Systems Engineering at the Undergraduate Level: Boom or Bust?

Sonja Streuber, Valparaiso University

Valparaiso, IN 46383

sonja.streuber@valpo.edu

Abstract

Starting from stark differences in degree-level distributions between Systems Engineering and Mechanical Engineering as a traditional engineering discipline, this paper looks at the needs and drivers of undergraduate education in Systems Engineering. By investigating how the Concept of Operations for a Systems Engineering Education Community (SEEC) proposed by INCOSE's Education Management Working Group in 2004 applies to three different types of undergraduate curricula currently in use, the paper concludes that Systems Engineering education must go beyond even the widest academic context and reach into the professional competency development lifecycle of each Practitioner of Systems Engineering (PSE) in order to preserve the integrity of the discipline.

1. Introduction

Systems Engineers, with their broad skillsets, are one of the highest-paid engineering groups today, as *Money Magazine* acknowledged in 2009[1] and 2010[2], and the 2010 survey shows that its subgroups such as Software Architects, Risk Management Managers, etc., enjoy similar popularity and marketability. And yet, given its relatively short history as an academic discipline, Systems Engineering education is still, to some, a strange beast. Nestled somewhere between "hardcore" engineering disciplines that build bridges or design high-efficiency, and business management, the discipline of Systems Engineering may, depending on the eye of the beholder, look, at best, "high-level" or "holistic," and at worst "amorphous" or "not mature enough yet." And it's true: If we believe the latest ASEE data, Systems Engineering is still the somewhat strange hippie kid that may not quite fit the paradigm of the "real" engineering disciplines and their programmatic distributions.

While the ASEE Data Mining Tool [3] lists 81 graduate programs under the search term "Systems Engineering" currently conferring MS degrees, and 39 PhDs, it only lists 56 active undergraduate programs in the same discipline. In contrast, ASEE lists 310 4-year undergraduate programs in Mechanical Engineering, 245 MS programs, and 163 doctoral programs. The interesting aspect here is not the difference in size between the two disciplines, but the relative degree-level distribution:

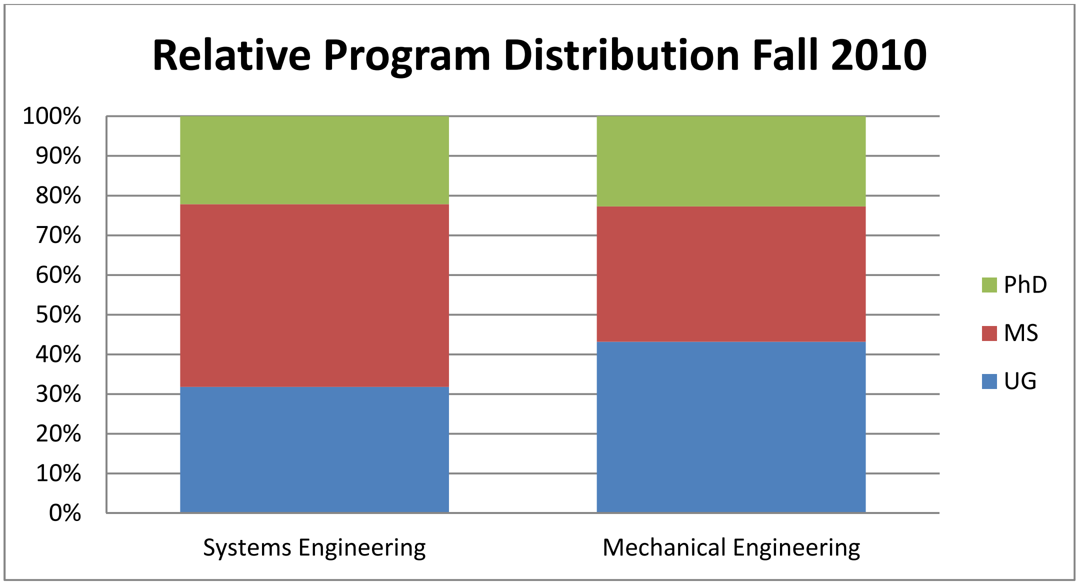

Figure 1: Relative Program/ Degree Distribution

As Figure 1 shows, on a relative scale, Systems Engineering appears top-heavy, with 69% of degree programs being offered at the graduate level, compared to only 58% of Mechanical Engineering graduate programs.

