AC 2011-958: DEVELOPING SYSTEMS ENGINEERING GRADUATE PROGRAMS ALIGNED TO THE BODY OF KNOWLEDGE AND CURRICULUM TO ADVANCE SYSTEMS ENGINEERING (BKCASE(TM)) GUIDELINES

Alice F Squires, Stevens Institute of Technology

Alice Squires has nearly 30 years of professional experience and is an industry and research professor in Systems Engineering at Stevens Institute of Technology in the School of Systems and Enterprises. She is a Primary Researcher for the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE) and Systems Engineering Experience Accelerator projects. She has served as a Senior Systems Engineer consultant to Lockheed Martin, IBM, and EDO Ceramics, for Advanced Systems Supportability Engineering Technology and Tools (ASSETT), Inc. Alice previously served as a senior engineering manager for General Dynamics (GD), Lockheed Martin (LM) and as a technical lead for IBM. Alice is a lifetime member of Beta Gamma Sigma (Business), Tau Beta Pi (National Engineering), and Eta Kappa Nu (National Electrical Engineering) Honorary Societies and is an International Council on Systems Engineering (INCOSE) Certified Systems Engineering Professional (CSEP) in both base and Acquisition (CSEP-Acq). She is in the process of completing her doctorate dissertation in "Investigating the Relationship Between Online Pedagogy and Student Perceived Learning of Systems Engineering Competencies" and her research interests include systems engineering competency development, systems thinking and systems engineering education. Alice is the Chair of the Systems Engineering Division of ASEE and has a Masters in Business Administration (MBA) and Bachelors of Science in Electrical Engineering (BSEE). Alice received the Stevens Institute of Technology Provost's Online Teaching Excellence Award in 2007.

David H. Olwell, Naval Postgraduate School

Dr. Olwell is Professor and immediate past chair of the Department of Systems Engineering at the Naval Postgraduate School. He is currently the co-principal investigator (with Dr. Art Pyster of Stevens Institute) on a multi-year, multi-national effort to define the systems engineering body of knowledge and a graduate reference systems engineering curriculum for international use.

Timothy L.J. Ferris, University of South Australia

Dr Tim Ferris is the Associate Director: Teaching and Learning in the Defence and Systems Institute at University of South Australia. He is the lead author of the GRCSE product of the BKCASE project. He has worked in the University for 20 years and taken an active research interest in education in addition to research intersts related to systems engienering and research methods for use in advancing systems engineering.

Nicole A.C. Hutchison
Arthur Pyster, Stevens Institute of Technology

Arthur Pyster is a Distinguished Research Professor in the School of Systems and Enterprises at Stevens Institute of Technology and the Deputy Executive Director of the Systems Engineering Research Center, a Department of Defense University Affiliated Research Center. Before joining Stevens in March 2007, he served as the Senior Vice President and Director of Systems Engineering and Integration for SAIC. Earlier, he served as the Deputy Chief Information Officer for the Federal Aviation Administration and held several other executive, management, and technical roles in systems and software engineering. Dr Pyster is a Fellow of the International Council on Systems Engineering (INCOSE) and sits on their Board of Directors. He has a PhD in computer and information sciences from Ohio State University.

Stephanie Enck, Naval Postgraduate School

Stephanie Enck is a research assistant at the Naval Postgraduate School's Systems Engineering Department. She has a Bachelor of Science in Communication, sales and marketing management experience, and volunteered to assist Army families for several years before joining the SE department at NPS. Her research interests and project coordination efforts include M&S education, project management, and SE education.

Developing Systems Engineering Graduate Programs Aligned to the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE™) Guidelines

Abstract

The Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE™) team, comprised of about 50 systems engineering experts around the world, is in the process of developing two products: a Guide to the Systems Engineering Body of Knowledge (SEBoK), followed by a Graduate Reference Curriculum for Systems Engineering (GRCSE™). Versions 1.0 of the two products are due out by fall 2012, preceded by two annual interim reviews. This paper reviews the knowledge areas and curriculum guidelines addressed in the initial draft versions of these products. A framework for categorizing the alignment of systems engineering programs to GRCSE is presented. Based on their categorization as initial, emerging, developed, or highly developed, programs can design a strategy for further systems engineering curriculum development. The paper ends with a request for reviewers to participate in the upcoming open (public) GRCSE version 0.5 review scheduled to begin year end 2011.

Introduction

There are many strategies that can be used to develop new systems engineering graduate programs. One method is to develop the program within an existing department by combining new curriculum into a base or core set of courses and adding existing courses to address specializations or electives.[1] Often, the focus of newly developed systems engineering curricula is based on industry partnerships and feedback.[2] In some cases a new department may be established to support a graduate systems engineering program; alternatively new programs may be combined with existing departments such as industrial engineering or engineering management; or new programs may have a multidisciplinary focus and be shared across a set of existing engineering departments.[3] The initial success of these programs in attracting a student base may depend on the reputation of the university and other engineering programs within the university and partnerships with companies seeking systems engineering workforce development support. As the program develops, a stand-alone department or in some cases a separate school may be established.[4] At the point where the program has matured, curriculum has typically been developed and faculty hired within the department or school to support course offerings across the entire program; however, adjunct faculty may also be used to address specialty areas or to offer the courses at remote locations or through online delivery.[5]

The length and effort required to transition from one phase to the next in systems engineering graduate program development depends on many factors including:

- the starting foundation of existing curriculum, faculty expertise, university support structure, and other associated resources;
- the support and strength of the relationships with industry and government;
- the level of gap between the desired focus and end state of the mature program and the existing state; and

- the ability of the university to evolve as needed for each phase of systems engineering graduate program development.

The heart of this paper discusses a potential framework for categorizing the alignment of systems engineering graduate programs to the Graduate Reference Curriculum for Systems Engineering (GRCSE™) (still under development). First, background information related to systems engineering graduate programs collected prior to and during the GRCSE effort, is presented. Next, the paper covers SEBoK's set of knowledge areas and topics, and GRCSE's approach for expected student background, graduate outcomes, longer-term objectives and curriculum architecture. In the main section, the paper provides guidance on systems engineering curriculum development, based on a program's categorization as initial, emerging, developed, or highly developed. The paper ends with a request for reviewers to participate in the upcoming open (public) GRCSE version 0.5 review scheduled to begin year end 2011.

Background

The Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE™) team has grown from a small core team of five members to a team of over 50 members. A list of the authors can be found at http://www.bkcase.org/about-bkcase/authors/. About half of the author team are from academia, the other half from industry; and about two thirds of the authors are based in the United States, and the remainder abroad. In general, the authors are from around the world and represent a variety of domains. The BKCASE project is supported by several professional societies including the International Council on Systems Engineering (INCOSE) (3 author representatives) and the Institute of Electrical and Electronics Engineers (IEEE) (3 author representatives) and by funding and sponsorship primarily from the U.S. Department of Defense. Two products, the Systems Engineering Body of Knowledge (SEBoK) and the Graduate Reference Curriculum for Systems Engineers (GRCSE), are being developed to inform systems engineering education and practice. Initial drafts of these products were released in fall 2010 (versions 0.25) for limited review; a second draft is planned for release in fall 2011 (versions 0.5) for open review; and the final version of the products will be released to the public in fall 2012 (versions 1.0). More information about the project can be found from the project's website: www.bkcase.org and from various BKCASE publications.[6-8]

GRCSE's focus is on system-centric systems engineering programs rather than domain-centric systems engineering programs.[17] In anticipation of the development of systems engineering graduate program guidelines, the GRCSE team developed a survey designed to gather data on the state of practice in systems engineering master's programs with regards to: entrance requirements, core or required courses, delivery methods, program length, program outcomes, and other information related to program structure. Many of the programs solicited in the United States (U.S) were part of the list of systems-centric systems engineering programs provided in Fabrycky (2010)[9] and the GRCSE team augmented the list with additional universities outside of the U.S. However, because it was important to gather as much information as possible; each author focused on gathering data from universities where he or she had at least one point of contact. The survey was sent out to sixty-one universities worldwide: thirty-five U.S. programs and twenty-six programs from Europe, Asia, Australia, and South America. The survey was returned from 18 U.S. universities and 14 universities outside of the U.S; however, the names of

respondents have been kept anonymous as part of the agreement between the GRCSE team and the responding universities. The top ten systems-centric graduate program courses identified from the GRCSE survey[10], as compared to results from a previous 2006 study[5], is shown in Table 1.

