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Applying a Competency-Based Education Approach for Designing a Unique Interdisciplinary Graduate Program: A Case Study for a Systems Engineering Program

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Dr. Amy Thompson joined UConn in August 2017 as an Associate Professor-In-Residence of Systems Engineering and as the Associate Director for the Institute for Advanced Systems Engineering at the University of Connecticut. She currently teaches graduate-level engineering courses in model-based systems engineering and systems engineering fundamentals, and coordinates the online graduate programs in Advanced Systems Engineering for the UConn IASE. Prior to joining UConn, she received her B.S. in Industrial Engineering, M.S. in Manufacturing Engineering, and Ph.D. in Industrial and Systems from the University of Rhode Island. Prior to entering graduate school, she worked in industry as a manufacturing engineer, process engineer, and production maintenance supervisor, and led efforts to develop and scale-up new production facilities and production lines. Her current research portfolio includes the application of model-based systems engineering for the design and optimization of complex systems, model-based fault detection and diagnostics (FDD) for HVAC-R systems; design of smart manufacturing systems, facilities, and buildings; supply chain design; and undergraduate, graduate, and online systems engineering education development and assessment. In 2018, she started the SmartBuildings CT program at UConn with funding from Eversource and the United Illuminating Company. She is part of the leadership team at the University of Connecticut that leads the newly awarded US Department of Energy's Southern New England Industrial Assessment Center and that offers no-charge energy audits to 20 manufacturing facilities in CT each year to help them lower their energy usage and costs. Dr. Thompson was the recipient of the US EPA Environment Merit Award, Region 1 (2017).

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Dr. Song Han received the B.S. degree in computer science from Nanjing University, Nanjing, China, in 2003, the M.Phil. degree in computer science from the City University of Hong Kong, Hong Kong, in 2006, and the Ph.D. degree in computer science from the University of Texas, Austin, TX, USA, in 2012. He is currently an Associate Professor and Castleman Term Professor in Engineering Innovation in the Department of Computer Science and Engineering, University of Connecticut, Storrs, CT, USA. His research interests include cyber–physical systems, real-time and embedded systems, and wireless networks. He is an Associate Editor of the ACM Transactions on Cyber-Physical Systems.

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Dr. Qian Yang is an Assistant Professor with the Computer Science & Engineering Department and the Institute for Advanced Systems Engineering at the University of Connecticut. She received her PhD in Computational and Mathematical Engineering from Stanford University and her BA in Applied Mathematics with computer science focus from Harvard College. Prior to her academic career, she worked in industry with a startup developing AI-driven diagnostics for fall detection, and an established software company in the healthcare space. At UConn, her lab's research interests lie at the intersection of machine learning with physical sciences and systems, with the ultimate goal of enabling scientific discovery through new data-driven paradigms for modeling and computation.

Dr. Fei Miao, University of Connecticut

Fei Miao is an Assistant Professor of the Department of Computer Science & Engineering, a Courtesy Faculty of the Department of Electrical & Computer Engineering, University of Connecticut since 2017. She is also affiliated to the Institute of Advanced Systems Engineering and Eversource Energy Center. She was a postdoc researcher at the GRASP Lab and the PRECISE Lab of the University of Pennsylvania from 2016 to 2017. She received the Ph.D. degree and the Best Doctoral Dissertation Award in Electrical and Systems Engineering, with a dual M.S. degree in Statistics from the University of Pennsylvania in 2016. She received the B.S. degree in Automation from Shanghai Jiao Tong University. Her research focuses on reinforcement learning, robust optimization, uncertainty quantification, and game theory, to address safety, efficiency, robustness, and security challenges of cyber-physical systems. Dr. Miao is a receipt of the NSF CAREER award and a couple of other awards from NSF, including awards from the Smart & Autonomous Systems, the Cyber-Physical Systems, and the Smart & Connected Communities programs. She received the Best Paper Award and Best Paper Award Finalist at the 12th and 6th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS) in 2021 and 2015, respectively.

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Dr. George Bollas is the Pratt & Whitney Endowed Chair Professor in Advanced Systems Engineering with the Chemical & Biomolecular Engineering Department at UConn. He is also the Director of the Pratt & Whitney Institute for Advanced Systems Engineering at UConn. Prior to joining UConn, he was a postdoctoral fellow at the Massachusetts Institute of Technology and before that he received his BS and PhD in Chemical Engineering from the Aristotle University of Thessaloniki in Greece. His interdisciplinary research merges the fields of energy technology, process systems engineering and model-based systems engineering. His laboratory pursues a balanced approach to information theory for the design, optimization, control, operation, and maintenance of cyber-physical systems, with applications on energy, chemical industry, manufacturing, naval and the aerospace industry. Dr. Bollas is the recipient of the NSF CAREER and ACS PRF Doctoral New Investigator awards; the UConn Mentorship Excellence award; the UConn School of Engineering Dean's Excellence award; AIChE Teacher of Year award; and the Chemical & Biomolecular Department Service award. He was a member of the 2016 Frontier of Engineering Education of the NAE and was elected as member of the Connecticut Academy of Science and Engineering in 2020. He has partnered with over 100 industry professionals and executives in generating and managing funding for UConn that exceeds $40M leading to joint R&D, technology, patents, and professional training programs. He manages a portfolio of over $7M in research projects, while his Institute manages active research funding that totals over $30M.

Applying a Competency-Based Education Approach for Designing a Unique Interdisciplinary Graduate Program: A Case Study for a Systems Engineering Program

Abstract

Starting in 2020, ten faculty members of the University of Connecticut's (UConn) Master of Engineering program in Advanced Systems Engineering applied four existing competency frameworks to define the unique aspects of their professional training program using a competency-based education approach. The four frameworks include the 21st Century Cyber-Physical Systems Education report published by the National Academies Press, the Applied Mathematics at the U.S. Department of Energy report published by Lawrence Livermore National Laboratory, the INCOSE (International Council on Systems Engineering) Systems Engineering Competency Framework, and the INCOSE Model-Based Enterprise Capabilities Matrix. The purpose of the use of these frameworks and reports was to identify generally desirable competencies that a professional should acquire when training at the graduate level in systems engineering for the development of complex CPS. The competency-based education process included a mapping of previously defined student learning outcomes to competencies defined in the frameworks. This paper explains the systems engineering education program background, competency-based education initiative goals, methods, process, and results. The paper concludes that a tailored approach to graduate education programming, based upon this competency-based education and course assessment method, can be used to differentiate graduate systems engineering programs from each other. The paper also concludes that customized learning, targeting specific systems engineering skillsets, can be achieved by each systems engineering student based upon offering an open and customizable course curriculum. Students can use their competency-based learning plans and social-media-recognizable badges to signify their unique systems engineering competencies and learning outcomes achieved either through a four-course Graduate Certificate or a ten-course Master of Engineering program offered by UConn. The competency definitions by graduate course can be used by graduate students to create a longer-term systems engineering professional development plan that supports life-long learning.

Keywords: competency-based learning, competency-based education, graduate education, workforce development, systems engineering, digital engineering, computational engineering, cyber-physical systems

Introduction and Education Program Background

In 2014, the University of Connecticut (UConn) created three graduate certificates in Systems Engineering that focused on the design and development of a complex cyber-physical system (CPS). The certificate programs were developed to teach working professional engineers in a for-credit graduate program and consisted of four courses with three credit-hours each. The three certificates were focused on three key areas of CPS engineering: systems design, embedded systems, and controlled systems. High-level competencies were identified that included: requirements modeling, requirements formalization, systems architecting, physics modeling, data-driven modeling, model abstraction and reduction, data and model-based diagnostics and prognostics and health management (PHM), uncertainty management in systems generating big data, robust and resilient system control and optimization and supervision, and cybersecurity as applied to CPS. This knowledge base was created based upon identified barriers shown in Figure 1, based upon a workshop held at UConn with systems engineering experts from industry.

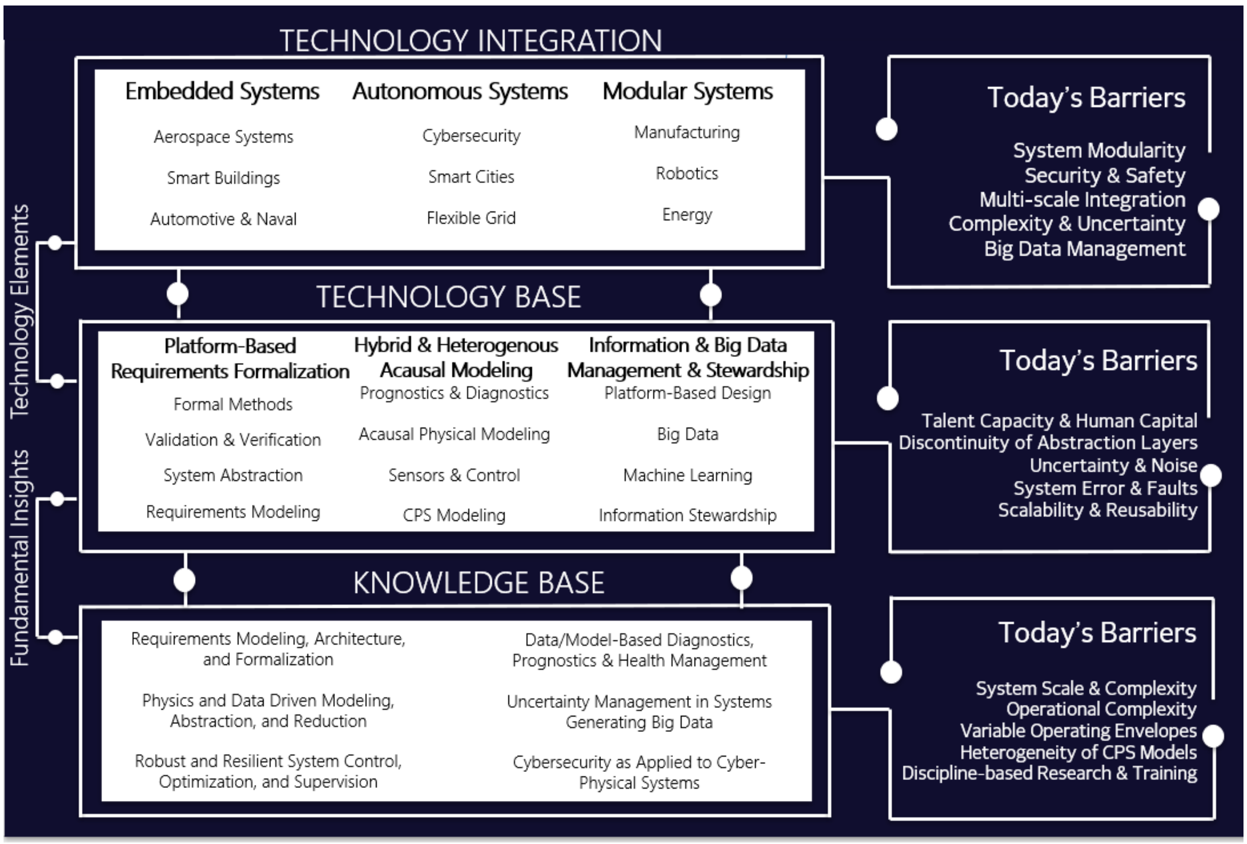


Figure 1. The development of a knowledge base for a CPS-focused systems engineering graduate program is illustrated in this diagram. Technology integration, technology base, and knowledge base are related, and the current barriers are identified for each.

Defining stakeholder needs. The need for this type of education and training program was identified by industry leaders and by members of the UConn systems engineering program industrial advisory board. The need was also identified by leading researchers at the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) and the knowledge, skills, and abilities for engineers working in the development of complex CPS were defined in their report [1]. A summary of key CPS engineering competencies is shown in Table 1 from the NASEM report with a full detailed list of competencies extracted for UConn shown in Appendix 1. These competencies were defined in 2020 as part of this competency-based education (CBE) initiative to represent skills necessary for designing, operating, and developing CPS.

Table 1. The Key CPS Competencies Relevant to the Systems Engineering Program Identified and Extracted from the National Academies of Sciences, Engineering, and Medicine [1].

Computer and Network Security
Computer Architecture
CPS Architecture
Embedded and Real-Time Systems Architecture
Feedback Control
Formal Methods
Hybrid Systems
Inference under Uncertainty
Machine Learning
Medical Embedded Systems
Modeling from Data
Networked Control Systems Architecture
Robotics and Mechatronics
Sensor Networks
Signal Processing
Systems Engineering
Systems Thinking and Meta Modeling

Other researchers have identified the importance of teaching students skills and competencies in the area of CPS, which include similar competencies identified by NASEM: supervisory control, maintenance of system availability using distributed control, assurance of integrity of control functions under cyber-attack, dealing with uncertainty in human interactions, need to achieve high levels of safety and security, ensure privacy of data and control access, the ability to evaluate CPS resilience in different environments, and the ability to make hard design decisions and tradeoffs in system performance, safety, and security in uncertain environments [2].

Graduate program launch, Version 1.0. From 2014 to 2017, UConn ran the three graduate certificates in Systems Engineering (SE) as three possible tracks. Courses in the SE design certificate included (1) Foundations of Physical Systems Modeling (2) Uncertainty Analysis, Robust Design, and Optimization, (3) Design Flows for Robust Design and (4) Capstone Projects for System Design. Courses in the SE embedded systems certificate included (1) Embedded and Networked Systems Modeling Abstractions, (2) Formal Methods, (3) Design Flows for Embedded and Networked Systems, and (4) Capstone Projects for Embedded Systems. Courses in the controlled systems certificate included (1) Foundations of Thermal Fluid Systems, (2) Foundations for Control, (3) Design Flows for Control and Verification, and (4) Capstone Projects for Controlled Systems. These graduate courses were offered in the evenings in-person and were run as cohorts with about 30-40 students in each cohort. The cohort followed the prescribed sequence of four courses across four semesters over two years. Courses were taught with a mix of instructors from academia and industry.

Growth in contributing faculty members. With industry funding, new faculty members were hired between 2014 to 2020 that would bring innovative teaching and research capabilities in systems engineering to UConn's School of Engineering, specifically in CPS engineering. These faculty were hired on tenure-track positions, assigned to a home department of their original engineering or computer science background, and then participated in teaching systems engineering through an interdisciplinary institute established to move forward new systems engineering education and research programs. Faculty would often develop a cross-listed course with the systems engineering course in their home department to attract students to SE curriculum from not only the systems engineering program, but also students from their home department (for example: mechanical, electrical, computer, or chemical engineering). Existing tenured and tenure-track faculty members of the school of engineering and computer science were also identified who could create new courses to teach identified skills and knowledge in systems engineering.

Master of Engineering program launch and program re-design, Version 2.0. In 2017, the program's leadership decided to expand the certificate program and offer a new master's degree targeted to working professional engineers and offering two new courses in Systems Engineering. A full-time professor-in-residence (PIR) was hired, who had a mix of academic and industry background and was focused on engineering education for graduate and systems engineering programs, to lead the expansion of the academic programs and develop new courses. The PIR faculty member developed and taught the first new course, Introduction to Systems Engineering that teaches Systems Engineering principles, practices, and methods according to ISO 15288 [3] and the INCOSE Systems Engineering Handbook [4]. The faculty member then developed and taught a second new course in model-based systems engineering (MBSE), which introduced students to systems modeling using descriptive modeling languages like the systems modeling language (SysML) and MBSE methods like the object-oriented systems engineering method (OOSEM), and advanced MBSE tools. In 2016, with the hiring of a new tenure-track faculty member, the robust design course was modified in 2018 from a more qualitative course to a more quantitative course renamed Uncertainty Analysis, Robust Design, and Optimization. The same year, the three graduate certificates were merged into one certificate in Systems Engineering, and strict course prerequisites were removed from all systems engineering to flatten the curriculum. This was implemented so that students could select any SE course to take, given they had the prescribed recommended preparation. Once a student is accepted into the graduate certificate or degree, a student can choose any four SE courses for the certificate and any seven courses, including a capstone, for the new master's degree, based upon prescribed recommended preparation for each course. The Introduction to Systems Engineering is recommended to each student for starting the program but can be skipped for working professionals who already had a strong background and knowledge of systems engineering and wanted to move on to the more analytical courses. It is also recommended to most students to start with the Advanced Engineering Mathematics course, which is a refresher for working professionals who have been out of school for a while and need a math refresher before taking the more highly analytical courses later in the program. Otherwise, graduate students can take any systems engineering courses with the only prerequisite of having an undergraduate degree in engineering or computer science. A list of all ten systems engineering program courses with one-page summaries-flyers and full syllabi are listed at the UConn Institute for Advanced Systems Engineering website (https://iase.engr.uconn.edu/course-descriptions/).

Master of Engineering and Graduate Certificate program format and course delivery model. In addition, in 2017, all courses were transitioned to a hybrid-online delivery with the help of UConn's Center for Teaching and Learning (CETL). Through this program, faculty members were provided a stipend and a well-structured six-to-nine-month plan to transition existing courses or develop new courses in a hybrid-online format. The goals and outcomes of these changes tailored the programs to a working professional's schedule, opened the courses and programs so that students anywhere in the world could take the courses, and allowed students to choose courses and tailor curriculum to their professional needs. The hybrid-online courses are designed to be hybrid, and flipped, so that students can read materials, and watch short, pre-recorded videos on their own time, and then attend a one-hour live session each week with the professor and students to ask questions and participate in live discussions. The courses were also changed to be all project-based to emphasize skills development, and typically include a course-long individual project. Class sizes were kept small at 10-20 students so that professors graded all projects and interacted heavily with course participants. A new tenure-track faculty member was hired the following year who developed a new course in Data Science for Materials and Manufacturing to support the effort to optimize manufacturing based upon real-time big data sets. By 2020, the systems engineering academic programs had nine (9) full-time faculty teaching ten graduate systems engineering courses as shown in Figure 2.

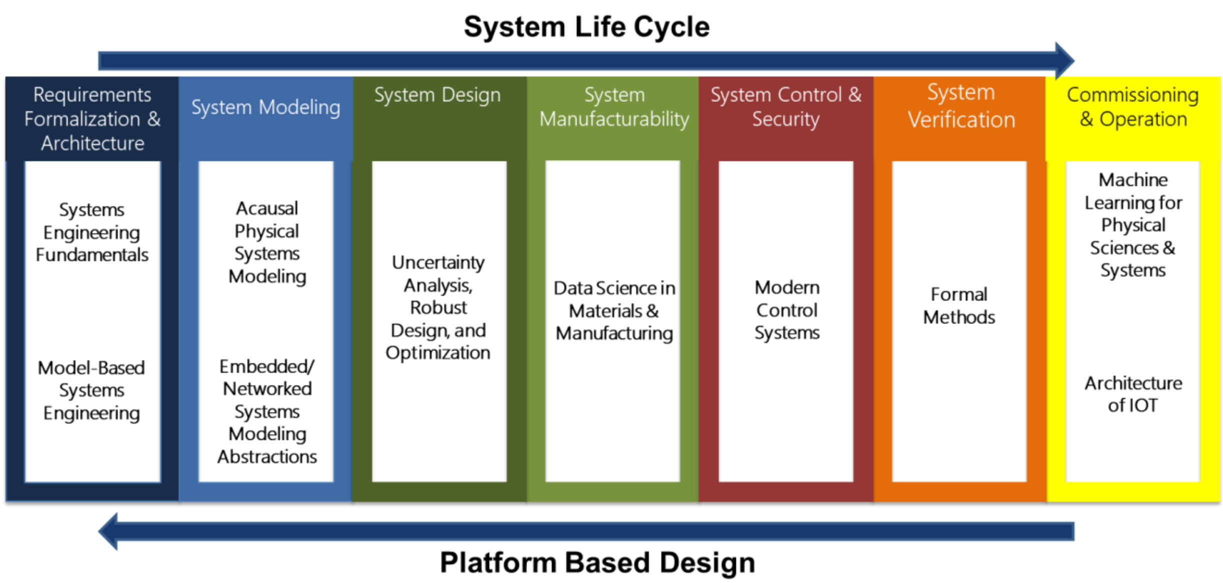


Figure 2. The graduate Systems Engineering courses and overall program (2017-2020) are illustrated as a continuum representing skills development across a platform and a system lifecycle.

From 2017 to 2020, the programs had grown to a peak of about 70-80 students per semester enrolled in four to five SE courses each semester. Additional courses were added over this time: Architecture of Internet of Things (IoT), Data Science for Materials and Manufacturing, Machine Learning for Physical Sciences and Systems. One new course was developed in 2021 called Model-Based Design for Real-Time CPS and one new course is currently (2023) being developed in Systems Engineering Management, both taught by new adjunct faculty members. In 2020, UConn's faculty members began a competency-based education (CBE) initiative to better define the competencies taught in this innovative curriculum and to differentiate and better communicate its program to industry, academia, and prospective students.

This paper describes the steps, processes, and results of a competency-based education (CBE) initiative applied to a graduate program in Systems Engineering based upon four competency frameworks.

Background on Competency-Based Education

The use of multiple competency frameworks for academic programs. The transition to digital engineering and organizational digital transformation along with advances in artificial intelligence is transforming and expanding the skills and competencies needed to perform many systems engineering activities [5]. Engineering and manufacturing design decisions that were made with traditional systems engineering approaches are being augmented and supported with data-driven and model-driven approaches with connected repositories of data and models, often now referred to as a digital thread. There is a need for academic programs that are evolving more quickly than industry standards or that are transdisciplinary or interdisciplinary in nature to define and assess their programs with multiple competency frameworks. There is prior work aligned with these purposes applying multiple competency frameworks to an individual program [6], [7], [8].

CBE history, motivation, and approaches. Although the CBE approach was first introduced in 1906 by the Carnegie Foundation for the Advancement of Teaching, it has gone in and out of popularity over the years [9]. A CBE approach is typically applied to better align and close the gap between academic teaching and learning with industry and labor market skills needs. CBE strives to more formally, and specifically, align teaching and learning outcomes with needed industry skills defined by well-stated competencies [10]. The gap between student outcomes and industry-defined competencies often occurs due to fast-paced changes in industry [1], [11]. Some areas, where technology and skills are advancing faster than higher education institutions can develop curriculum to meet needs, include Artificial Intelligence [12], Industry 4.0 [6], Digital Engineering [13], and Digital Competence [7]. However, it should be noted that these advances and need for new skills in industry often occur due to emerging technologies or methods that are an outcome of research that originally occurred in academia. There is sometimes a delayed feedback loop between the creation of new methods and technologies in academia and their adoption in industry, which in turn drives the need for these new skills on a larger-scale basis. Really, this means a need for broader scale education of engineers in masse vs. specialized training of a few graduate students. A CBE approach can be applied where competencies are defined (1) to create a new program, (2) for an existing curriculum without significant changes, or (3) to drive curricular redesign where gaps are identified and learning outcomes are re-written to align with published competency frameworks. A CBE initiative can be defined for a traditional course-based graduation model where students need to complete a certain number and type of courses and credit hours, or CBE can transform the curriculum and model so that students graduate based upon a certain set of competencies achieved.

The value of using CBE. A CBE approach has been identified previously as having the benefits of being student-centered achieving with the following aspects: (1) student responsibility for the selection of and adherence to a learning path, (2) students choose courses and competency attainment that they feel will differentiate themselves in a competitive labor market, (3) students choose courses and competencies that build upon prior experience providing them validation of the skills they have attained previously, and (4) students have clear expectations and relevance of work to the ultimate academic goal: competency maps create cohesive and transparent program sequencing that allow students to have a clear view of the direction and requirements for their learning. Also, the program design using CBE allows for better competency descriptions, assessment, transparency, accountability, assessment at differing attainment levels, education affordability, demand-driven education, transition to mentoring and coaching vs. lecturing, description of student's knowledge, skills, abilities, and learning outcomes. All of this results in putting more power into the hands of students to "curate" their learning paths, which can support life-long learning [14]. Other researchers have identified that competency frameworks are valuable for preparing students for workplace readiness [15]. These values helped to form the UConn Systems Engineering program's CBE mission statements that would guide the CBE process for this project.

Mind the gap. Industrial organizations and companies have found that tailoring competency frameworks is necessary to, "handle variation both in the nature of the Systems Engineering that the organization does, and the nature of the existing organization in which Systems Engineering is performed [16]." Academic institutions need to tailor competency frameworks to not only match with the needs of students, but also to align with current course offerings, faculty expertise, interests, and capabilities. The gaps identified between the frameworks and what is taught and learned in current course offerings at an academic institution does not have to be viewed as deficiencies, but used to define the flavor or type of academic program it is. Systems Engineering is a broad field, and most institutions will not be able to teach all competencies needed in one graduate certificate or master's degree. If some of the gaps identified align with academic program partner needs, and faculty interest, those competencies can be identified to be incorporated and added to existing or new courses.

Higher education institutions implement CBE differently than private corporations. Academic institutions need to apply and tailor competency frameworks to courses differently than private corporations, understanding that higher education institutions (HEIs) are different, and that they have a broader mission [17]. HEIs deliver education services to meet students' learning needs, but they also need to make opportunities for faculty to explore their teaching and research interests and priorities. In addition, HEIs need to prepare students for society so they can not only meet employer needs, but also social, economic, and environmental needs of society. Students need to progress as individuals in an intellectual and ethical way, and some professional competency frameworks may not address these dimensions. Many HEIs are responsible for and have a mission to grow and produce citizens, not just competent employees. HEIs also need to consider administrative structures, services, and resources available to pursue competency-based learning, which may differ from human resource structures in private companies. HEIs also have high-level goals for focusing on research activities and advancing their reputation, which may or may not conflict with designing a competency-based curriculum.

Competency vs. student learning outcomes. Several consulting companies (Personnel Decisions Research Institutes, Inc. (PDRI) in 2005, JBS International, Inc., Aguirre Division in 2012, and Coffey Consulting, LLC and JBS International, Inc. in 2015) contributed to a technical assistance guide that details best practices for developing competency models [18]. The guide was developed and supported by funding from the U.S. Department of Labor, Employment & Training Administration under Contract DOLQ121A21895, Order No. DOL-ETA-15-U-00001. The guide states that:

> "Competency models serve as a bridge for information sharing between employers and the education system. By providing a common language for discussions of regional skill needs, competency models foster industry-education collaboration in developing curricula, planning and assessing career and technical education programs, and developing apprenticeship programs. Models are a resource for the planning, design, and delivery of educational and training opportunities that meet employers' needs. By providing a framework of the knowledge, skills, and abilities required for satisfactory performance in an industry or occupation, competency models present education and training providers with an industry-validated resource."

The guide also explains that competency models, "support curriculum development by (1) identifying essential skill requirements within industries and occupations, (2) providing a business-oriented framework for developing teaching and learning objectives, (3) supplying content for enriching instructional materials, (4) providing a resource for instructional designers to tailor courses to specific student populations or industry needs, (5) reducing the development time of instructional materials, courses, and program curricula, (6) establishing common terminology for use by business and education communities to facilitate collaboration on technical education projects, and (7) highlighting gaps in current training offerings."

The terms competency and student learning outcome cannot be used interchangeably. In 2004, Hartel and Foegeding defined and differentiated competencies from outcomes as:

> *"Competency:* A general statement that describes the desired knowledge, skills, and behaviors of a student graduating from a program (or completing a course). Competencies commonly define the applied skills and knowledge that enable people to successfully perform in professional, educational, and other life contexts.
> *Outcome:* A very specific statement that describes exactly what a student will be able to do in some measurable way. There may be more than one measurable outcome defined for a given competency."

For this CBE initiative, faculty members mapped competencies to learning outcomes by course modules, where in many cases the learning outcomes were more specific and measurable, and in many cases, there was more than one learning outcome mapped to a competency. Here are two examples:

> **Example 1.**
> **Competency:** Analyze and model materials and processes. Can perform modeling and analysis to determine optimal properties of materials based upon historical material and process data.
> **Learning Outcome:** The student can apply a design of experiments method to determine optimal properties of materials based upon historical material and process data.
> **Assessment:** Student takes supplied data set and determines the correct optimal solution. The student accurately describes their assumptions, process, and methodology with correct use of terminology and determines the confidence that the identified solution is optimal.

> **Example 2.**
> **Competency:** Modeling skills. Can analyze systems by simulation.
> **Learning Outcome:** The student can define the behavior of an engineered system using a state machine and activity diagram and can use an MBSE tool simulator to simulate the behavior to determine how well an identified technical performance measure is met.
> **Assessment:** The student delivers a model that correctly defines states and state transitions based upon modeling language standards and engineering principles. The student creates and runs a simulation that produces a result that can be compared to the identified technical performance measure. The student accurately describes their assumptions, process, and methodology with correct use of terminology and determines the confidence that the model produces accurate results.

David Gosselin provides other differentiating examples for critical thinking, creative thinking, and self-awareness in his article and at his webpage, “Interdisciplinary Teaching about Earth for a Sustainable Future [20].”

Path and Process to Implement Competency-Based Education for Graduate Programs

Getting started with a CBE initiative: Literature Review. The CBE initiative began with a literature review for competency-based education practices and for relevant competency frameworks that contained defined competencies that aligned with the current curriculum, the long-term mission and strategy for the systems engineering institute, and the high-level competencies defined previously in the Introduction and Education Program Background section. The industrial advisory board provided input and suggestions for frameworks and papers to consider. The following four competencies were found to be most relevant to the current curriculum and mission for the systems engineering institute: 21st Century Cyber-Physical Systems Education report published by the National Academies Press [1], Applied Mathematics at the U.S. Department of Energy report published by Lawrence Livermore National Laboratory [21], INCOSE Systems Engineering Competency Framework [22], and INCOSE Model-Based Enterprise Capabilities Matrix [23].

Setting a CBE Mission. The outcome of the study of competency-based education practices was the development of a CBE mission statement to aid in driving process decisions for this effort, *"Create a CBE program that is student-centered, drives students to take responsibility for their learning path, encourages students to participate in life-long learning, supports students in defining and differentiating themselves and their skills in the labor market, supports their understanding of what they are learning and why, supports their understanding of their level of competency in certain skills, and provides a social media mechanism for them to share their competency attainment and success."*

Analyzing and applying the CBE competency frameworks. Each framework was analyzed, and competency statements were extracted from each framework. The competency statements were then organized for each framework individually to define any needed hierarchical structure, important relationships or categories, or competency levels. The industrial advisory board members reviewed the competency statements and ranked importance levels by framework to prioritize competency attainment and course content. Competency level definitions were adopted from the INCOSE Systems Engineering Competency Framework [22]. Competency statements were then compared across the four competency frameworks to understand overlaps and relationships, where many relationships and overlaps were discovered. It was decided due to the complexity of the overlaps and relationships found, it would be easier to start by mapping each competency statement in each individual framework first to each existing course learning module and then student learning outcomes within those modules. By understanding how multiple competencies are mapped across the four frameworks to student learning outcome statements in existing courses, it would then be easier to resolve hierarchical relationships, competency achievement levels, or overlaps in statements. A list of competency statements that were applied to the current curriculum and courses for the remaining three frameworks are listed in Appendices 2, 3, and 4. Table 2, Table 3, and Table 4 summarize the major categories of competencies for each framework.

Table 2. Relevant Competencies Extracted from the Applied Mathematics at the U.S. Department of Energy Report, Lawrence Livermore National Laboratory [21].

Competency Category	**One Competency Level**
Perform computationally tractable approximations through modeling	SUPERVISED PRACTITIONER Intermediate

Competency Category	One Competency Level
Describe, analyze, model, and simulate large scale meta systems	SUPERVISED PRACTITIONER Intermediate
Manage design change through modeling and incorporating new data types and technologies	SUPERVISED PRACTITIONER Intermediate
Perform multi-physics, multiscale modeling, numerical modeling, model scalability	SUPERVISED PRACTITIONER Intermediate
Perform uncertainty quantification and modeling	SUPERVISED PRACTITIONER Intermediate
Apply experimental data and numerical analysis methods	SUPERVISED PRACTITIONER Intermediate
Analyze and model materials and processes	SUPERVISED PRACTITIONER Intermediate

Table 3. Relevant Competencies Extracted from the INCOSE
Systems Engineering Competency Framework [22].

Competency Category	Competency Area	Two Competency Levels
SE Management	Decision Management	AWARENESS, SUPERVISED PRACTITIONER
SE Management	Risk and Opportunity Management	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Design For…	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Requirements Definition	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Operation and Support	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	System Architecting	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Interfaces	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Integration	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Transition	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Validation	AWARENESS, SUPERVISED PRACTITIONER
SE Technical Processes	Verification	AWARENESS, SUPERVISED PRACTITIONER

Table 4. Relevant Competencies Extracted from the INCOSE
Model-Based Enterprise Capabilities Matrix [23].

INCOSE MBSE Management Competency. Can Perform MBSE Management Practices for a Real-World Problem	**Two Competency Levels**
MBSE Management. Can Describe Modeling Roles and Responsibilities.	AWARENESS, Fundamental
MBSE Management. Can Describe Knowledge, Skills, and Abilities for MBSE Practitioners.	AWARENESS, Fundamental
MBSE Management. Can Develop an MBSE Use Strategy for their Organization.	SUPERVISED PRACTITIONER Intermediate
MBSE Management. Can Conduct Model-Based Verification and Validation.	SUPERVISED PRACTITIONER Intermediate
INCOSE MBSE Modeling Competency. Can perform Model Based Systems Engineering by System Modeling Using a Systems Modeling Language.	**Two Competency Levels**
Modeling Skills. Can Describe Different Types of Model Languages.	AWARENESS, Fundamental
Modeling Skills. Can Describe Different Types of System Modeling Methods.	AWARENESS, Fundamental
Modeling Skills. Can Develop a Systems Engineering-Driven Model Plan.	AWARENESS, Fundamental
Modeling Skills. Can Define Model Metrics.	AWARENESS, Fundamental
Modeling Skills. Can Describe and Apply the Systems Engineering Technical Processes to a real-world problem.	AWARENESS, Fundamental
Modeling Skills. Can Develop a High-Quality Systems Model Based Upon a Defined Purpose.	AWARENESS, Fundamental
Modeling Skills. Can Model Stakeholder Requirements.	AWARENESS, Fundamental
Can Develop a High-Quality Systems Model Using SysML or other standard System Model Language.	AWARENESS, Fundamental
Modeling Skills. Can Analyze Systems by Simulation.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Verify and Validate Models.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Define and Develop Model Libraries.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Conduct Model-Based Reviews.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Integrate Models.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Quantify Model Process Quality.	SUPERVISED PRACTITIONER Intermediate
Modeling Skills. Can Use Existing Models for Analysis Based Upon Different Types of Needs.	SUPERVISED PRACTITIONER Intermediate

Defining the CBE competency levels. Higher level competencies should be built on previous knowledge and competencies, so that competencies built are stackable. Two primary competency levels were adapted from the INCOSE's Systems Engineering Competency Framework five competence levels [22]. Higher education institutions can teach for short periods of time in courses and workshop formats to achieve either Awareness Level or Supervised Practitioner Level competencies. Supervised Practitioner level competency levels can be achieved through instructors guiding students through course-long or program-long projects that involve hands-on experiential learning with feedback provided by expert instructors. Practitioner, Lead Practitioner, and Expert levels of competency are best achieved through longer-term industrial and research practice.

Table 5. Competencies Level Definitions from the INCOSE
Systems Engineering Competency Framework [22].

"Awareness: The person displays knowledge of key ideas associated with the competency area and understands key issues and their implications. They ask relevant and constructive questions on the subject. This level characterizes engineers new to the competency area. It could also characterize an individual outside Systems Engineering who requires an understanding of the competency area to perform their role."
"Supervised Practitioner: The person displays an understanding of the competency area and has some limited experience. They require regular guidance and supervision. This level defines those engineers who are "in-training" or are inexperienced in that competency area."

Involve faculty members in competency mapping process. The process for developing and applying a CBE approach involved several key steps. Once the relevant frameworks were identified, the ten faculty members reviewed the published frameworks and met to discuss the competencies defined and extracted. The faculty members agreed all four frameworks were relevant to what was being taught in the program. A timeline was defined over several months to have each faculty member review and apply one framework at a time to current competencies taught in each course. This process resulted in a competency mapping of each competency for each of the four (4) frameworks to the learning outcomes achieved in each learning module of each systems engineering course.

Development and Analysis of Competency Maps – A Course Module Example

This example explains how four (4) different competency frameworks were applied to one module that teaches Requirements Modeling in the graduate level systems engineering course called Model-Based Systems Engineering. It also demonstrates the improvements to the learning module that occurred due to its application. First, the competency statements from the four frameworks were analyzed to identify which competencies related to the module. 19 competency statements were identified as relating to the learning activities and outcomes for the module and are shown in Table 6. Next, a competency hierarchy was defined within the module. Some competency statements were relevant and described at the Course level because the statement could pertain to every activity of the course. For this example, one competency statement was identified at the Module level because the competency could relate to every module activity. The remaining competencies were identified at the activity level because each competency could map to a learning outcome and specific module activity that included (1) a case study, (2) a discussion board activity, and (3) a course-long project related modeling activity. At the activity level, competency numbers 12 and 13 were identified to overlap and competency numbers 14, 15, and 16 were identified to be strongly related.

Table 6. Module Competencies Identified Across Four (4)
Competency Frameworks Competency Hierarchy Level Defined.

#	**Module Competencies**	**Hierarchy or Level**
1	Can develop and update formal specifications for cyber-physical designs and systems.	Course
2	Can apply systems engineering methods and principles to the design and operation of a CPS.	Course
3	Can design large-scale meta systems and predict behavior and performance with systems models during early phase design.	Course
4	Can perform modeling and analysis to design and predict operating characteristics for a complex system.	Course
5	Can perform modeling and analysis of a stochastic system and simulate it to understand performance based upon performance measures.	Course
6	Can use modeling and simulation tools and techniques to represent a system or system element.	Course
7	Can contribute to the model development and interpretation activities.	Course
8	Can describe and apply the systems engineering Technical Processes to a real-world problem.	Course
9	Can model stakeholder needs and system requirements.	Module
10	Can apply knowledge of how CPS methods integrate at the large, meta system level.	Module Activity
11	Can perform modeling and analysis to quantify cost, schedule, and technical risk.	Module Activity
12	Can conduct model-based verification and validation.	Module Activity
13	Can develop and update verification and validation methods for cyber-physical designs and systems.	Module Activity
14	Can manage design change through system modeling.	Module Activity
15	Can perform modeling and analysis to design and predict the effects of introducing a new technology into a current complex system.	Module Activity
16	Can modify a model of a complex system to introduce new data types and formats.	Module Activity

#	Module Competencies	Hierarchy or Level
17	Can define and quantify uncertainty in systems flows and processes for a systems model.	Module Activity
18	Can interpret and use outcomes of modeling and analysis, with guidance.	Module Activity
19	Can develop a high-quality systems model using SysML or other standard language.	Module Activity

Next, the existing module student learning outcomes were then mapped to the competencies at the module activity level. This mapping is shown in Table 7.

Table 7. Existing Module Student Learning Outcomes.

Module Student Learning Outcome	Competency
Use an MBSE tool to create, organize, and categorize requirements.	N/A
Create requirement relationships using an MBSE approach.	Can apply knowledge of how CPS methods integrate at the large, meta system level.
Model and visualize requirement relationships using the SysML requirements diagram.	
Model and handle requirement risks and concerns in an MBSE tool.	Can perform modeling and analysis to quantify cost, schedule, and technical risk.
Define how requirements are satisfied and verified using SysML and an MBSE tool.	Can conduct model-based verification and validation
	Can develop and update verification and validation methods for cyber-physical designs and systems.

Next, competencies were assessed to see if they were relevant, and removed if not. The first learning outcome was removed because it was not specific enough and too broad to be a learning outcome. Next, the competencies were analyzed to determine whether they should be added and supported with new learning content. This determination was made by comparing the industrial advisory board’s rank of importance relative to the competencies for the existing learning outcomes. All six competencies were ranked highly by the advisory board, so new learning outcomes were added to the course along with some new course content that supported them. The module’s new learning outcomes with competencies are shown in Table 8.

Table 8. New Learning Outcomes for Module.

LO #	Change Status	Learning Outcome	Competency	COMP #
1	Existing	Create requirement relationships using an MBSE approach.	Can apply knowledge of how CPS methods integrate at the large, meta system level.	1
2	Existing	Model and visualize requirement relationships using the SysML requirements diagram.	Can apply knowledge of how CPS methods integrate at the large, meta system level.	1
3	Existing	Model and handle requirement risks and concerns in an MBSE tool.	Can perform modeling and analysis to quantify cost, schedule, and technical risk.	2
4	Existing	Define how requirements are satisfied and verified using SysML and an MBSE tool.	Can conduct model-based verification and validation	3
			Can develop and update verification and validation methods for cyber-physical designs and systems.	4
5	**New**	**Define and conduct a process to import a set of changed requirements into the model and update the requirements model.**	**Can manage design change through system modeling.**	**5**
6	**New**	**Define a process to change a requirement for the introduction of a new technology.**	**Can perform modeling and analysis to design and predict the effects of introducing a new technology into a current complex system.**	**6**
7	**New**	**Define a process to change a requirement for the introduction of a new data type.**	**Can modify a model of a complex system to introduce new data types and formats.**	**7**
8	**New**	**Write requirements with additional language to handle the uncertain nature of the operating environment.**	**Can define and quantify uncertainty in systems flows and processes for a systems model.**	**8**
9	**New**	**Describe and interpret the results of the requirements model.**	**Can interpret and use outcomes of modeling and analysis, with guidance.**	**9**
10	**New**	**Assess the requirements model for quality using model quality metrics.**	**Can develop a high-quality systems model using SysML or other standard language**	**10**

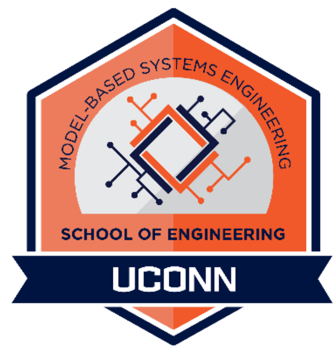
Additional tasks were added to the discussion board activity and the course-long project. New training videos were added to the module to demonstrate techniques for student learning outcomes 6-10. Table 9 demonstrates a competency mapping table provided to students in modules to enhance their understanding of how curriculum relates to international standards for systems engineering.

Table 9. Example Competency Mapping Table Inside Learning Module.

LO #	Learning Outcome	Competency	CP #	Standard
1	Create requirement relationships using an MBSE approach.	Can apply knowledge of how CPS methods integrate at the large, meta system level.	1	Standard [1] NAE-CPS
2	Model and visualize requirement relationships using the SysML requirements diagram.	Can apply knowledge of how CPS methods integrate at the large, meta system level.	1	Standard [1] NAE-CPS
3	Model and handle requirement risks and concerns in an MBSE tool.	Can perform modeling and analysis to quantify cost, schedule, and technical risk.	2	Standard [2] DOE-SIAM
4	Define how requirements are satisfied and verified using SysML and an MBSE tool.	Can conduct model-based verification and validation	3	Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix
4	Define how requirements are satisfied and verified using SysML and an MBSE tool.	Can develop and update verification and validation methods for cyber-physical designs and systems.	4	Standard [1] NAE-CPS
5	Define and conduct a process to import a set of changed requirements into the model and update the requirements model.	Can manage design change through system modeling.	5	Standard [2] DOE-SIAM
6	Define a process to change a requirement for the introduction of a new technology.	Can perform modeling and analysis to design and predict the effects of introducing a new technology into a current complex system.	6	Standard [2] DOE-SIAM
7	Define a process to change a requirement for the introduction of a new data type.	Can modify a model of a complex system to introduce new data types and formats.	7	Standard [2] DOE-SIAM

LO #	Learning Outcome	Competency	CP #	Standard
8	Write requirements with additional language to handle the uncertain nature of the operating environment.	Can define and quantify uncertainty in systems flows and processes for a systems model.	8	Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix
9	Describe and interpret the results of the requirements model.	Can interpret and use outcomes of modeling and analysis, with guidance.	9	Standard [3] INCOSE ISECF
10	Assess the requirements model for quality using model quality metrics.	Can develop a high-quality systems model using SysML or other standard language	10	Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix

Development of Badging Program



UConn partnered with Credly to launch ten (10) badges based upon the CBE initiative and competency mapping results: Robust Design, Applied Machine Learning for Physical Systems, Introduction to Systems Engineering, Model-Based Systems Engineering, Embedded Real-Time Systems, Data Science for Materials and Manufacturing, Architecture of Internet of Things (IoT), Cyber-Physical Control Systems, CPS Modeling, and Model-Based Design for CPS. Each badge correlates to an existing systems engineering course. Each is defined by the competencies that were mapped to each course. An example badge is shown in Appendix 5 for the Model-Based Systems Engineering course and all other Systems Engineering badges with detailed competencies defined can be viewed live at the Credly University of Connecticut page (https://www.credly.com/organizations/university-of-connecticut/badges). The process for implementing the badging program followed Credly's guidelines and is shown in Figure 3.

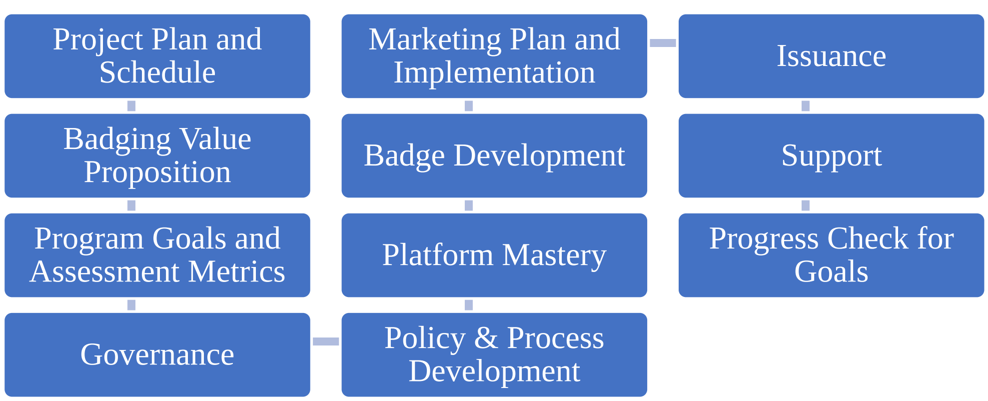


Figure 3. The badging program development process is illustrated in this flow diagram, following Credly's guidelines.

Results, Lessons Learned, Next Steps, and Future Work

UConn's CBE process and approach is summarized and shown in . Although a badging program is implemented for all courses, some steps are still in process.

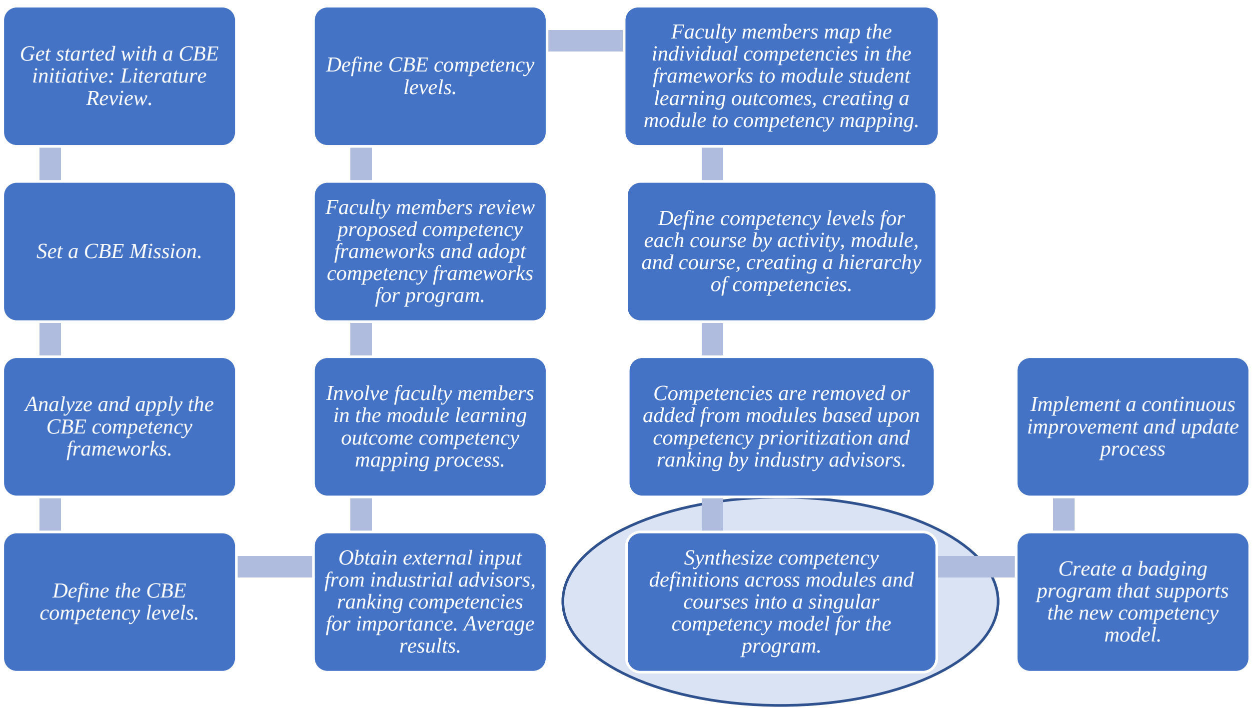


Figure 4. The competency-based education (CBE) process is illustrated in this block diagram.

On-going process. The current CBE project is on-going at UConn and the next steps are to implement these methods and approach across all courses and then continue to further develop the competency framework and continue to improve the quality and relevance of the systems engineering content. Expected next steps include to define levels of learning more clearly for the competencies when analyzed in the context of building competencies across courses and more clearly define how competencies achieved in each module and course relate to other modules in other courses: *Synthesize competency definitions across modules and courses into a singular competency model for the program*.

Value of CBE approach. The value in applying a competency-based education approach for this program has already been realized due to its ability to drive curriculum improvement in its courses and align student outcomes with industry needs through the collaboration with its industrial advisory board. Challenges in developing a CBE approach at a programmatic level with many faculty members involved are coordination and collaboration between all faculty members in the creation of the competency mappings consistently and analyzing competencies across courses. Coordination of activities and results in this case was more challenging because the program is interdisciplinary in nature and involves coordination between faculty members from five different departments.

Tailoring by CBE process. The level of detail and specificity varied greatly between the four frameworks. The INCOSE Systems Engineering Competency Framework (ISECF) has the greatest level of detail of competencies in that it had defined five major groups, or high levels of systems engineering competencies, at Level 1: Core, Professional, Management, Technical, and Integrating. These were then broken down into several categories at Level 2. The Level 2 categories were then broken down further into another set of competencies for each Level 2 category and defined at five building levels of competency from Awareness level to Expert level. For this CBE study, 112 different ISECF competencies were mapped to existing courses and student learning outcomes from the Core and Technical categories and at the awareness and Supervised Practitioner levels. Some competencies from Core and Technical categories at awareness and Supervised Practitioner did not map to existing curriculum due to the focus of this program on analytical and modeling aspects of systems engineering. In addition, Professional and Management competencies are not a focus of the ten systems engineering courses, and these competencies are the focus of two general graduate engineering courses required as part of the Master of Engineering degree: Professional Communication and Information Management and Engineering Project Planning and Management. Although many of the Professional and Management competencies are covered in these two courses, the courses are not taught in relation to the Core and Technical systems engineering competencies since these two courses are offered to the engineering population in the School of Engineering, not just those studying systems engineering. The systems engineering program is currently developing a new course called Systems Engineering Management that will teach many of these Professional and Management competencies in a more integrated way with references to the Core and Technical competencies. In contrast, although many ISECF competencies have depth of details given the three levels, the depth of detail in the ISECF Systems Modeling category did not go into enough details or depth to cover some of the analysis, modeling, and simulation competencies achieved in this systems engineering program. Because of this, the other frameworks were necessary and helpful in defining the systems modeling competencies in more depth. One recommendation would be for INCOSE to investigate these other three (3) systems competency frameworks to detail their Systems Modeling competency category in more depth.

All competencies from the NAE and DOE reports were written at a high level and could map easily to many student learning outcomes in the ten systems engineering courses. