INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

THE SYSTEM DESIGN AND OPERATIONAL EFFECTIVENESS (SDOE) PROGRAM: EXPERIENCES AND LESSONS LEARNED

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Abstract

The SDOE program at Stevens Institute of Technologies was created to address the graduate level education requirements of integrators and users of complex, multi-functional, knowledge intensive, and distributed systems. The motivation behind the program, its objectives and rationale, and its programmatic structure and delivery modes were presented in [8]. The objective of the program is to inculcate and nurture skills associated with abstract problem solving to address design synthesis and the quantitative modeling, simulation, and optimization techniques for design analysis and evaluation. A key aspect of the program is the use of project-based and case-based learning to facilitate understanding of the overarching "cause and effect" dependency between system design and system operations/support, with a view to enhancing System Operational Effectiveness (SOE). The SOE concept was developed and explained in [8]. This technical paper presents adaptations made to the program structure and the curriculum over the past two years, along with a sample course outline and student evaluations. Specific lessons learned are also discussed.

Key Words: Design Education, Systems Engineering Education, Life Long Learning, Experiential Learning.

1. Introduction

With the increasing complexity of systems, evolving requirements, a growing focus on affordability and profitability, and ever more challenging customer expectations and competitive pressures, premier organizations are more and more assuming the role of system integrators. These organizations are adopting an evolving business model -- selling and sustaining a function, a capability or a solution, rather than just selling systems, system components or products. The trend is not limited to commercial industry. The United States Department of Defense has initiated "Performance Based Contracting" [9, 10], a key tenet of which is contracting for a capability or functionality, rather than for a system or product.

The system integration team is responsible for managing functional, physical, and operational baselines beyond the deployment phase, into and throughout the system operational and support phases. While this often requires the procurement of system elements (hardware and software) from vendors, suppliers and partners, the system integrator assumes overall ownership of the program and the system risk (performance, schedule, and cost) associated with integrating the elements into a comprehensive system that delivers the required capability. This is reflected in Figure 1. It results in an increased emphasis on the subsequent phases of the system life-cycle, since the integrator is responsible for sustaining the capability in an affordable fashion.

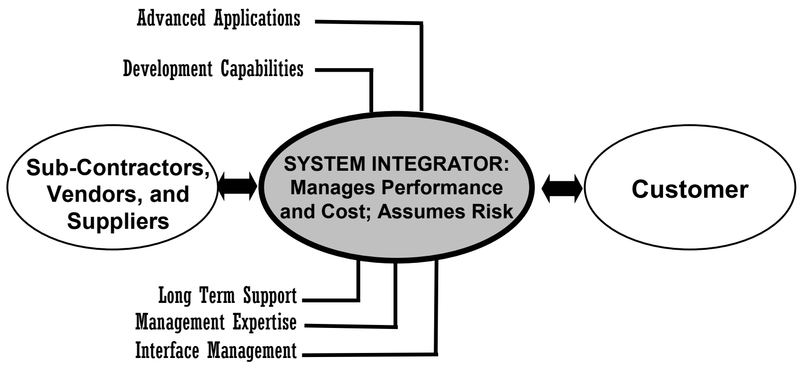


Figure 1. Role of a Systems Integrator.

Systems engineering and integration for the entire life-cycle requires discipline and a long-term perspective during design and architecture development. This includes explicit focus on system reliability, maintainability and supportability so that operations, maintenance, and logistics requirements are comprehensively addressed in the design. The integrator must deal with the realities of changing requirements and customer expectations, evolving technologies, and developing standards and regulations. Capturing the cause and effect relationship between system design decisions and system operations and support costs is critical to achieving the affordability goals of the customer and the profitability goals of the system integrator.

System Operational Effectiveness (SOE) reflects the holistic objective of systems engineering and integration: achieving the best balance between system performance, availability, process efficiency (operational, maintenance, and support processes), and total system ownership costs. SOE is depicted in Figure 2. In this regard:

SOE = f (System Performance, System Availability, Process Efficiency, Life-Cycle Cost)

Numerous tradeoffs between system performance, availability, and process efficiency are required to maximize system operational effectiveness. Maximizing operational effectiveness requires proper attention and balance among all the factors included in the SOE model. For example, disproportionate allocation of resources and attention to system performance can lead to an imbalance in process efficiency, logistics or training, as well as unaffordable cost of ownership. On a complex project, there are a multitude of stakeholders, stakeholder priorities and associated trade-offs that must be addressed by the systems engineering and integration team.

As systems become more information and knowledge intensive, increasing commercial-off-the-shelf (COTS) components are increasingly being used in the compute infrastructure. This introduces risks and challenges associated with end-of-life and obsolescence issues. System physical and operational baselines are likely to change with increasing frequency, over and above any changes necessitated by changing customer requirements and changing system functionality and capability. A technology refreshment strategy is required to address these risks [11, 12]. Operational and maintenance training programs for complex systems must also address the flux to sustain required levels of system operational effectiveness.

While many market leaders are evolving toward the model of systems integration, there are few academic programs in the United States geared to the development and nurturing of domain-independent systems engineering design skills and competencies. This issue has been highlighted in a number of publications in the literature [1, 2, 3, 4, 5]. As an illustration, a recent comparison of systems engineering programs in the United States identified only 23 departments offering "systems engineering" degrees [6]. According to the authors, systems engineering education has four primary threads:

- Systems analysis and design,
- Industrial engineering,
- Traditional control systems, and
- An eclectic mix of control systems and other topics.

The study argues that, in their current state, the majority of U.S. programs are traditional industrial engineering programs, with only seven focused on systems analysis and design. Even fewer programs address systems engineering and design from the longer-term perspective of system operation, maintenance and support, as captured in the SOE concept. This was the rationale behind the formulation of the curriculum for the SDOE Program.