Table 1. Systems Engineering Graduate Program Comparison

Evolved SE Curriculum Framework Categories[5]	2010 GRCSE Survey Top Ten Courses Identified, plus Capstone (% of Programs)[10]	2006 Study Topic Areas[5] (% of Programs)
Pre-Requisite Courses	Probability and Statistical Analysis (19%)	Linear, Matrix, Differential Equations (22%)
		Probability and Statistics (22%)
Fundamentals	Introduction to Systems Engineering (56%)	Fundamentals of Systems Engineering (62.5%)
	Systems Management (25%)	Introduction to Systems Engineering Management (47%)
System Life Cycle Technical Processes	Modeling and Simulation (53%)	Modeling, Simulation and Optimization (62.5%)
	Systems Architecture and Design (38%)	Systems Design/Architecture (28%)
	Systems Integration (34%)	Systems Integration and Test (31%)
	Systems Requirement Analysis (25%)	-
	Systems Analysis (25%)	-
	-	Software Systems Engineering (28%)
	-	Quality, Safety and Systems Suitability (28%)
	-	Manufacturing, Production, & Operations (9%)
System Life Cycle Project Processes	Risk and Decision Analysis (25%)	Decisions, Risk and Uncertainty (25%)
	Project Management (38%)	General Project Management (19%)
		Finance, Economics, and Cost Estimation (25%)
Other Broad SE Applicable Areas	'-	Organizational Leadership (12.5%)
		Engineering Ethics/Legal Considerations (6%)
Capstone	Project Thesis or Capstone Project (94%)	Masters Project or Seminar (28%)

GRCSE builds on the work summarized in Table 1, and earlier efforts for developing a reference curriculum for systems engineering[5,11-15] completed by current GRCSE authors as well as other members of the systems engineering academic community.

Systems Engineering Knowledge Areas and Topics

The SEBoK builds on earlier efforts for developing an integrated body of knowledge for systems engineering.[16-21] The major groupings for the systems engineering knowledge areas and topics addressed in the initial version 0.25 draft of the SEBoK[22] are:

- Introductory material
- Service/Enterprise SE
- Organization and Management
- System Life Cycle
- Broad Areas

The following sections describe each knowledge area briefly as they are defined in the initial version of the body of knowledge.

Introductory material

The introductory system content of SEBoK version 0.25 addresses the following knowledge areas:

- *Systems Concepts:* provides a foundation for understanding types of systems and topologies and their role and includes a discussion of system-of-interest, system perspectives, and complexity.
- *Systems Thinking:* describes hard and soft systems thinking, paradoxes, models and languages.
- *Systems Engineering Overview:* provides an overview of different perspectives and approaches for SE in the context of products, services, and enterprises.
- *Generic Life Cycle Stages:* provides an overview of the more common systems life cycle models.

Service/Enterprise SE

The three types of systems addressed by the SEBoK are products, services, and enterprises; however, there is still ongoing work to come to a consensus on the definitions of service and enterprise systems. Due to a traditional focus on systems engineering for product development, two chapters of the initial SEBoK version 0.25 were dedicated to service systems engineering and enterprise systems engineering; however, only one chapter was written for this early version and the other chapter is in initial draft stages:

- *Service SE (not yet written):* will address systems engineering concepts and principles specific to the design and creation of service systems.
- *Enterprise SE:* provides insights into the engineering of enterprise systems and defines key considerations unique to enterprise systems.

Organization and Management

Organizational factors and systems engineering management are also covered in dedicated chapters of SEBoK version 0.25:

- *Enabling Systems Engineering in the Organization:* addresses the incorporation of systems engineering activities within an organization including effective governance, staffing, and resource allocation approaches.
- *Systems Engineering Management:* focuses on the administration and oversight of SE activities and provides insights on managing the technical aspects of SE.

System Life Cycle

System life cycle processes typically discussed in handbooks and standards such as the INCOSE Handbook and the ISO/IEC/IEEE 15288:2008(E) standard are covered across five chapters of the SEBoK version 0.25 with specific life cycle stages grouped by topics as listed:

- *System Definition:* provides insight into the early stages of the systems life cycle, including needs and requirements analysis and architecture development. Stages covered are: stakeholder requirements and mission analysis, system requirements, architectural design, and system analysis.
- *System Realization:* focuses on the actual construction of the system, including testing to confirm appropriate functionality and use. Stages covered are: implementation, system integration, system verification, and system validation.
- *System Deployment and Use:* addresses the utilization of the system once it is "complete" and includes insights on how a system can be sustained over time. Stages covered are: operations, maintenance, and logistics.
- *System Life Management:* focuses on the continuation of the system life, including changing and adding functionality to a system in operation, and retiring a system. Stages covered are: service life extension, capability updates, upgrades and modernization, and system disposal and retirement.
- *Systems Engineering Agreement:* provides insight on the contractual aspects of SE. Stages covered are: acquisition and supplier Processes.

Broad Areas

The final chapters of the SEBoK version 0.25 cover broader areas of systems engineering including specialty areas, systems engineering competency, and application case studies:

- *Cross-Cutting:* provides a foundation for non-functional characteristics (the "-ilities") of systems engineering discussed throughout the SEBoK including: integration of specialty

engineering, affordability/design to cost, human system integration, safety, security, spectrum management, electro-magnetic interference, radiation hardness, reliability and maintainability, manufacturing and production, quality, logistics/supportability, occupational health/work environment, disposal and resilience.
- *Systems Engineering Competency:* addresses systems engineering competencies at the individual, team, and organization level.
- *SE Applications/Case Studies:* defines the method and criteria for accepting case studies for a companion guide that will provide domain-dependent examples for the SEBoK.

Systems Engineering Graduate Reference Curriculum Guidelines

The systems engineering graduate reference curriculum areas addressed in the initial version 0.25 draft of the GRCSE[10] include:

- Expected Student Background
- Outcomes
- Objectives
- Curriculum Architecture
- Assessment

The following sections describe the areas and categories for each area, and provide some examples of the material presented in the initial draft.

Expected Student Background

GRCSE assumes that students entering the graduate systems engineering program will have a wide variety of backgrounds, yet recommends the entering student meets certain criteria in order to start directly into the program. The suggestion is that students who do not meet these criteria may complete preparatory material to offset gaps in education or experience. The recommended background covers:

- the equivalent of certain types of undergraduate degrees (for example: engineering, the natural sciences, mathematics, or computer science)
- a certain level of practical experience in some aspect of systems engineering (for example: two years, includes general and domain specific), and
- demonstration of the ability to effectively communicate technical information (for example: in the program's language of instruction).

Please note: Of the universities that responded to the GRCSE survey, 44% did not require work experience as an entrance requirement for the systems engineering graduate program, 16% adhered to company sponsor requirements for work experience, and the remaining 40% required, on average, 3 years of work experience.[5] In addition, 28% of the universities stated that they required GRE exams.[5]

Outcomes

Outcomes are statements about the competencies possessed by a graduate upon completion of the program (graduation) and are ideally derived from objectives (next section). GRCSE outcomes cover the following categories:

- Outcomes related to achievement of specified Bloom's levels in specified knowledge area topics (for example: achieving Bloom's 'application' level in oral and written communication).
- Outcomes related to demonstration and application of systems engineering to an application area within a domain (for example: agility within the medical industry).
- Outcomes related to broad professional skills (for example: being an effective member of a multi-disciplinary team)
- Outcomes related to skills needed across the systems engineering life cycle (for example: ability to reconcile conflicting requirements)
- Outcomes related to the relationship of systems engineering and other disciplines (for example: software engineering)
- Outcomes related to professional ethics (for example: ethics in systems engineering practice)

Objectives

Objectives are important statements about the future professional activities of the graduates of a program. In GRCSE, the objectives are intended to cover about three to five years after graduation and concern:

- Level of ability in areas of systems engineering practice and types of systems (products, services and enterprises)
- Professionalism and continuing development
- Societal contributions through ethical and responsible behavior
- Effective communications using new modes and media
- Level of success in a variety of roles within multi-disciplinary teams
- Effective leadership in projects that span the systems life cycle

Curriculum Architecture

The recommended graduate systems engineering curriculum architecture covers five areas of knowledge and a capstone experience:

- Preparatory Knowledge – Missing knowledge needed to cover any gaps in education or experience of the incoming student (see Expected Student Background).
- Core Foundation Knowledge – The core knowledge that all systems engineering students should learn.
- Core Extension Knowledge – Knowledge in a specific focus area; the student chooses at least one focus area to learn.

- Domain-Specific Knowledge – Knowledge in a domain that is outside of and in addition to the core foundation and extension knowledge that the student chooses from to learn.
- Program-Specific Knowledge – Knowledge based on program or institution focus and/or expertise that the student chooses from to learn.
- Capstone Experience – Each program expects students to demonstrate their accumulated skills and knowledge in a mandatory capstone experience. The capstone can be implemented through a variety of methods, including individual or team capstone projects, a practicum, or a master's thesis.

The core foundation and core extension material is intended to constitute about half the coursework for the degree, leaving the remaining portion of the program for domain-specific, program-specific and capstone work.

Assessment

GRCSE covers assessment approaches for program outcomes and objectives. These assessments form the basis for a continuous improvement process for the curriculum. Assessments can either indirect or direct measures of student achievement; direct measures are preferred.

SE Graduate Program Alignment with GRCSE

A program that adopts or chooses to align with GRCSE will go through several phases. These phases reflect the maturity of the program, from the initial planning through to a mature program. Existing programs will align to GRCSE in varying degree. To aid universities in determining the degree of alignment, assessment rubrics are provided in Table 2. The assessment categories can also be used to provide a basis for program improvement. For example, a program can use the categories initial, emerging, developed, and highly developed, as a basis to develop a strategy for systems engineering curriculum development. Examples of how this can be done are discussed in the next four sections.

Initial

In the initial phase, the university does not have a systems engineering graduate program and is looking to establish one, or their current program does not align with GRCSE. The university can apply GRCSE to provide a framework and reference as it begins its program planning. In particular, the objectives and outcomes in GRCSE provide an excellent starting point for discussion with program stakeholders about the desired emphases of the program. The core body of knowledge identified from the SEBoK provides a starting point for the identification of course objectives and topics, and can be used to create a checklist to assure that important topics are not omitted from the portfolio of developed courses. Based on the domain and program emphases that the university chooses, the university can develop a profile of their faculty requirements as a guide to faculty hiring and development.

Table 2. Systems Engineering Program Development Phases Mapped to GRCSE

	Initial	Emerging	Developed	Highly Developed
Expected Student Background	Meets none of the GRCSE expectations.	Requires a technical undergraduate degree or two years of experience.	Most students meet the expected GRCSE background.	All students meet the expected GRCSE background.
Objectives	Objectives are not established or do not align with GRCSE.	Objectives have been established and address level of ability in systems engineering practice.	Objectives address most of the GRCSE objectives.	Program objectives have been shaped by program stakeholders and address all GRCSE objectives.
Outcomes	Program outcomes are not established or do not align with GRCSE.	Outcomes address the core body of knowledge.	Outcomes address most of the GRCSE outcomes.	Program outcomes address all GRCSE outcomes.
Preparatory Knowledge	The program admits students without preparatory knowledge and are not remediated.	The program provides students with opportunities to master some of the preparatory knowledge.	The program provides students opportunities to master all of the preparatory knowledge.	The program requires students to demonstrate mastery of all preparatory knowledge before proceeding in the program.
Core Foundation Knowledge*	The program does not address the GRCSE knowledge area.	The program addresses portions of the knowledge area according to the GRCSE recommendations.	Each knowledge area is fully addressed according to the GRCSE recommendations.	The program requires students to demonstrate mastery at the appropriate Bloom's level for each knowledge area. Each knowledge area is fully addressed according to the GRCSE recommendations.
Core Extension Knowledge*				
Domain-Specific Knowledge*				
Program-Specific Knowledge*				
Capstone Experience	The program does not offer a capstone experience.	The program offers, but does not require, a capstone experience.	The program requires a capstone experience.	The program requires students to demonstrate their accumulated skills and knowledge in a capstone experience.
Program Assessment	The program does not have a formal assessment plan.	The program has an assessment plan.	The program has an assessment process that includes evidence of resulting program improvement.	The program has a comprehensive assessment process that includes direct measures and evidence of resulting program improvement.

*Mapping description should be separately applied to each knowledge area.

Emerging

In this phase of development, the university can leverage GRCSE and SEBoK for self-assessment and evaluation of their existing program. This evaluation would identify gaps in the program including the absence of program outcomes and objectives and missing topics in the knowledge areas. The evaluation can also support updating student entrance requirements; identifying new core extension, domain specific and program specific knowledge, and additional considerations for the capstone experience; and developing an assessment plan to verify the program plan when implemented. The results from the evaluation can be used to update the course portfolio checklist to assure that important topics are not omitted in the program and that required faculty and expertise are on path to be hired or developed.

Developed

In this phase, the program is already addressing a significant portion, if not all, of the core foundation topics identified in GRCSE and defined in more detail in the SEBoK as part of their curriculum, and offers multiple core extension focus areas. The developed program has formalized, assessed and validated outcomes and has a baseline set of intended objectives and has developed domain and program specific knowledge to support its objectives and outcomes. In this phase, industry is often directly involved in most capstone experiences provided to the student.

In the developed phase of development, the university may already be involved in the GRCSE and/or SEBoK efforts, as part of the author or review teams, and would use the guides as affirmation of the direction being taken. The university could use the guides to identify improvement areas and from this the university could develop new topics, or provide additional depth in some areas to meet more advanced levels of Bloom's taxonomy level of mastery. The university could develop an action plan that included suggestions to revise entrance requirements, outcomes, objectives and curriculum; and identified areas for revamping the program plan to take the program to the next level.

Highly Developed

In the highly developed phase, the systems engineering program fully aligns with GRCSE. The university has objectives and outcomes established that align well with the GRCSE recommendations. The curriculum architecture has two or more extension areas, and completely covers the core foundation and core extension portions of the core body of knowledge recommended in GRCSE and expanded upon in the SEBoK. The domain and program specific material in the program is based on stakeholder input and meets stakeholder needs. Industry directly supports and is involved as feasible in the capstone experience; and the experience provides evidence that students have met the program outcomes. Students enter the program with an appropriate and strong background and the program has an effective system of continuous improvement in place.

As a highly developed program, the university is most likely driving portions of the GRCSE development. The university would use GRCSE to monitor that it continues to meet the

expectations of the community. The highly developed university program would evolve as GRCSE and the SEBoK evolve. Both guides would be used as a benchmark for the program's already high performing assessment system.

Future Plans

Version 0.25 for the SEBoK and GRCSE were released in 2010. Both products are still undergoing an annual revision and review in 2011 (version 0.5) and 2012 (version 1.0). Once the final products are released in 2012, it is the vision of the core team and authors that the relevant professional societies will jointly assume the stewardship and maintenance of the SEBoK and GRCSE. However, one core tenet of the project is that these products would remain freely available (at no charge for viewing) to the public. The team believes that both products are living documents that require future revisions to accommodate changes in systems engineering in response to changes in the environment and demands placed upon practitioners. For this reason, any approach to developing a graduate systems engineering program should include a strategy for updating curriculum.

Conclusion

This paper provides a brief overview of the systems engineering related knowledge areas and graduate level reference curriculum introduced in the initial draft versions of SEBoK and GRCSE. The intent of these guides is to serve as authoritative sources for systems engineering knowledge. In addition, GRCSE provides a framework for understanding and communicating about systems engineering graduate programs and their curriculum. A common framework will aid potential students and employers in understanding and selecting from the various areas of focus of graduate degrees offered in systems engineering. The paper describes approaches for aligning systems engineering graduate programs to GRCSE based on initial, emerging, developed and highly developed phases of development. The SEBoK and GRCSE are currently under development and the community is asked to participate in the open public reviews that will take place in the latter part of 2011 for version 0.5 of each product (see www.bkcase.org). Input from the community will help guide the final delivery of these products as well as ensure buy-in from the community on the validity and use of these products.

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