Enabling individuals to perform systems engineering (SE) requires an understanding of SE competencies, roles, and tasks; plus knowledge, skills, abilities, and attitudes (KSAA). Within a business or enterprise, SE responsibilities are allocated to individuals through the definition of SE roles associated with a set of tasks. For an individual, a set of KSAAs enables the fulfillment of the competencies needed to perform the tasks associated with the assigned SE role. SE competencies reflect the individual’s KSAAs, which are developed through education, training, and on-the-job experience. Traditionally, SE competencies build on innate personal qualities and have been developed primarily through experience. Recently, education and training have taken on a greater role in the development of SE competencies.

Contents

- 1 Relationship of SE Competencies and KSAAs
- 2 SE Competency Models
  - 2.1 Commonality and Domain Expertise
  - 2.2 INCOSE Certification
  - 2.3 Domain- and Industry-specific Models
- 3 SE Competency Models — Examples
  - 3.1 INCOSE SE Competency Model
  - 3.2 United States DoD Engineering Competency Model
  - 3.3 NASA SE Competency Model
- 4 Relationship of SE Competencies to Other Competencies
- 5 References
  - 5.1 Works Cited
  - 5.2 Primary References
  - 5.3 Additional References

Relationship of SE Competencies and KSAAs

There are many ways to define competency. It can be thought of as a measure of the ability to use the appropriate KSAAs to successfully complete specific job-related tasks (Whitcomb, Khan, White 2014). Competencies align with the tasks that are expected to be accomplished for the job position (Holt and Perry 2011). KSAAs belong to the individual. In the process of filling a position, organizations have a specific set of competencies associated with tasks that are directly related to the job. A person possesses the KSAAs that enable them to perform the desired tasks at an
acceptable level of competency.

The KSAAs are obtained and developed from a combination of several sources of learning including education, training, and on-the-job experience. By defining the KSAAs in terms of a standard taxonomy, they can be used as learning objectives for competency development (Whitcomb, Khan, White 2014). Bloom’s Taxonomy for the cognitive and affective domains provides this structure (Bloom 1956, Krathwohl 2002). The cognitive domain includes knowledge, critical thinking, and the development of intellectual skills, while the affective domain describes growth in awareness, attitude, emotion, changes in interest, judgment, and the development of appreciation (Bloom 1956). The affective does not refer to additional topics which a person learns about, but rather to a transformation of the person in relation to the original set of topics learned. Cognitive and affective processes within Bloom’s taxonomic classification schema refer to levels of observable actions, which indicate learning is occurring. Bloom’s Taxonomy for the cognitive and affective domains define terms as categories of levels that can be used for consistently defining KSAA statements (Krathwohl 2002):

**Cognitive Domain:**
- Remember
- Understand
- Apply
- Analyze
- Evaluate
- Create

**Affective Domain:**
- Receive
- Respond
- Value
- Organize
- Characterize

Both cognitive and affective domains should be included in the development of systems engineering competency models, because the cognitive domain learning concerns the consciously developed knowledge about the various subjects and the ability to perform tasks, whilst the affective learning concerns the interest in or willingness to use particular parts of the knowledge learned and the extent to which the systems engineer is characterized by taking approaches which are inherently systemic. Using the affective domain in the specification of KSAAs, is also important as every piece of information we process in our brains goes through our affective (emotional) processors before it is integrated by our cognitive processors (Whitcomb and Whitcomb 2013).

**SE Competency Models**

Contexts in which individual competency models are typically used include:

- **Recruitment and Selection:** Competencies define categories for behavioral event interviewing (BEI), increasing the validity and reliability of selection and promotion decisions.
- **Human Resources Planning and Placements:** Competencies are used to identify individuals to fill specific positions and/or identify gaps in key competency areas.
- **Education, Training, and Development:** Explicit competency models let employees know which competencies are valued within their organization. Curriculum and interventions can be designed around desired competencies.
Commonality and Domain Expertise

No single individual is expected to be proficient in all the competencies found in any model. The organization, overall, must satisfy the required proficiency in sufficient quantity to support business needs. Organizational capability is not a direct summation of the competency of the individuals in the organization, since organizational dynamics play an important role that can either raise or lower overall proficiency and performance. The articles Enabling Teams and Enabling Businesses and Enterprises explore this further.