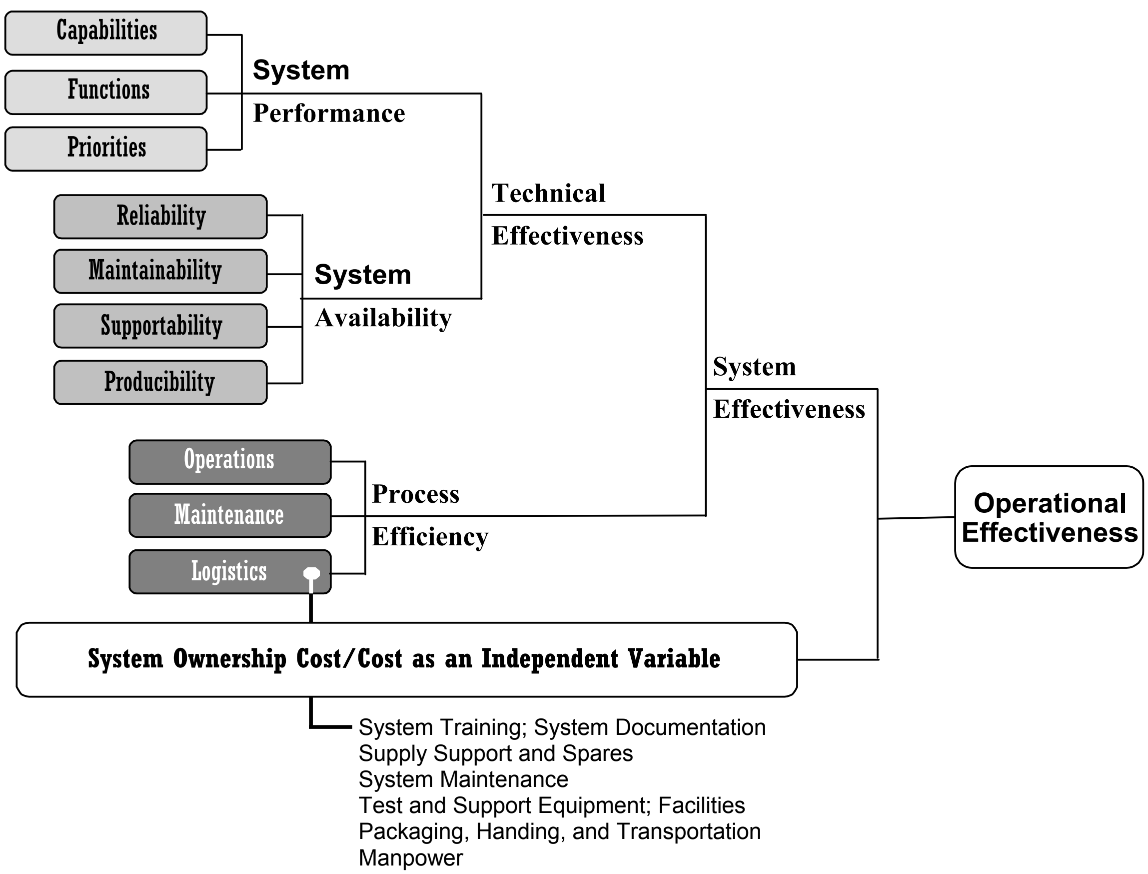


Figure 2. System Operational Effectiveness (SOE). (Adapted from [8])

2. Specific skills and competencies

In order to formulate the systems engineering curriculum for the SDOE Program, numerous sessions were conducted to assess and evaluate the education and training requirements of potential sponsors. These included developers and integrators of complex systems, as well as buyers and users of such systems, in the commercial and defense sectors of the United States, Europe (primarily the Nordic countries), and Asia (primarily the Indian Sub-Continent). The input gleaned from the sessions was consolidated into six functional competencies, as defined and described in Table 1.

Subsequent to the needs assessment, the curriculum and program structure were formulated and launched in April 2001. The programmatic structure has since been refined and adapted in response to feedback from graduate students and sponsoring organizations. The adaptations and refinements are described in the following section.

Table 1. Description of Systems Engineering and Integration Competencies.

Competency	Description	Associated Courses
Business Processes and Operational Assessment	• Support clients and stakeholders in the identification of business and operational shortfalls – Elicit, gather, and confirm business and mission requirements and processes • Translate shortfalls into solution and system requirements • Identify and manage functional and operational baselines • Identify and assess what is achievable within schedule and cost constraints • Address both functional and non-functional requirements	SYS-625: System Operational Effectiveness and Life-Cycle Analysis – Fundamentals of Systems Engineering
System/ Solution/Test Architecture	• Identify preferred implementation approach • Develop solution and test architecture – Adhere to open architecture guidelines to ensure scalability, modularity, and future upgrades and enhancements – Adhere to consistency with system management and OMI (operator-machine interfaces) – Adhere to consistent solution testing, validation, and verification approach • Determine and manage the impact on currently fielded solutions	SYS-650: System Architecture and Design

Table 1. Description of Systems Engineering and Integration Competencies (continued).

Competency	Description	Related Courses
Life-Cycle Cost and Cost-Benefit Analysis	• Integrate life-cycle costing and cost-benefit analysis into the systems engineering process a. Architecture and implementation trade space must be constrained by cost • Understand the system cost drivers • Focus on total ownership costs, not just development and deployment cost	SYS-620: Simulation-Based System Life-Cycle Costing

Serviceability and Logistics	• System supply support and spares management
	  – Increase commonality across subsystems and platforms
	  – Coordinate system upgrades, scaling, and technology refreshment
	• System operational and servicing skill requirements
	  – Incorporate the end user into the definition of the human-computer interface
	  – Rapid prototyping and use of standard display formats
	• System and platform documentation
	• System training requirements
		SYS-645: Design for System Reliability, Maintainability and Supportability
		
		SYS-640: System Supportability and Logistics

Modeling, Simulation, and Decision Analysis	• System performance modeling and forecasting • System architecture modeling and analysis • System risk and decision analysis • System user interface analysis	SYS-611: System Modeling and Simulation SYS-660: Decision and Risk Analysis
Management: Risk, Configuration and Subcontractors and Suppliers	• Supplier, vendor, and subcontractor management • System configuration management • Risk management • Technology and obsolescence management • Commercial hardware/software evolution • Evolving standards, technology projections, and monitoring	SYS-612: Project Management

3. Program and structure updates

The SDOE program has been structured to satisfy varying levels of graduate and continuing education requirements for the developers/integrators and users/operators of complex systems. The program offers a number of formal and focused intensive short courses on relevent themes (e.g., COTS-Intensive Open Systems Architectures). Short courses can be combined to generate a variety of graduate certificate programs, a master's degree program, and even a doctoral program. The primary focus is the master's degree.

The Master's Degree requires 30 credits, 12 of which are from required core courses. Of the other 18 elective credits, up to 6 may be satisfied by a thesis or project. Unless otherwise stated, each semester course is equivalent to 3 credits. The core courses are:

- SYS-625: Fundamentals of Systems Engineering
- SYS-650: System Architecture and Design

plus, two of the following three:

- SYS-612: Project Management
- SYS-611: Modeling and Simulation
- SYS-660: Decision and Risk Analysis

The decision and risk analysis course was added to satisfy the needs of mature professionals whom a project management course is unnecessary. Candidates have the option of selecting additional courses from a number of electives to specialize and focus on a particular aspect of system design and system operational effectiveness.

A candidate seeking to specialize in system design and architecture can structure a program of study that emphasizes abstract problem solving, needs assessment and requirements analysis; concept definition and development; system architecture definition and development; modeling and simulation; and organizational theory. Focusing on customer needs and design requirements is an important aspect of the educational experience that is reinforced through hands-on exercises. The criticality of this focus is also identified in [7].

A student wishing to specialize in supportability engineering and logistics can structure a program of study to focus on supportability in the context of design, modeling and prediction; practices and tools to influence design for supportability; optimization of system logistics and the support infrastructure; and the dependency between system reliability, maintainability, and supportability. Yet another example of specialization could be a program in system and project management.

To round out the educational program, a candidate can elect to undertake a thesis or project (up to a maximum of 6 credits) that addresses a research question or problem of interest. Students can create a specialization that meets their professional needs through the judicious selection of electives and the formulation of a relevant capstone project, in concert with a faculty advisor.

A number of specific graduate certificate options have been developed in the last two years and are currently offered to participating students. These are:

- A graduate certificate in Systems Engineering
- A graduate certificate in Value Chain Enterprise Systems
- A graduate certificate in Systems and Supportability Engineering, developed in collaboration with SOLE -- The International Society of Logistics

In each case, a graduate certificate requires 12 credits (four graduate courses) and is a stepping-stone toward a Master's Degree in Systems Engineering.

4. Modular course format for dual delivery modes

SDOE courses have been structured to provide flexibility for working professionals. The courses are offered in one of two delivery formats:

- One-week classroom delivery
- Entirely web-based delivery.

Formats are designed to minimize a student's time away from "home base." Group exercises help students develop teamwork, leadership and real-time negotiation and tradeoff skills in a realistic project environment. Students are given reading assignments prior to the beginning of a one-week course and they complete an extensive homework assignment over the ten weeks following the course.

Although the core courses were originally offered only in the weeklong, live format, they are being modularized for transition to web-based delivery through the sponsorship of the IBM Corporation (specifically, IBM Global Services). The course outline for SYS-625: Fundamentals of Systems Engineering, along with its modularization, is reflected in Table 2.

Table 2. Modularization of Core Courses for Transition into a Web-Based Course.

Course Outline for SYS-625: Fundamentals of Systems Engineering	Corresponding Modules for Web-Based Implementation
Business drivers for systems engineering and system integration	Module 1: Business Drivers for Systems Engineering; Formation of Project Teams
Overview of system engineering process; Systems engineering terms and definitions; Systems thinking and systems engineering concepts and principles; Systems engineering process models (waterfall/spiral/vee/ evolutionary); Introduction to the concept of system operational effectiveness (SOE), and the root cause analysis between system design and system support; Structure of a problem solving process; Concept of system design reviews or gates; System Requirements Review (SRR); Preliminary Design Review (PDR); Critical Design Review (CDR); SEA metrics	Module 2: Overview of the Systems Engineering Process; Project Launch
Need/deficiency/opportunity identification; Needs analysis; Different kinds of system and program stakeholders; Priorities and values	Module 3: Identifying Stakeholders and Stakeholder Requirements
Development of system concepts; Pugh's concept generation and selection methodology; Concept selection matrix	Module 4: Generating, Evaluating, and Selecting Concepts
Understanding of system context; Articulation of system scope and boundary; Understanding and articulating expected system behavior; Development of external system interfaces	Module 5: System Scope, Context Diagrams, and Use Case Scenarios

Table 2. Modularization of Core Courses for Transition into a Web-Based Course (continued).

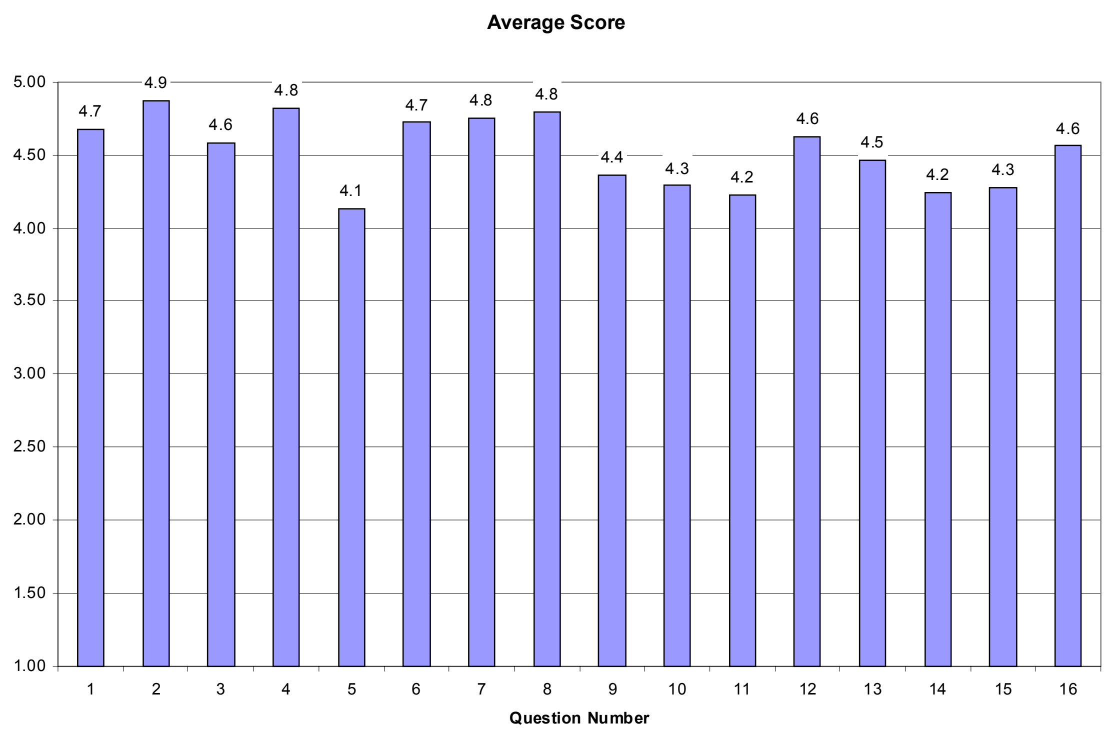
Course Outline for SYS-625: Fundamentals of Systems Engineering	Corresponding Modules for Web-Based Implementation
Differentiating between stakeholder requirements and system/solution requirements; QFD; Development of system objectives – goal and threshold values; Non-functional requirements	Module 6: From Stakeholder Requirements to System Objectives
Development of a complete set of system requirements; Classification of system requirements; Writing good requirements; Requirements management; Validation and verification of system requirements	Module 7: Completing the System Requirements
Using an SE tool to do requirements management and traceability	Module 8: Using a Requirements Management Tool (CORE)
Development of a system logical architecture; Development and identification of internal interfaces; Use of various architecture development templates	Module 9: Developing the Functional Architecture
Using an SE tool to do system functional modeling; Introduction to various system modeling languages – pros and cons of various system functional languages	Module 10: Using a Functional Modeling Tool (CORE)
Understanding the opportunities for influencing system requirements and the system logical architecture with regard to system reliability, maintainability, and supportability; A brief introduction to methods and practices for "Design for System Reliability, Maintainability, and Supportability"	Module 11: Fundamentals of Life-Cycle Analysis
Identification of system performance and programs risks – technical, cost, and schedule	Module 12: Risk Management
System Requirements Review (SRR); Group project presentations and course review	Module 13: System Requirements Review

5. Student feedback and lessons learned

Weeklong courses have been taught approximately 40 times in the last 2 years, both in the United States and at a number of locations in Europe and Asia. SYS-625: Fundamentals of Systems Engineering has been presented in Scandinavia as the Scandinavian Summer School in August every year for the past 4 years (1999 – Utö, Sweden; 2000 – Bolkesjö, Norway; 2001 – Aavaranta, Finland; 2002 – Utö, Sweden). The Fifth Scandinavian Summer School is scheduled for 2003 at a location near Bergen, Norway.

A global orientation is introduced into the instructional material through the selection of case studies that highlight issues and sensitivities that are important when working on projects and designs involving team members or customers from multiple countries and cultures. Participants have consistently praised the relevance of the course material and the real world examples used to illustrate concepts. They also cite the applications orientation of the instruction and the use of case studies and project-based learning as the strong points.

Figure 3 presents the composite evaluation of the ten weeklong sections of SYS-625: Fundamentals of Systems Engineering offered in 2002. Not only are the average scores very high, ranging from 4.1 to 4.9 out of a possible 5.0, but scores on the final question, "OVERALL – This was an Excellent Course," increased from 4.5 to 4.7 during the year as a result of specific changes made in response to student feedback. Clearly, the program has been very well received and is meeting a genuine need.



Instructor evaluation:

9. Explains the objectives of the course clearly
10. Is prepared for class
11. Presents material in an organized manner
12. Has command of the subject
13. The guest lecturers were effective
14. Successfully communicates the subject
15. Is fair and consistent
16. **OVERALL – The course was effectively communicated**

Course evaluation:

9. The course is well structured
10. The course material (notes and books) is well organized
11. The material was adequately covered in the allotted time
12. The course was structured to facilitate discussion and participant contribution
13. The subject matter has significant usefulness to my organization
14. I can apply what I learned in this course on projects in my organization
15. The course will enable me to enhance my career objectives
16. **OVERALL – This was an Excellent Course**

Figure 3. SYS 625 Course Evaluations from 2002.

6. Summary and Conclusions

Over the past four years, the SDOE Program has grown from little more than a concept for systems engineering education to address the system life-cycle, into a vibrant program that has found broad support across a wide range of market domains and geographical regions. The program has been enthusiastically embraced by students and sponsors in the defense, aerospace, information technology, and telecommunications industries in the United States, Scandinavia, and the Indian sub-continent. It fills a gap in traditional engineering programs by integrating the full spectrum of operational and support issues into the system design process, addressing user needs not only for a desired functional capability but for producibility, reliability, supportability, and maintainability in pursuit of high system availability and cost-effective life-cycle support.

The program provides educational formats geared to the needs of practicing professionals, both one-week short-courses for concentrated study and fully asynchronous online courses that enable students to participate on their own time, without the need for travel to a central location or extended time away from their jobs. Both formats make extensive use of project-based learning that gives students an opportunity to apply what they learn as they do so. This feature of the program has consistently been identified by students as one of its most valuable aspects.

Ongoing evaluation of the program takes place in three ways. Student evaluations at the conclusion of each module provide immediate feedback on their perceptions of the learning experience, identify elements of the program that worked particularly well, and are an ongoing source of suggestions for improvement, many of which have been implemented. Second, student presentations of their projects at the conclusion of each module allow instructors to see how well the concepts of a course have been understood and applied in near real time. Course content and structure are continually refined in response to these observations and the quality of the student presentations has steadily improved as a result of changes that have been made. Finally, many students in the program are sponsored by their organizations and the testimony of these sponsors provides strong evidence of the relevance of the material in the program and its effectiveness in improving students' contributions on-the-job. Several sponsors have become true partners, working with the program to tailor its content to meet the needs of their internal processes and providing case studies that have been integrated into the instructional material. Particularly rewarding have been a number of instances in which SDOE material has found its way into a sponsor's own presentations and processes, as has occurred with both government and industry partners.

The SDOE Program clearly meets the needs of both individual students and government and industry organizations for continuing education in systems engineering to address to evolving role of the system integrator. We expect demand for the program, and for other similarly based programs, to continue to grow as that role further develops.

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