains, in the present or in the past. This perspective leads to the:

- Understanding of analogies/parallelism between systems.
- Tolerance for ambiguity.
- Inheritance of domain requirements from similar systems.
- Adoption of lessons learned from other projects and determination if those lessons are applicable to current project.
- Adoption of innovative design approaches in the system domain using approaches from other domains. One application of generic thinking is TRIZ, a problem solving process that has evolved over the last 50 years whose underlying concept is "*Somebody someplace has already solved this problem (or one very similar to it.) Creativity is now finding that solution and adapting it to this particular problem*" (Barry, et al., 2007) namely incorporating lessons learned from other people into the problem solving process by definition.

Other applications of the generic perspective include pattern matching, and benchmarking.

**Continuum perspective.** The continuum perspective recognizes that:

- Things are not necessarily 'either-or', there may be states in between. This leads to concepts such as 'fail soft' in operation and the replacement of 'either-or' questions such as "is systems engineering an undergraduate or a postgraduate subject?" by questions in the form of "*to what degree is systems engineering a postgraduate subject?*" or "*what is the knowledge needed by a systems engineering engineer and how much of it can be taught as an undergraduate subject*?" This is a very different perspective to the traditional 'either-or' 'one right way' perspective.
- There may be more than one correct solution to a problem.
- Changing conditions may cause movement along the continuum. This leads to the insight that systems can exhibit different types of behaviour in different situations rather than always behave in the same way and that the transition conditions causing that change in behaviour may not be known. In the case of human systems, the continuum perspective points out that:

1. Maslow's hierarchy (Maslow, 1970) may not be so much as a pyramid, but a pie, and motivating people becomes a matter of figuring out which slices of the pie to offer them (Kasser, 1995).
2. Theory X and Theory Y (McGregor, 1960) behaviour may be two ends of a situational continuum of behaviour rather than two opposing behaviour patterns.

The 'fail soft' perspective leads to an analysis of failure modes for the system and each of its components. The analysis may influence the structural and functional perspectives in the design of the system. The perspective also leads to a risk analysis of the probability and effect of internal and externally induced failures and ways to mitigate the failures. Internal failures are failures of components due to aging and normal wear and tear (Moubray, 2005), external failures are those inflicted from without, such as natural disasters, sabotage and enemy action.

Application of the continuum perspective also leads to a tolerance for ambiguity.

**Temporal perspective.** The temporal perspective looks at how the system behaves over time. If the system exists, past patterns of behaviour are examined and future patterns are predicted using this perspective. Insights from this perspective include:

- Understanding the implications of a proposed change.
- The consideration of availability, maintenance, logistics, obsolescence, etc.
- The concept of prevention.
- The need to consider the effects due to aging, the need for upgrades and replacement and the effect of diminishing manufacturing sources and material shortages (DMSMS) and the technology to be used in the system.
- Lessons to be learned from the system implementation and improvements for future iterations of the system.
- An understanding that even if the implemented solution works it may introduce further problems that only show up after some period of time. These time delays were grouped (Kasser, 2002) as:
    - First order - noticeable effect within a second or less.
    - Second order - noticeable effect within a minute or less.
    - Third order - noticeable effect within an hour or less.
    - Fourth order - noticeable effect within a day or less.
    - Fifth order - noticeable effect within a week or less.
    - Sixth order - noticeable effect within a month or less.
    - Seventh order - noticeable effect within a year or less.
    - Eighth order - noticeable effect within a decade or less.
    - Ninth order - noticeable effect within a century or less.
    - Tenth order – noticeable effect after a century or more.

Temporal cause and effect loops are considered and the reflection on the past provides lessons learned from the system. This perspective also alerts analysts that past performance may not be a useful predictor of future performance unless the factors contributing to the past performance are understood.

**Quantitative perspective.** The quantitative perspective relates to the big picture and to the operational and functional perspectives to develop the performance requirements. According to (Richmond, 1993), the quantitative perspective however is not about the need to measure everything, "*it is more the recognition that numbers must be useful, not necessarily perfect and need not be absolute*". Sometimes relative comparisons are more useful. This perspective is about quantification rather than measurement, and helps to understand relationships and leads to the mathematical relationships in (functional) models and simulations. An example of quantification is the Likert scale, named after its originator Rensis Likert (1903-1981). The Likert scale offers a means of determining attitudes across a continuum of choices, such as “strongly agree,” “agree”, “don’t care”, “disagree” and “strongly disagree.” A numerical value can then be allocated to each statement for further analysis. The numerical values may not necessarily be in a linear relationship, namely they may be weighted.

**Scientific perspective.** Whereas the other descriptive perspectives are used to examine (and document) a system, problem or situation, this prescriptive perspective covers the formulation and testing of hypothetical candidate representations of the solution system to meet the need that will be constructed in the design and implementation phases of the system development life cycle (SDLC), and the construction of the tests used to validate the representation by the Test and Evaluation (T&E) function of systems engineering.

## *Critical thinking*

The skills needed for critical thinking include comprehension, application, analysis, synthesis, and evaluation of information. The challenge was how to assess the level of critical thinking by systems engineers. A literature review showed that the problem of measuring the degree of critical thinking in students seemed to have already been solved (Eichhorn, 2002; Wolcott and Gray, 2003; Allen, 2004). For example, (Eichhorn, 2002) informed students that their written answers would be judged for their clarity, accuracy, precision, relevance, coherence, logic, depth, consistency, and fairness. (Wolcott and Gray, 2003) aggregated lists of critical thinking abilities by defining five levels of critical thinking. In addition, Wolcott’s method for assessing a critical thinking level was very similar to that used by (Biggs, 1999) for assessing deep learning. Since a modified version of the Biggs criteria had been used successfully at the University of South Australia (Kasser, et al., 2005) for assessing student’s work, Wolcott’s method was adopted for the maturity model. Wolcott’s five levels (from highest to lowest) are:

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

Consider each of them

**0 Confused fact finder** is a person who is characterised by the following:

- Looks for the “only” answer
- Doesn’t seem to “get it”
- Quotes inappropriately from textbooks
- Provides illogical/contradictory arguments
- Insists professor, the textbook, or other experts provide “correct” answers even to open-ended problems

**1 Biased jumper** is a person whose opinions do not seem to be influenced by facts. This person is characterised by the following:

- Jumps to conclusions
- Does not recognise own biases; accuses others of being biased
- Stacks up evidence for own position; ignores contradictory evidence
- Uses arguments for own position
- Uses arguments against others
- Equates unsupported personal opinion with other forms of evidence
- Acknowledges multiple viewpoints but cannot adequately address a problem from viewpoint other than own

**2 Perpetual analyzer** is a person who can easily end up in “analysis paralysis”. This person is characterised by the following:

- Does not reach or adequately defend a solution
- Exhibits strong analysis skill, but appears to be “wishy-washy”
- Write papers that are too long and seem to ramble
- Doesn’t want to stop analysing

**3 Pragmatic performer** is a person who is characterised by the following:

- Objectively considers alternatives before reaching conclusions
- Focuses on pragmatic solutions
- Incorporates others in the decision process and/or implementation
- Views task as finished when a solution/decision is reached
- Gives insufficient attention to limitations, changing conditions, and strategic issues
- Sometimes comes across as a “Biased Jumper”, but reveals more complex thinking when prompted

**4 Strategic Re-Visioner** is a person who is characterised by the following:

- Seeks continuous improvement/lifelong learning
- More likely than others to think “out of the box”
- Anticipates change
- Works toward construction knowledge over time

### *Individual traits*

The individual traits include communications, personal relationships, team playing, influencing, negotiating, self-learning, establishing trust, managing, leading, and more (Covey, 1989; Frank, 2010).

## The horizontal dimension

The horizontal dimension provides a way to measure of the skill of the person in each broad area of the vertical dimension. Ability refers to how well a person is required to perform. It is a combination of aptitude, experience and training. The ability is characterized in five maturity levels which were presented as the following five types of systems engineers 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 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 Type IIIs 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.

Types I and II are levels through which a person grows with education and experience. The debate on 'nature' or 'nurture' comes into play at Levels III, IV and V. However, irrespective of the debate, it is important to identify people with the potential to become Type IV's and V's as early as possible in their careers and then to provide them with fast track training to enable their organization to obtain the best use of their capabilities in the future.

## A two dimensional maturity model

The two-dimensional maturity model showing the assessment of the competency (the skill in each of the areas) is summarised in Table 1. 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.

This maturity model is simple enough to be practical and broad enough to be useful. As in similar maturity models, candidates must qualify for the appropriate

**Table 1 A Maturity Model for Systems Engineers**

| | Type I | Type II | Type III | Type IV | Type V |
|---|---|---|---|---|---|
| **Knowledge** | | | | | |
| **Systems engineering** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Domain (problem solution)** | Declarative | Declarative | Conditional | Conditional | Conditional |
| **Cognitive characteristics** | | | | | |
| **System Thinking** | | | | | |
| **Operational** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Functional** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Big picture** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Structural** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Generic** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Continuum** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Temporal** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Quantitative** | Declarative | Procedural | Conditional | Conditional | Conditional |
| **Scientific** | No | No | Procedural | No | Conditional |
| | | | | | |
| **Critical Thinking** | Confused fact finder | Perpetual analyser | Pragmatic performer | Pragmatic performer | Strategic re-visioner |
| | | | | | |
| **Individual traits** | | | | | |
| **Communications** | Yes | Yes | Yes | Yes | Yes |
| **Management** | No | Yes | Yes | Yes | Yes |
| **Leadership** | No | No | Yes | Yes | Yes |

ability in all three dimensions to be recognised as being competent that maturity level.

## Developing an assessment approach

Assessment of a candidate against the maturity model is simple in concept as follows. For the purpose of assessment of knowledge, examination questions may be written to require the respondent to demonstrate the different types of systems engineering, domain and systems thinking knowledge. While examination questions can require the respondent to use conditional knowledge, the successful application of conditional knowledge in the real world may be directly demonstrated by results documented in the form of KSAs if supported by awards, letters and certificates of appreciation from third parties (e.g. employers, customers, etc.). Assessing the degree of critical thinking has been described by (Wolcott and Gray, 2003).

The assessment is thus in is two parts, one part is by examination, the second is by demonstrated successful experience and an interview which would determine if the candidate is a person who goes by the book (Type II systems engineer (Kasser, et al., 2009)), is able to write the book (Type V systems engineer) or is something in between.

## Summary

This paper has introduced a way of assessing the competency of systems engineers that instead of measuring years of experience is based on an assessment of an individual’s skill against ability in each of three broad dimensions – knowledge (systems engineering and domain), cognitive characteristics (systems thinking and critical thinking) and individual traits. The maturity model is also designed in such a manner so as to be a generic maturity model for assessing competency in many practitioner professions simply by changing the knowledge requirements.

## Conclusions

By aggregating the knowledge, traits, abilities and other characteristics of successful systems engineers into three broad areas and using ability against which to assess an individual’s skill in the three broad dimensions, we seem to have developed a maturity model that is simple enough to be practical, broad enough to be useful and is applicable to many professions or part of a profession just by changing the knowledge component. Further research is necessary to validate and fine tune the maturity model.

## 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.

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