SE competency models generally agree that systems thinking, taking a holistic view of the system that includes the full life cycle, and specific knowledge of both technical and managerial SE methods are required to be a fully capable systems engineer. It is also generally accepted that an accomplished systems engineer will have expertise in at least one domain of practice. General models, while recognizing the need for domain knowledge, typically do not define the competencies or skills related to a specific domain. Most organizations tailor such models to include specific domain KSAAs and other peculiarities of their organization.

INCOSE Certification

Certification is a formal process whereby a community of knowledgeable, experienced, and skilled representatives of an organization, such as the International Council on Systems Engineering (INCOSE), provides formal recognition that a person has achieved competency in specific areas (demonstrated by education, experience, and knowledge). (INCOSE nd). The most popular credential in SE is offered by INCOSE, which requires an individual to pass a test to confirm knowledge of the field, requires experience in SE, and recommendations from those who have knowledge about the individual's capabilities and experience. Like all such credentials, the INCOSE certificate does not guarantee competence or suitability of an individual for a particular role, but is a positive indicator of an individual's ability to perform. Individual workforce needs often require additional KSAAs for any given systems engineer, but certification provides an acknowledged common baseline.

Domain- and Industry-specific Models

No community consensus exists on a specific competency model or small set of related competency models. Many SE competency models have been developed for specific contexts or for specific organizations, and these models are useful within these contexts.

Among the domain- and industry-specific models is the Aerospace Industry Competency Model (ETA 2010), developed by the Employment and Training Administration (ETA) in collaboration with the Aerospace Industries Association (AIA) and the National Defense Industrial Association (NDIA), and available online. This model is designed to evolve along with changing skill requirements in the aerospace industry. The ETA makes numerous competency models for other industries available online (ETA 2010). The NASA Competency Management System (CMS) Dictionary is predominately a dictionary of domain-specific expertise required by the US National Aeronautics and Space Administration (NASA) to accomplish their space exploration mission (NASA 2009).

Users of models should be aware of the development method and context for the competency model they plan to use, since the primary competencies for one organization might differ from those for another organization. These models often are tailored to the specific business characteristics, including the specific product and service domain in which the organization operates. Each model typically includes a set of applicable competencies along with a scale for assessing the level of proficiency.

SE Competency Models — Examples

Though many organizations have proprietary SE competency models, published SE competency models can be used for reference. Table 1 lists information about several published SE competency
models, and links to these sources are shown below in the references section. Each model was
developed for a unique purpose within a specific context and validated in a particular way. It is
important to understand the unique environment surrounding each competency model to determine
its applicability in any new setting.

<table>
<thead>
<tr>
<th>Competency Model</th>
<th>Date</th>
<th>Author</th>
<th>Purpose</th>
<th>Development Method</th>
<th>Competency Model Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCOSE UK WG</td>
<td>2010</td>
<td>INCOSE</td>
<td>Identify the competencies required to conduct good systems engineering</td>
<td>INCOSE Working Group</td>
<td>(INCOSE 2010), (INCOSE UK 2010)</td>
</tr>
<tr>
<td>ENG Competency Model</td>
<td>2013</td>
<td>DAU</td>
<td>Identify competencies required for the DoD acquisition engineering professional</td>
<td>DoD and DAU internal development</td>
<td>(DAU 2013)</td>
</tr>
<tr>
<td>NASA APPEL Competency Model</td>
<td>2009</td>
<td>NASA</td>
<td>To improve project management and systems engineering at NASA</td>
<td>NASA internal development - UPDATE IN WORK</td>
<td>(NASA 2009)</td>
</tr>
<tr>
<td>MITRE Competency Model</td>
<td>2007</td>
<td>MITRE</td>
<td>To define new curricula for systems engineering and to assess personnel and organizational capabilities</td>
<td>Focus groups as described in (Trudeau 2005)</td>
<td>(Trudeau 2005), (MITRE 2007)</td>
</tr>
<tr>
<td>CMMI for Development</td>
<td>2007</td>
<td>SEI</td>
<td>Process improvement maturity model for the development of products and services</td>
<td>SEI Internal Development</td>
<td>(SEI 2007), (SEI 2004)</td>
</tr>
</tbody>
</table>

