Systems Engineering Education and the Role of Analytics, Modeling, and Simulation

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Introduction

The University first introduced its Master of Science degree in Systems Engineering (MSSE) in 2004. It was not and is not software systems engineering but multi-disciplinary systems engineering emphasizing the whole system. The principal engineering disciplines involved in this field are system dependent but often include electrical, mechanical, optical, aerospace, computer, and software engineering. Students entering the program should have a bachelor's of science degree in one of the disciplines above, though software engineering graduates may need additional preparation in mathematics. This program is unique in its extensive use of modeling and simulation.

The MSSE was subsequently extended to the online modality and later taught out for that modality while continuing to thrive at the main campus. It will be re-introduced for online in 2016. This program is rooted in mathematics and is substantially hands-on, making much use of simulation and analysis tools. In this article we describe its initial rationale and curriculum, our discovery about student retention and our response, improvements to reflect updates to industry-academic curriculum recommendations subsequently published by IEEE Computer Society, INCOSE (International Council on Systems Engineering), and others as well as improvements to better address faculty and student inputs such as a richer treatment of Bayesian, and future plans to embrace industry advisory board inputs such as treatment of Big Data Analytics.

In the Beginning

Boeing approached us in 2002 with the observation that the US defense and aerospace industry would be experiencing a large number of retirements of systems engineers in the very near future and that Academia needed to step up to the challenge and provide the education needed by their replacements. Conversations were held then with representatives of Lockheed Martin, Northrop Grumman, Honeywell, and other such companies and with the membership of INCOSE to confirm the need and to begin to develop the requirements. We determined that the best way to address this need was to develop and introduce at the master's degree level, expecting that entering students would have engineering bachelor's degrees with the appropriate disciplines and would have industry experience.

We were subsequently able to validate the curriculum with input from engineering management at commercial corporations involved in the development and operation of complex systems requiring both high-level and detailed treatment of multiple engineering disciplines, most notably KLA-Tencor and Rudolph Technologies.

There were very few universities offering systems engineering at that time, but notable in the field were University of Southern California, University of Missouri at Rolla (now Missouri University of Science and Technology), Air Force Institute of Technology, Naval Postgraduate School, and the military service academies. The curriculum was designed after reviewing those programs for best practices and text book recommendations. We gave considerable weight to the evolving body of knowledge being

encapsulated by INCOSE in their *Guide to the Systems Engineering Body of Knowledge* (SEBoK, 2015), itself inspired by the work of the Project Management Institute (PMI).

The MSSE was stood up at the main campus in 2004 with the following course list:

- SE600 Systems Engineering I
- SE610 Systems Engineering II
- SE620 System Dynamics, Modeling and Simulation
- SE630 Systems Acquisition Processes and Standards
- SCM620 Design and Production Considerations
- MGMT600 Applied Managerial Decision-Making
- PM610 Project Planning, Execution and Closure
- PM620 Schedule and Cost Control Techniques
- Plus three electives chosen from CS/CE/IT/EE 600 level courses

The four SE6xx courses were also stood up at that time, the rest being established courses in project management and supply chain disciplines at the school.

Due to its wide use in systems engineering in industry and academia, MATLAB was chosen as the standard in analysis and simulation. The following text books were selected for the SE6xx courses and are cited at the end of this article, though with their latest editions:

- *Systems Engineering and Analysis* for SE600 and SE610 (Blanchard & Fabrycky, 2010)
- *Discrete-Event Systems Simulation* for SE620 (Banks, Carson, Nelson & Nicol, 2009)
- *The Engineering Design of Systems: Models and Methods* for SE630 (Buede & Wilson, 2016)

In addition, readings were assigned as well from the many journal and online sources which were rich in retrospective analyses of the development of complex systems, post-mortems if you will. A notable archive was in place at the Air Force Institute of Technology.

Shake-down Cruise

After a couple of terms, the program was extended to our satellite campus as well. The experience was satisfying enough for the first few Honeywell employees that we began to teach a section on their site. That lasted two terms before Honeywell decided to take a variation of it in-house. The program has been running at both the main and the satellite campuses ever since its introduction.

We decided it should be offered in the online modality to online students and stood that up in 2009. It ramped up quickly to a population of about 35 and plateaued there.

At about that time we had discovered two problems that were driving a retention problem. First, we had committed to a rigorous modeling and simulation regime. It put a heavy demand on the SE620 course for which many of the students were not adequately prepared. In that course, students were required to use MATLAB (or suitable tool of their choosing) to achieve both discrete-event and continuous-time simulations of systems. Some of these involved numerical integrations of differential

equations describing such systems. We considered this a very important part of the program that we were not going to sacrifice.

The second problem was that some of the students were from software engineering rather than from one of the more traditional hardware-intensive disciplines which meant that they usually did not have the math and physics background required to be successful in the program as defined. This is understandable in that the computer science and software engineering disciplines recognize a systems engineering sub-discipline that is not consistent with our broader view of the field.

To address the first problem, we designed SE612 Quantitative Analysis for Systems and made it a pre-requisite for SE620. This provided a more relaxed experience wherein the students learned or reviewed linear algebra, probability and statistics, differential equations, and Laplace and Fourier transforms while using MATLAB for modeling and simulation. The application of all that then occurred in SE620, which followed.

The result was impressive. Prior to the introduction of SE612, the failure rate for SE620 was nine percent over the period Q1 2010 through Q1 of 2012. SE612 was first taught in Q1 2012 and was immediately made a prerequisite to SE620. Then from Q2 2012 through Q2 2015, the SE620 failure rate was zero. In addition, it became possible to raise the bar somewhat in SE620 because the preparation was substantially better.

Addressing the second problem was more difficult in that it required a better explanation in our catalog and promotional material as well as re-training and on-going training for the admissions and advising functions of the organization. Our broad definition of systems engineering needed to be clear enough in the face of a competing popular impression. We then had and still have something for the software systems engineer in the MS Computer Science with a concentration in Software Engineering. Thus we went about revising our catalog and promotional material and educating our admissions and advising teams. This continues to be a challenge.

Meanwhile, the MSSE was not sustainable for online. While its population was steady at about 35, that is not a sustainable level for the online modality business model. No doubt the problems cited above were impactful and the solutions not yet identified and in place. We discontinued new enrollments for the online modality. The program continued at the campuses, and the changes were made.

More Improvements

We pick up here in 2015 with the emphasis now on the campus program. The 2012 publications of both the *Guide to the Systems Engineering Body of Knowledge* (SEBoK, 2015) and the *Graduate Reference Curriculum for Systems Engineering* (Pyster, et al., 2012) provided the opportunity to fine-tune our curriculum which we did. We had provided representation to IEEE Computer Society which in turn provided that representation to both of these efforts in publication. Our changes included a greater emphasis on commercial best practices, especially on the infusion of a more comprehensive modeling and simulation footprint and in the insertion of Bayesian technique in both probability and statistics and management decision making in the presence of uncertainty.

First, consider the commercial best practices. Certainly, we understand how important systems engineering is to the US Department of Defense (DoD) systems acquisition process. Making formal the requirements and interfaces involved in the acquisition of complex systems that may or may not involve the risk of invention and which may be composed of sub-systems that come from different sources under different contracts is essential for that environment. We recognize that DoD and other Federal agencies and their contractors and subcontractors face a more demanding systems engineering challenge than developers of other kinds of systems. Thus we recognize that they lead the way in many processes as is recognized in our SE630 course. However, systems engineering is practiced in the commercial world as well. Consider the challenge of semiconductor manufacturing capital equipment manufacturers such as KLA-Tencor and Rudolph Technologies. Each makes many products for this market, and both make semiconductor wafer inspection systems. Such systems are comprised of many subsystems developed and supplied by their suppliers and of their own making. On top of that, these companies must develop firmware, software, optical subsystems, etc.; the algorithms to support all that; and then integrate a product for a very rapidly changing set of requirements over time. Further, they must have revision control, supply chain management, and support in the field. When something goes wrong at the customer site, it often becomes necessary to duplicate the problem back at the engineering site or on the production line or with the supplier of the subsystem. A discipline of systems engineering that formalizes requirements allocation and interfaces is essential there, too. We noted the use of MATLAB and other tools in simulating phenomena to compare with observations as part of a rigorous fault isolation methodology that was well established. Changes were made to all of the courses SE6xx in response.

Second, Bayesian methods have enjoyed periods of high and low acceptance over the centuries since their first use by the Reverend Thomas Bayes and development and refinement by Pierre Laplace (McGrayne, 2011). They are poorly understood and thus often neglected in standard probability and statistics. Simply stated, Bayesian allows that the probability of an occurrence of an event in the presence of uncertainty should be modified in the presence of new information that clarifies some of that uncertainty. The process of improving upon the estimate of that probability has been formalized. We simply provide that formalization in our program and have the students understand and use it in multiple contexts. It is especially useful in decision making situations.

Going Forward

We plan to re-introduce the MSSE for online in 2016 based on the improvements made to the campus programs. In a recent meeting of our industry advisory council, we asked them to suggest future directions. High on the list was data analysis. This is consistent with the emergence of Big Data Analytics as a discipline usually associated with computer science and/or business and management. Big Data is the term often used to describe how transformative it is and has been in this age of information to have access to both the massive amounts of data and the computation and storage necessary to process it to inform decisions (Mayer-Schonberger & Cukier, 2013). Our board said that systems engineering needs to make more use of data to make better decisions. We have a concentration in our Doctor of Computer Science degree called Big Data Analytics. Thus we have some experience in education in the field and in the use therein of Hadoop, Spark, R, Python, and other tools

relevant to that. We plan to develop a course suitable for inclusion in our MSSE that provides the background and practice necessary to address this need.

The University has conducted surveys during the last several years with local key industry members to evaluate our SE program. Members of this advisory board have consistently rated modeling and simulation as a very important analytical skill with some rating it as high as essential. This is especially true when traditional control techniques based on models developed from experiments may no longer be viable. For example, current sensors generating large data such as images, ultrasonic data, and vibrational data may not have fundamental models or relationships with the theory of the domain space. This in turn may require the use of more hybrid models where one needs to combine theoretical calculations with empirical data. The hybrid approach may involve similar or be a modified large-scale version of the Kalman filter or other approaches using probabilistic methods. The modeling, simulation and control of large-scale systems involving large data will provide further research opportunities. In fact, other disciplines such as large-scale systems theory may need to be applied to address the management of large data when it comes to real-time control of complex systems.

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