Enrollment numbers speak for themselves, too: As of Fall 2010, all Systems Engineering PhD programs combined contain 1238 students, all MS programs contain 4469 students, and all relevant undergraduate programs taken together serve 5566 full- and part-time students. In Mechanical Engineering, however, ASEE data show that the 310 4-year undergraduate programs serve 111,988 students, the 245 MS programs serve 14,599 students, and the 163 doctoral programs serve 9,487 students. While nobody will argue with the absolute enrollment data, again, normalized data show an interesting disparity:

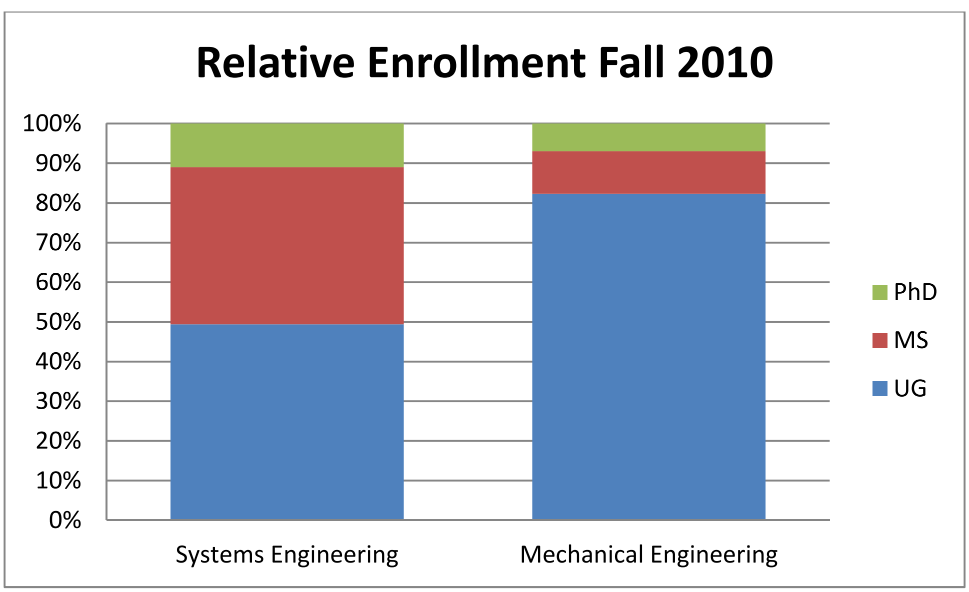

Figure 2: Relative Enrollment

Figure 2 shows that little over 50% of all Systems Engineering students are graduate students—compared to about 19% of all Mechanical Engineering students. Abstracting from Mechanical Engineering to the totality of traditional engineering disciplines, we can conclude that their student body clearly consists of mostly undergraduates.

Of course, these numbers raise more questions than they answer. While we can assume that a graduate student in, say, Mechanical Engineering was most likely also an undergraduate student in Mechanical Engineering, admissions criteria to most Systems Engineering graduate programs allow a larger pool of engineering and non-engineering disciplines, provided that any missing undergraduate prerequisites can be backfilled.[4] So, what do these numbers tell us? Obviously, first, that there must be a bigger employment market for bachelors-degree-holders in the traditional engineering disciplines (an argument hard to contend). Second, we know how to teach, and bound, the traditional engineering disciplines—we have a long history of curricula and a well-defined knowledge body; we have the prerequisites figured out; we have a firm stand from which to wage interdisciplinarity with other engineering disciplines and even disciplines outside of engineering. Third, we know what good traditional engineers need in order to succeed professionally; once employed and aided by some company-specific process training, engineering graduates usually hit the ground running.

But do we really know what education good Systems Engineers need? And do we know what makes a “good” Systems Engineer?