Other models and lists of traits include: Hall (1962), Frank (2000; 2002; 2006), Kasser et al. (2009), Squires et al. (2011), and Armstrong et al. (2011). Ferris (2010) provides a summary and evaluation of the existing frameworks for personnel evaluation and for defining SE education. Squires et al. (2010) provide a competency-based approach that can be used by universities or companies to compare their current state of SE capability development against a government-industry defined set of needs. SE competencies can also be inferred from standards such as ISO-15288 (ISO/IEC/IEEE 15288 2015) and from sources such as the INCOSE Systems Engineering Handbook (INCOSE 2012), the INCOSE Systems Engineering Certification Program, and CMMI criteria (SEI 2007). Whitcomb, Khan, and White describe the development of a systems engineering competency model for the United States Department of Defense based on a series of existing competency models (Whitcomb, Khan, and White 2013; 2014).

To provide specific examples for illustration, more details about three SE competency model examples follow. These include:

- The International Council on Systems Engineering (INCOSE) UK Advisory Board model (INCOSE 2010), (INCOSE UK 2009);
- The DAU ENG model (DAU 2013); and
- The NASA Academy of Program/Project & Engineering Leadership (APPEL) model (NASA 2009)

**INCOSE SE Competency Model**

The INCOSE model was developed by a working group in the United Kingdom (Cowper et al. 2005). As Table 2 shows, the INCOSE framework is divided into three theme areas - systems thinking, holistic life cycle view, and systems management - with a number of competencies in each. The
INCOSE UK model was later adopted by the broader INCOSE organization (INCOSE 2010).

Table 2. INCOSE UK Working Group Competency (INCOSE UK 2010). This information has been published with the kind permission of INCOSE UK Ltd and remains the copyright of INCOSE UK Ltd - ©INCOSE UK LTD 2010. All rights reserved.

<table>
<thead>
<tr>
<th>Systems Thinking</th>
<th>Determining and Managing Stakeholder Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System Concepts</td>
</tr>
<tr>
<td></td>
<td>Super-System Capability Issues</td>
</tr>
<tr>
<td></td>
<td>Enterprise and Technology Environment</td>
</tr>
<tr>
<td></td>
<td>Systems Design</td>
</tr>
<tr>
<td></td>
<td>Architectural Design</td>
</tr>
<tr>
<td></td>
<td>Concept Generation</td>
</tr>
<tr>
<td></td>
<td>Design For...</td>
</tr>
<tr>
<td></td>
<td>• Functional Analysis</td>
</tr>
<tr>
<td></td>
<td>• Interface Management</td>
</tr>
<tr>
<td></td>
<td>• Maintaining Design Integrity</td>
</tr>
<tr>
<td></td>
<td>• Modeling and Simulation</td>
</tr>
<tr>
<td></td>
<td>• Selecting Preferred Solution</td>
</tr>
<tr>
<td></td>
<td>• System Robustness</td>
</tr>
<tr>
<td></td>
<td>Systems Integration &amp; Verification</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
</tr>
<tr>
<td></td>
<td>Transition to Operation</td>
</tr>
<tr>
<td></td>
<td>Systems Engineering Management</td>
</tr>
<tr>
<td></td>
<td>Concurrent Engineering</td>
</tr>
<tr>
<td></td>
<td>Enterprise Integration</td>
</tr>
<tr>
<td></td>
<td>Integration of Specialties</td>
</tr>
<tr>
<td></td>
<td>Lifecycle Process Definition</td>
</tr>
<tr>
<td></td>
<td>Planning, Monitoring, and Controlling</td>
</tr>
</tbody>
</table>

United States DoD Engineering Competency Model

The model for US Department of Defense (DoD) acquisition engineering professionals (ENG) includes 41 competency areas, as shown in Table 3 (DAU 2013). Each is grouped according to a “Unit of Competence” as listed in the left-hand column. For this model, the four top-level groupings are: analytical, technical management, professional, and business acumen. The life cycle view used in the INCOSE model is evident in the ENG analytical grouping but is not cited explicitly. Technical management is the equivalent of the INCOSE SE management, but additional competencies are added, including software engineering competencies and acquisition. Selected general professional skills have been added to meet the needs for strong leadership required of the acquisition engineering professionals. The business acumen competencies were added to meet the needs of these professionals to be able to support contract development and oversight activities and to engage with the defense industry.

Table 3. DoD Competency Model (DAU 2013) Defense Acquisition University (DAU)/U.S. Department of Defense (DoD).

<table>
<thead>
<tr>
<th>Analytical (11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mission-Level Assessment</td>
</tr>
<tr>
<td>2. Stakeholder Requirements Definition</td>
</tr>
<tr>
<td>3. Requirements Analysis</td>
</tr>
<tr>
<td>4. Architecture Design</td>
</tr>
<tr>
<td>5. Implementation</td>
</tr>
<tr>
<td>6. Integration</td>
</tr>
</tbody>
</table>
### NASA SE Competency Model

The US National Aeronautics and Space Administration (NASA) APPEL website provides a competency model that covers both project engineering and systems engineering (APPEL 2009). There are three parts to the model: one that is unique to project engineering, one that is unique to systems engineering, and a third that is common to both disciplines. Table 4 below shows the SE aspects of the model. The project management items include project conceptualization, resource management, project implementation, project closeout, and program control and evaluation. The common competency areas are: NASA internal and external environments, human capital and management, security, safety and mission assurance, professional and leadership development, and knowledge management. This 2010 model is adapted from earlier versions. Squires et al. (2010, 246-260) offer a method that can be used to analyze the degree to which an organization’s SE capabilities meet government-industry defined SE needs.

| Technical Management (10) | 12. Decision Analysis  
| | 13. Technical Planning  
| | 14. Technical Assessment  
| | 15. Configuration Management  
| | 16. Requirements Management  
| | 17. Risk Management  
| | 18. Data Management  
| | 19. Interface Management  
| | 20. Software Engineering  
| | 21. Acquisition  
| Professional (10) | 22. Problem Solving  
| | 23. Strategic Thinking  
| | 24. Professional Ethics  
| | 25. Leading High-Performance Teams  
| | 26. Communication  
| | 27. Coaching and Mentoring  
| | 28. Managing Stakeholders  
| | 29. Mission and Results Focus  
| | 30. Personal Effectiveness/Peer Interaction  
| | 31. Sound Judgment  
| Business Acumen (10) | 32. Industry Landscape  
| | 33. Organization  
| | 34. Cost, Pricing, and Rates  
| | 35. Cost Estimating  
| | 36. Financial Reporting and Metrics  
| | 37. Business Strategy  
| | 38. Capture Planning and Proposal Process  
| | 39. Supplier Management  
| | 40. Industry Motivation, Incentives, Rewards  
| | 41. Negotiations  

Table 4. SE Portion of the APPEL Competency Model (APPEL 2009). Released by NASA APPEL.

<table>
<thead>
<tr>
<th>System Design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SE 1.1 - Stakeholder Expectation Definition &amp; Management</td>
<td></td>
</tr>
<tr>
<td>SE 1.2 - Technical Requirements Definition</td>
<td></td>
</tr>
<tr>
<td>SE 1.3 - Logical Decomposition</td>
<td></td>
</tr>
<tr>
<td>SE 1.4 - Design Solution Definition</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product Realization</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SE 2.1 - Product Implementation</td>
<td></td>
</tr>
<tr>
<td>SE 2.2 - Product Integration</td>
<td></td>
</tr>
<tr>
<td>SE 2.3 - Product Verification</td>
<td></td>
</tr>
<tr>
<td>SE 2.4 - Product Validation</td>
<td></td>
</tr>
<tr>
<td>SE 2.5 - Product Transition</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Management</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SE 3.1 - Technical Planning</td>
<td></td>
</tr>
<tr>
<td>SE 3.2 - Requirements Management</td>
<td></td>
</tr>
<tr>
<td>SE 3.3 - Interface Management</td>
<td></td>
</tr>
<tr>
<td>SE 3.4 - Technical Risk Management</td>
<td></td>
</tr>
<tr>
<td>SE 3.5 - Configuration Management</td>
<td></td>
</tr>
<tr>
<td>SE 3.6 - Technical Data Management</td>
<td></td>
</tr>
<tr>
<td>SE 3.7 - Technical Assessment</td>
<td></td>
</tr>
<tr>
<td>SE 3.8 - Technical Decision Analysis</td>
<td></td>
</tr>
</tbody>
</table>

Relationship of SE Competencies to Other Competencies

SE is one of many engineering disciplines. A competent SE must possess KSAAs that are unique to SE, as well as many other KSAAs that are shared with other engineering and non-engineering disciplines.

One approach for a complete engineering competency model framework has multiple dimensions where each of the dimensions has unique KSAAs that are independent of the other dimensions (Wells 2008). The number of dimensions depends on the engineering organization and the range of work performed within the organization. The concept of creating independent axes for the competencies was presented in Jansma and Derro (2007), using technical knowledge (domain/discipline specific), personal behaviors, and process as the three axes. An approach that uses process as a dimension is presented in Widmann et al. (2000), where the competencies are mapped to process and process maturity models. For a large engineering organization that creates complex systems solutions, there are typically four dimensions:

1. **Discipline** (e.g., electrical, mechanical, chemical, systems, optical);
2. **Life Cycle** (e.g., requirements, design, testing);
3. **Domain** (e.g., aerospace, ships, health, transportation); and
4. **Mission** (e.g., air defense, naval warfare, rail transportation, border control, environmental protection).

These four dimensions are built on the concept defined in Jansma and Derro (2007) and Widmann et al. (2000) by separating discipline from domain and by adding mission and life cycle dimensions. Within many organizations, the mission may be consistent across the organization and this dimension would be unnecessary. A three-dimensional example is shown in Figure 1, where the organization works on only one mission area so the mission dimension has been eliminated from the framework.
The discipline, domain, and life cycle dimensions are included in this example, and some of the first-level areas in each of these dimensions are shown. At this level, an organization or an individual can indicate which areas are included in their existing or desired competencies. The sub-cubes are filled in by indicating the level of proficiency that exists or is required. For this example, blank indicates that the area is not applicable, and colors (shades of gray) are used to indicate the levels of expertise. The example shows a radar electrical designer that is an expert at hardware verification, is skilled at writing radar electrical requirements, and has some knowledge of electrical hardware concepts and detailed design. The radar electrical designer would also assess his or her proficiency in the other areas, the foundation layer, and the leadership layer to provide a complete assessment.

References

Works Cited


Jansma, P.A. and M.E. Derro. 2007. "If you want good systems engineers, sometimes you have to grow your own!" Paper presented at IEEE Aerospace Conference, 3-10 March, 2007, Big Sky, MT, USA.


Primary References


Additional References