Reference Curriculum for a Graduate Program in Systems Engineering

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1. Abstract

Numerous Systems Engineering (SE) departments and programs worldwide have developed courses and programs within the field of systems engineering, architecting, and integration. These programs are often a function of their academic legacy and strengths, along with their perception of the educational needs of their primary audience – students and sponsors, both within industry and government. This perception or sense for the needs of audience is often based on interviews, exchange forums, and surveys, and informal assessments through a variety of interchanges. Academia and industry often differ in the definition of the scope of a systems engineering curriculum. The assessment of industry and government requirements for SE competencies represents the “demand side” of the SE education and competency development enterprise. One aspect of the “supply side” is represented by academia.

This paper proposes a reference systems engineering curriculum at the graduate level. This is based on a study of systems engineering programs at 36 Universities in the US and Europe, and the correlation of these programs with some published reports from industry and government on systems engineering competency requirements. This study was initiated based on a request from the Academic Council of INCOSE, and supported by the Systems Engineering Curriculum Working Group within INCOSE.

The proposed framework takes into consideration the commonalities and patterns in SE education content as it is taught today. One of the main objectives of proposing a reference curriculum of SE is to try to bridge the gap between the expected systems engineering competencies by the potential employers and the graduate SE program curriculums. The framework is proposed to support the development of new graduate programs in systems engineering and the enhancements to the existing SE graduate programs. The proposed framework has the following three dimensions: Topical Areas, Levels, and SE Competencies.

2. Introduction

An increasing number of universities are offering graduate programs in Systems Engineering, while simultaneously a number of corporations in the commercial and defense sectors have articulated needs for systems engineering skills and competencies. These programs often are structured by their academic legacy and strengths and their perception of the educational needs
of their primary audience —students and sponsors, both within industry and government. This perception of audience needs is often based on interviews, exchange forums, surveys, and informal assessments. Industry and academia often differ in the definition of the scope of a systems engineering curriculum. Consequently, the need for a reference curriculum has often been articulated in a variety of meetings within the systems engineering community. This study was initiated on the request of the INCOSE Academic Council, and supported by the Systems Engineering Curriculum Working Group. This paper presents this research and a proposed reference curriculum. This curriculum has also been reviewed by members of the SE University Leadership Roundtable of INCOSE.

The research methodology for developing the reference curriculum was developed by the working group. The group met through teleconferences during April – July 2006. The methodology for undertaking this research on SE curriculum was conducted as illustrated in Figure 1:

![Figure 1 The research methodology followed to develop this reference curriculum.](image)

For this research effort we focused our attention on systems engineering centric programs as proposed by Fabrycky [2005]. According to Fabrycky [2005] Systems Engineering Centric (SEC) Program includes “basic and advanced level programs leading to a bachelors or higher degree in Systems Engineering comprise a distinct category with a discipline-like focus. Included herein are only those degree programs where the concentration is designated as Systems Engineering; where SE is the intended major area of study”. Domain Centric Systems Engineering (DCSE) Programs on the other hand includes “Basic and advanced level programs leading to a bachelors or higher degrees with the major designated as X Systems Engineering, Systems and X Engineering, etc”.

Survey of Systems Engineering Centric Programs: The graduate systems engineering programs included in this study are listed in INCOSE report on this subject. 32 out of the total 35 universities offer graduate degrees (M.S. and M.E.), a fourth of them have undergraduate degrees, and a third of them have doctoral programs.
Survey of systems engineering skills and competencies: A number of industry and government surveys and studies [Kasser, 2004], [Kasser et al, 2006], [MIT, 2003], [Lockheed Martin, 2006], [INCOSE UK, 2005], [Stevens Institute of Technology, 2003] were the basis for understanding the required systems engineering competencies and skills. Detailed references to a selection of these studies are provided in the report. A list of SE Competencies from these sources is included in a more detailed version of the INCOSE report [Jain, Verma, 2007] on this subject.

3. Review of Systems Engineering Programs and Curricula

Initially, the analysis focused on the core courses for a systems engineering degree. In some cases, elective courses were included when applicable. From the 35 universities listed, 203 graduate courses were analyzed. We reviewed course descriptions and outlines and defined an initial set of topical areas. As we received more information on course offerings through our research, we modified and refined our topical areas. This analysis for looking for overlaps, gaps, and redundancies continued until each course was defined and reviewed through several iterations (Jain 2006). This was done to reduce the confusion caused by multiple course titles for similar topics, and similar course titles for a diversity of topics.

This consolidation and synthesis produced a comprehensive list of course descriptions that can be used for a proposed systems engineering curriculum framework. Once the baseline course descriptions (Jain 2006) were finalized, each course was placed into one of the four levels. The final grouping of the sixteen topical areas into four levels is shown in figure 3. The descriptions of each of the sixteen topical areas are provided in Jain and Verma (2007).

In the current systems engineering graduate programs, software engineering is included as part of the core courses. We believe that software engineering should be included as a specialization or elective track, and it is categorized as a specialization course in the proposed framework.

Next, we cross-referenced the topical areas and their curriculum level groupings to industry needs through a Quality Function Deployment (QFD) exercise to identify gaps in the process or gaps in the ability to meet industry needs, as shown in figure 3. This process was repeated until industry needs were sufficiently addressed, and the topical areas were refined into a suggested systems engineering curriculum. The correlation entries in figure 3 are “Strong Positive,” “Medium Positive,” “Weak Positive,” and “No Correlation,” as shown in figure 2.

In reviewing existing systems engineering programs and mapping their offerings to industry needs, we identified missing topics and topics that could be strengthened. The gap analysis showed that the current systems-engineering centric programs do not address three industry-required systems engineering competencies:

- System concepts
- Architectural design
- Modeling and simulation
In the current SE graduate programs, Software Engineering is included as part of the core courses. The authors believe that Software Engineering should be included as a specialization or Elective track and hence it has been moved from core courses to specialization courses in the proposed framework.

### Figure 2: The QFD Correlations Key

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Positive Correlation</td>
<td>+++</td>
</tr>
<tr>
<td>Medium Positive Correlation</td>
<td>++</td>
</tr>
<tr>
<td>Weak Positive Correlation</td>
<td>+</td>
</tr>
<tr>
<td>No Correlation</td>
<td>-</td>
</tr>
<tr>
<td>Identified Gaps</td>
<td>Yellow</td>
</tr>
<tr>
<td>Identified Improvements</td>
<td>Blue</td>
</tr>
</tbody>
</table>

### Figure 3: Gap Analysis Represented in a QFD Matrix

<table>
<thead>
<tr>
<th>Systems Thinking</th>
<th>Holistic Lifecycle View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems concepts</td>
<td>Maintaining Design Integrity</td>
</tr>
<tr>
<td>Super-system capability issues and technology</td>
<td>Modeling and Simulation</td>
</tr>
<tr>
<td>Determine and manage stakeholder</td>
<td>Select Preferred Solution</td>
</tr>
<tr>
<td>System Requirements</td>
<td>System Robustness</td>
</tr>
<tr>
<td>Architectural design</td>
<td>Integration &amp; Verification</td>
</tr>
<tr>
<td>Concept generation</td>
<td>Validation</td>
</tr>
<tr>
<td>Design for requirements of later</td>
<td>Transition to Operation</td>
</tr>
<tr>
<td>Functional analysis</td>
<td>Concurrent engineering</td>
</tr>
<tr>
<td>Interface Management</td>
<td>Systems Integration</td>
</tr>
<tr>
<td>Probabilistic thinking</td>
<td>Systems Engineering Management</td>
</tr>
<tr>
<td>Quality, Safety, and Systems Stability</td>
<td>Systems Design Architecture</td>
</tr>
<tr>
<td>Observations, Risks, and Uncertainty</td>
<td>Software Systems Engineering</td>
</tr>
<tr>
<td>Decisions, Risk, and Uncertainty</td>
<td>General Project Management</td>
</tr>
<tr>
<td>Level 3: Specialization Courses</td>
<td>Manufacturing, Production, and Operations</td>
</tr>
<tr>
<td>Level 2: Core Courses</td>
<td>Level 1: Introductory Courses</td>
</tr>
<tr>
<td>Level 0: Foundation Courses</td>
<td>General Mathematics</td>
</tr>
</tbody>
</table>

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*In the current SE graduate programs, Software Engineering is included as part of the core courses. The authors believe that Software Engineering should be included as a specialization or Elective track and hence it has been moved from core courses to specialization courses in the proposed framework.*
To fill these gaps, we recommend the following course offerings be revised and modified:

Level 1: Introductory courses
   Fundamentals of systems engineering

Level 2: Core course
   System design/architecture
   Systems integration
   Quality, safety, and systems suitability
   Decisions, risks, and uncertainty

The research revealed that the following three core courses had a weak relationship or absence of any relationship with the other topical areas:
   - Quality, safety, and systems suitability
   - Modeling, simulation, and optimization
   - Decisions, risks and uncertainty

The most serious gaps were between these three core courses and three specialized, elective courses:
   - General project management
   - Finance, economics, and cost estimation
   - Organizational leadership

The intent of this correlation is not to suggest a tight coupling between all topical areas and resulting courses, but rather the desire is to embed enough correlating themes in these courses to allow the emergence of an appreciation for the crosscutting implications of the topics when applying a systems approach. We believe that a mature and evolving curriculum will allow sufficient links across courses to exemplify this systems perspective.

Another approach to teach cross-cutting implications is through capstone projects and group work. Andy Sage (2000) discusses this approach and the major ingredients associated with reshaping the curriculum based on his 1994 study for the American Society of Engineering Education.

4. Proposed framework

A framework for a reference curriculum in systems engineering at the graduate level was proposed to the INCOSE Academic Council in Jain and Verma (2007). The proposed framework takes into consideration the commonalities and patterns in systems engineering education content as it is taught today. One of the main objectives of proposing a reference curriculum of systems engineering is to try to bridge the gap between the expected systems engineering competencies by the potential employers and the graduate systems engineering program curricula. The framework is proposed to support the development of new graduate programs in systems engineering, and the enhancements to the existing systems engineering graduate programs.
The proposed framework has the following three dimensions:

1. Topical area
2. Level
3. Systems engineering competencies

Figure 4 shows the proposed framework in two dimensions. The proposed framework does not provide guidance on the number and titles of courses that a graduate program should have under each topical area. It assumes that the pedagogy of the courses is specific to each graduate program. Therefore, the pedagogy and graduate-level courses will evolve as the field of systems engineering grows and matures.

5. Conclusions

The systems engineering community realizes that there are many perspectives on the scope and content of a systems engineering curriculum, and there is a need for relative convergence in this regard. The proposed curriculum uses a four-level approach, beginning with a foundation in mathematics and introductory systems engineering courses, and transitioning to core systems engineering courses supplemented with advanced and special courses related to systems engineering.

The recommended framework consists of a baseline of sixteen topical areas in systems engineering and related subjects for universities to consider when developing a graduate-level curriculum in systems engineering.

6. References


Kasser, J. 2006. Reorganizing SE. Presentation to SEEC RG, INCOSE-Australia and SESA-SA chapter meeting.


MIT Curriculum Design. 2003. Committee on curriculum approved CDIO design, Aero/Astro MIT, Fall '05 – Spring '06. Cambridge: Massachusetts Institute of Technology.