2. ConOps of a Systems Engineering Education Community

In their “Concept of Operations of a Systems Engineering Education Community,” a document published in 2004, INCOSE’s Education Measurement Working Group (EMWG) states that traditional academic institutions do, but only to a limited extent.[5] Here is why:

> “a) SE education needs are broader and more urgent than can be satisfied by academic institutions alone; b) significant improvement in the cost effectiveness of systems engineering education is necessary and the improvements must be made quickly, which is feasible if the systems engineering education community (SEEC) is systemized, and c) rating systems that focus on the value a customer [*i.e. an employer—author’s note*] may receive … are more meaningful than are the ‘capability maturity’ class of rating systems that are more concerned with supplier process than with actual value delivered to the customer …”[5]

In other words, the group calls for an integrated system of utility-driven knowledge delivery subsystems that provide flexible or on-demand learning opportunities to accompany the Practitioner of Systems Engineering (PSE) throughout multiple Systems lifecycles (and obviously her or his career lifecycle):

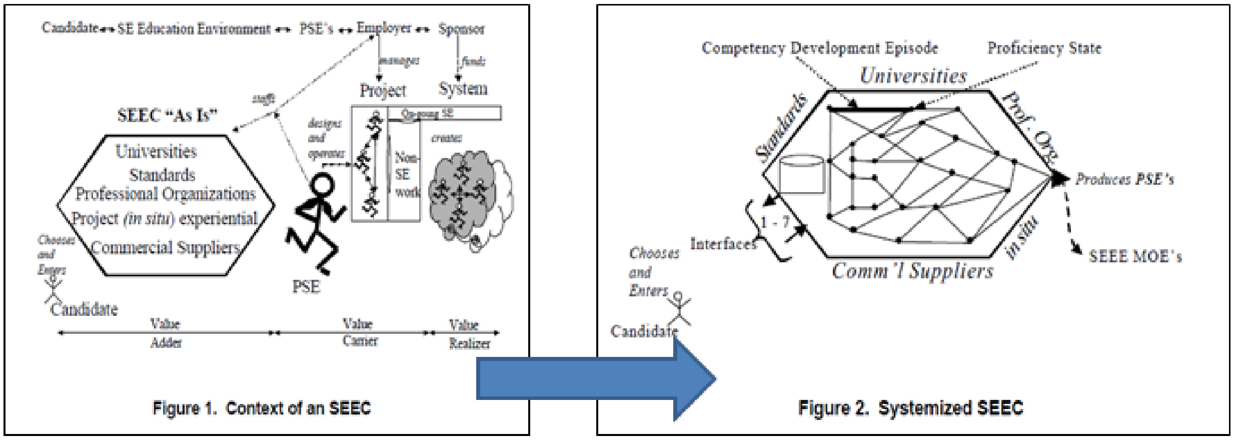

Figure 1. Context of an SEEC

Figure 2. Systemized SEEC

Figure 3: SEEC from "As Is" to "To Be" [5]

In the "As Is" portion of Figure 3, the five types of knowledge providers (universities and academic centers, commercial learning environments, relevant standards bodies, professional organizations, and on-the-job-training situations) inside the SEEC hexagon produce the PSE's competency baseline and thus add value to the Systems Engineering "System," to be realized by both, the PSE's employer, through successfully completed projects (i.e. budget/ schedule/ quality constraints) and through knowledge generation and advancements within the System itself. But the status quo graphic is missing two important elements: 1. The feedback loop from the employer to the SEEC, to ensure that the real-world practice and the demands of the System itself inform, and contribute to, continuous improvement of its knowledge baseline, and 2. The data exchanges, or internal interfaces, among the SEEC components themselves. With these omissions, INCOSE's EMWG indicates the lack of a concerted effort to systematize and streamline Systems Engineering education vertically, across various learning environments, and horizontally, across the Systems Engineering value chain—even though, as the group admits, students will cycle through the SEEC multiple times, either on the "real plane," through academic retraining, new internships, stretch assignments, and the like, or the "reflection plane," in which practitioners create new knowledge within a practice context, thereby mitigating at least partially the proverbial ivory-tower dilemma. [6] The "To-Be" portion of Figure 3, then, shows that the EMWG's suggested goal is for an SEEC to guide the PSE through a network of successfully completed "competency development episodes," universities, standards bodies, professional organizations, commercial education suppliers, and in situ training, interact in order to advance various proficiency states, produce PSE's, and, in the long run, generate, and continuously improve upon, Measures of Excellence (MOEs).

The basis for these Measures of Excellence within the "To-Be" state result, the EMWG outlines, from an understanding of Systems Engineering as "not a bounded, and perhaps not boundable, activity" but as "qualified people applying a body of knowledge to problem situations in order to produce a solution in the form of a problem suppression system model." [5] In other words, the EMWG understands Systems Engineers as professional problem solvers who build solutions architectures from sets of technical and technological options that increase exponentially each day. That latter point introduces the second success driver: "Change proficiency," or the ability to think agile. On a personal level, this means fast responsiveness and superior teamwork skills; on a practical level, this means sharp solution-space vigilance and the competencies to design and architect systems for constant change and scalability; on a professional level, this means superior forecasting skills to proactively adapt processes, procedures, behaviors, and the entire body of knowledge as needed. [5] These success criteria, specifically the emphasis on agility, go beyond what a structurally and culturally established semester- or even quarter-based academic environment can offer, which is why the EMWG insists that “the broader span of subject matter that a PSE must master as compared to discipline engineers, marketing, sales or other functional specialists” requires synergistic systematization of variegated learning resources across a curriculum that may include the “engineering” part of Systems Engineering in the form of a college degree, but also training in soft skills and, for lack of a better term, professional intuition to create PSEs who can create systems "better, faster, cheaper.” [5]

Given this hard, albeit by now 8-year-old judgment, and its comprehensive expectations for a trans-academic educational community, is academic preparation as it now occurs across the 56 undergraduate programs in Systems Engineering, doomed to fail Systems Engineering as both, a discipline and a professional practice? How can we establish curriculum within a practical discipline that, apparently, is still trying to define its own boundaries, and that, second, relies on soft skills as much as hard ones? How does an idea of “curriculum” either advance, or to throttle, the call for life-long learning in an integrated educational system? A look at three currently active approaches to these questions may help answer these questions.

3. Three Case Studies

The webpage of the Department of Systems Engineering at University of Arkansas Little Rock introduces the discipline thus: “Systems engineering can be broadly defined as the relational, people-oriented engineering profession that brings together all the fields of engineering into a fascinating, big picture perspective. … Systems Engineers, besides acquiring specialized skills in an Engineering discipline, also acquire the ability to lead a team of engineers with diverse skills and to coordinate and manage the design of large and complex systems.” [7] Framed by a 16-professionals-strong industrial advisory council that spans both, corporate and government contexts, the undergraduate major consists of three layers: A “Systems Engineering” core of 32 credits, an equal number of credits in a chosen engineering field (Computer Engineering, Telecom Engineering, Mechanical Engineering, or Electrical Engineering), and a 6-credit capstone project. Add to that 29 hours of communication, humanities, social science and business courses, and 30 hours of science and mathematics.[8] Interestingly, though, per the 2011/ 2012 undergraduate catalog, the required “Systems Engineering” core courses consist of: C/C++ Programming, Circuits and Systems, Computational Engineering Laboratory, Circuits and Systems Laboratory, Optimization Methods in Systems Engineering, Probability Theory and Random Variables, Discrete Event Systems Modeling and Simulation, Decision and Risk Analysis, Introduction to Systems Engineering, and Systems Engineering Design and Analysis. One course in Economics and one in Management are also required. [9] The catalog shows the following graphic:

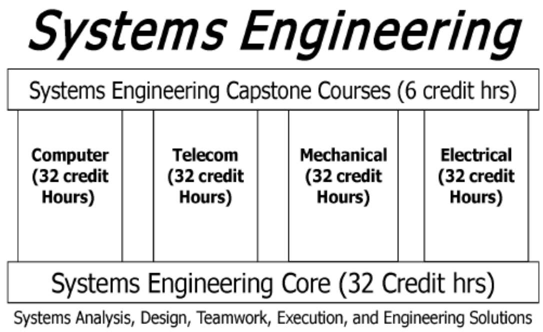

Figure 4: Bachelor of Science in Systems Engineering curriculum, University of Arkansas Little Rock.[9]

Thusly rooting the curriculum in the traditional engineering disciplines, and superimposing a core, which, to 30% also consists of traditional engineering courses, even if applied in cross-disciplinary fashion, implies a perception of Systems Engineering as management overhead to the "hard" disciplines. This understanding becomes especially obvious when the catalog suggests that students specializing in the ME and EE options take the Fundamentals of Engineering Examination in their senior year, and when the "Resources" tab on the department's website links to Software, Laboratories & Equipment, and IEEE, but not to INCOSE or SEI (however, the department does sponsor an INCOSE student chapter). Older versions of the path-to-degree flowchart and catalog excerpts show that the curriculum has remained mostly stable since 2005.

In contrast, Georgia Tech's School of Industrial and Systems Engineering, currently the nation's highest-ranked program, approaches the problem of Systems Engineering from a different angle: It describes Systems Engineering in the context of both, Industrial Engineering and Operations Research, two of its sister or—depending on the theoretical model—child disciplines

> "Industrial engineering (IE), operations research (OR), and systems engineering (SE) are fields of study intended for individuals who are interested in analyzing and formulating abstract models of complex systems with the intention of improving system performance. Unlike traditional disciplines in engineering and the mathematical sciences, the fields address the role of the human decision-maker as key contributor to the inherent complexity of systems and primary benefactor of the analyses. … At the undergraduate level, many find the fields' characteristic flexibility appealing. Not only does our BSIE curriculum provide the technical expertise that one would certainly expect in an engineering major, but it also provides excellent preparation to function in a great breadth of professional settings such as manufacturing, logistics, economic and financial modeling, transportation, consulting, etc." [10]

Consequently, rather than using some of the traditional engineering disciplines as focus areas, the following five tracks available to undergraduate students are as of March 2010: Economic & Financial Systems, Operations Research, Quality & Statistics, Supply Chain Engineering, and General Industrial Engineering. [11] In the Operations Research track, for example, the curriculum consists of courses in optimization, simulation, and stochastics, and three more courses from any of the three other specific tracks (such as logistics, economic decision analysis, and the like). Suggested electives are in subjects like game theory, biomedical networks, and genome theory. The program is capped with a senior design project requiring students to design a solution for a problem funneled to the program directly by the industrial or non-profit community via an official, formalized submissions process. Along with this actual connection to industrial practice (and the concomitant professional opportunity), the program also includes a mentoring facet that pairs students with mentors from industry or NPOs.

So far, we have seen how two curricula respond to the challenge of Systems Engineering education within a traditional, semester-bound context, and do so in two different ways—one by rooting SE education in the traditional disciplines, the other one by modelling the classic Systems framework advanced by Eisner and, later, Kossiakoff et al. [12] [13] The third model here is not a traditional academic knowledge provider *per se*, but rather, a joint venture between NASA's Exploration Systems Mission Directorate, the Texas Space Grant Consortium, and the University of Texas at Austin: The Space Systems Engineering Website. [14] The systems engineering materials on this website were developed by by Lisa Guerra, formerly of NASA Headquarters’ Exploration Systems Mission Directorate and piloted in the Department of Aerospace Engineering at UT Austin,[15] with the intent of morphing what started out as a 3-credit-hour prerequisite to the senior design course into a transferable curriculum that would feed the demands of aerospace engineering practice back into the undergraduate and eventually graduate, SE classroom. The materials featured on this website consist of 27 systems engineering lecture modules, accompanying example assignments and exams, reference documents and handbooks from NASA and other government sources, experiential video lectures by PSEs at Jet Propulsion Labs, presentations from NASA's Systems Engineering Workshop (2008) and more. Thus, rather than deductively teaching SE knowledge from SE theory, the materials take an inductive approach and are based on “systems engineering handbooks and primers from NASA and the Department of Defense organizations, … material from professional training courses offered at NASA and through organizations such as Project Performance International, … [and] the NASA experience base and documents to provide examples for systems engineering topics. In particular the James Webb Space Telescope project and the Constellation program are used as sources for example documentation on topics such as requirements, technology development, and project life cycle.” [14] The website states that this course was included in UT Austin’s Department of Aerospace Engineering ABET audit in 2010 and seems to be now part of course 374k. Space Systems Engineering Design.

Similar to the training available from the Defense Acquisition University (DAU), this project appears not only scalable horizontally and vertically in that it invites qualified visitors to contribute information and discussion points (although does not provide any means of input other than a webmaster email address), but also flexible in that it understands the knowledge it provides as modular to allow instructors at other institutions to resequence and reuse the materials in class as desired. In upcoming course revisions, the author considers expanding the presented materials to include software systems engineering, human factors, design for supportability and maintainability, and six-sigma quality methodology. [14] The applied nature of this course has, according to Dr. Wallace Fowler of UT Austin’s Aerospace Engineering Department, had a rather positive impact in the quality of students’ designs in that “[s]tudents are more realistic and realize what the real-world stakes are, looking at cost and some of the political realities of things as well as the engineering side of things.” [15] While it seems that any new material to this website is being reviewed by a faculty member from the aerospace engineering department of the University of Colorado-Boulder and other degreed and credentialed members of the Systems Engineering community, no clear indication of a site revision target exists, and website update and maintenance information is not immediately available.

How do these so obviously different programs fare in the context of INCOSE’s three MOEs for an integrated SEEC: Problem-solving capability on the basis of a “body of knowledge,” change proficiency, and on-demand availability of learning opportunities? While the more conservative program at University of Arkansas is clearly defined by engineering discipline track, Georgia Tech matrixes Systems Engineering knowledge onto management tracks and allows for a more loosely organized curriculum that will most likely be adjusted by students based on the needed skills profile for the industry-provided senior design project. These academically more or less formal curricula stand in contrast to the NASA website, with its experience- driven, on-demand modules. In terms of the EMWG’s first MOE—the capability to engage problem-solving skills based on a body of knowledge—graduates from programs such as Arkansas’s will still be more likely to engage a traditional engineering body of knowledge, whereas graduates from curricula like Georgia Tech’s are likely to implement a body of knowledge more in line with current INCOSE standards (which raises the question why Georgia Tech’s website seems not to address CSEP certification). “Graduates,” to use the term loosely, from the NASA/ UT Austin training will, on the other hand, bring a more practice-based “real-world” approach to the table, and be ready to revisit any missing theoretical basics when needed. While the quality of problem-solving skills depends, in the first two cases, largely on the delivery and assessment methods, but is measurable, the third case provides a quality gate only when the modules are being used in a curricular context, or when the envisioned self-study includes completion of the included assignments and exams. While a longitudinal study on the impact of SE undergraduate degree content on PSE proficiency (i.e. “customer confidence” in the entire Systems cycle) after, say, 1, 5, and 10 years, would be helpful in reaching a conclusion, anecdotal evidence supports the Georgia Tech and NASA/ UT Austin approaches. Considering flexibility (the second MOE) of content composition and delivery, the NASA/ UT Austin website with its strictly modular on-demand approach takes the cake within a self-selected student pool; if used as a resource in an academic course or curriculum, the degree of flexibility depends, naturally, on the surrounding curricular constraints. Georgia Tech’s solution of choice within a bounded pool of knowledge seems particularly intriguing here, especially since it promotes thinking across various facets of Systems Engineering practice, such that the method of composing a rather individualized body of knowledge really becomes an expression of one of the ideational tenets of Systems Engineering education itself.

The third MOE, however—integration of various learning methods and content delivery systems to achieve on-demand knowledge updates—presents not insignificant challenges. While, naturally, any credible engineering program will encourage or even require the use of internships and membership in professional societies to address different learning needs, styles, and modalities, invite guest speakers from industry, and arrange tours, etc., opening a curriculum to steady innovation and modification guided by industry needs is, in most academic settings, neither practical nor feasible. Lastly, collaborations with external knowledge providers, including commercial ones, to fill the disciplinary lacunae left open by academic contexts are still rare—where they do exist, as in the case of Georgia Tech’s senior design projects and mentoring arrangements, however, these beginning interchanges among members of a broader SEEC may, if we return to the EMWG’s To-Be schema, result in enhanced PSE qualifications:

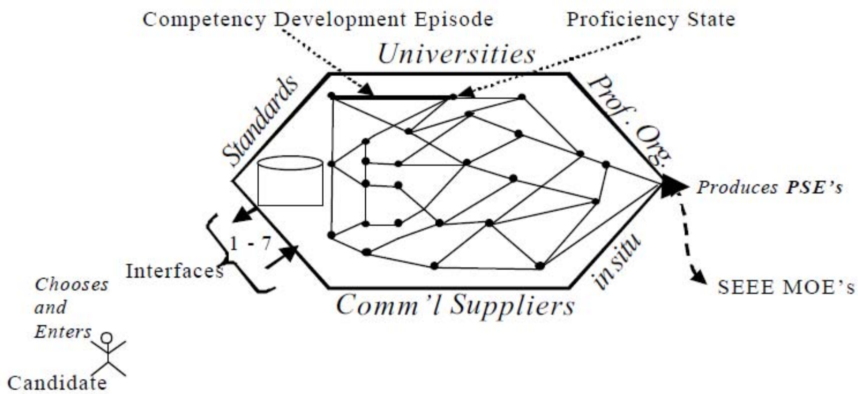

Figure 2. Systemized SEEC

Figure 5: To-Be SEEC [5]

Results with the NASA/ UT Austin model should be similar, especially since the "competency development episodes" are accessible on-demand (and for free), so that cycling through the materials even outside an academic setting is possible—which addresses EMWG's ultimate challenge to the SEEC: Making high-quality learning opportunities available independent from any geographical or situational constraints. If this author had her way, the optimal path to the To-Be State would lie either in the combination of all three models referenced above, or in a cross-section of these, combining both, a solid theoretical background with the problem-solving agility, and the realistic innovation-oriented thinking that only immediate professional experience can foster. What, then, do academic undergraduate programs in SE need to do in order to create "competency development episodes" that adequately identify, and address, this sweet spot?

4. Conclusion

If we consult any of the major resources currently framing SE as a practice discipline (I am consciously avoiding the static notion of "canon" here), we realize that what may have sounded like a copout earlier, namely the EMWG's assertion that SE is, above all, an activity, rather than a boundable discipline, still rings true, as confirmed very recently by Kossiakoff et al. in their attempts to differentiate Systems Engineering from the traditional engineering disciplines. [13]

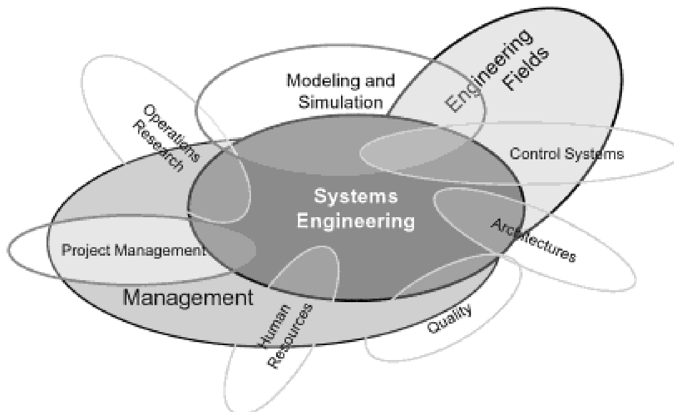

Figure 2.5. Examples of systems engineering fields.

Figure 6: System Engineering Fields, Kossiakoff [13]

If being a successful PSE often really means decision-making based on qualitative data, political judgments, and external constraints, and if the required knowledge to do so must bridge the traditional engineering disciplines in that PSEs interface and integrate their outputs and then add another engineering layer, such as Information Systems Security, Knowledge Management, Process Optimization, and so forth, then 8 or 10 semesters may simply not suffice to address the breadth of the discipline, especially while allowing SEEC-external customer needs to drive continuous improvement loops. [16] A few different models are imaginable:

1. Treat an undergraduate degree in Systems Engineering similar to an engineering certification and require periodic recertification based on a number of professional development units, to be completed with INCOSE-certified learning episode providers.
2. Treat an undergraduate degree in Systems Engineering like a medical degree or a PE certification and require a number of years of professional expertise to confer the actual degree.
3. Integrate CSEP certification preparation into the undergraduate curriculum to implement an external recertification loop.
4. Offer undergraduate degrees solely on a part-time basis to employees who already practice Systems Engineering.
5. Make an undergraduate degree in Systems Engineering non-terminal and require more semesters of study plus applied professional experience, then confer a graduate degree.

While the first two potential solutions aim to solidify academia's part of the SEEC "pie," and the third and fourth implement an external education interface in the EMWG's design of the To-Be SEEC, the last point already hints at a good reason behind the degree distribution numbers shown at the beginning of this paper. Because of its highly volatile practice content, Systems Engineering as a discipline goes beyond the model of a traditional 4-year degree and must thus exist in a community in which academia can step in with alternative, multivariate competency development episodes that directly derive from business needs, either in the form of modules derived directly from industrial practice, or in the form of alliances with other knowledge delivery partners that have already established such a feedback loop. At the same time, the structure of the curriculum will have to reflect the agile "nature of the beast," which either requires curriculum as a network of choices within a loosely bounded, and ever-changing pool of course offerings, or frequent curriculum revisions, perhaps even as often as once per semester.

References

[1] Best Jobs in America.” *Money Magazine.* 2009.
http://money.cnn.com/magazines/moneymag/bestjobs/2009/snapshots/1.html
[2] Best Jobs in America.” *Money Magazine.* 2010.
http://money.cnn.com/magazines/moneymag/bestjobs/2010/snapshots/49.html
[3] All numeric data in this paper taken from ASEE Data Mining Tool at http://www.asee.org/datamining
[4] See, for example, admissions criteria to MS program in Systems Engineering at Johns Hopkins University http://ep.jhu.edu/advising/systems-engineering#admissions
[5] Education Measurement Working Group, International Council on Systems Engineering (INCOSE). 2004. *Concept of Operations (ConOps) of a Systems Engineering Education Community (SEEC)*. Seattle, WA.
[6] This status quo leads the EMWG to conclude that “[a]lthough academic centers are striving to create more realistic learning environments [Axelband et al], [Frey, et al], [Kurstedt et al], [Lang, et al], we believe that structural and cultural limits in academia will preclude universities and related laboratories from being sufficiently responsive.”
[7] “Chair’s Message.” Department of Systems Engineering website. University of Arkansas, Little Rock. http://ualr.edu/systemsengineering/about/chairs-message/. Last accessed 01/20/2012.
[8] “Degree Program.” Department of Systems Engineering website. University of Arkansas, Little Rock. http://ualr.edu/systemsengineering/programs/undergraduate/degree-program/. Last accessed 01/20/2012.
[9] “Systems Engineering Curriculum Overview.” Department of Systems Engineering website. University of Arkansas, Little Rock. http://ualr.edu/academics/uploads/2008/06/SYEN.pdf Last accessed 01/20/2012.
[10] “What We Do.” H. Milton Stewart School of Industrial and Systems Engineering. Georgia Institute of Technology. http://www.isye.gatech.edu/about/what-we-do/ Last accessed 01/20/2012.
[11] Chen Zhou, Ph.D., “BSIE TRACK ADJUSTMENT,” March 2010, H. Milton Stewart School of Industrial and Systems Engineering. Georgia Institute of Technology.
http://www.isye.gatech.edu/academics/undergraduate/courses/NewISyE2010Tracks.pdf Last accessed 01/20/2012.
[12] Howard Eisner*, Essentials of Project and Systems Engineering Management*. 2nd ed. . Hoboken, NJ.: Wiley & Sons, 2002.
[13] Alexander Kossiakoff, William N. Sweet, Sam Seymour, Steven M. Biemer, *Systems Engineering Principles And Practice*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2011.
[14] Space Systems Engineering Website. http://spacese.spacegrant.org/ Last accessed 01/28/2012.
[15] Tara Haelle, “Bringing it All Together: Alumna Lisa Guerra Designs New Systems Engineering Course.” Aerospace Engineering and Engineering Mechanics.
http://www.ae.utexas.edu/newsArchive/2011/LisaGuerraDesignsNewSystemsEngineeringCourse.html . 01/27/2012.
[16] The new alliance between INCOSE and the Project Management Institute (PMI) of late 2011, for example, and the persistent emphasis on “better, faster, cheaper,” certainly shows a shift towards management and architecture competencies as efforts during the past two decades at process optimization are slowly approaching diminishing returns, highlighting the need for increased quality in requirements identification, gathering, and validation/ verification, mastery of various architecture methods, and in project management.

Sonja Streuber, “Systems Engineering at the Undergraduate Level: Boom or Bust?” ………………… 12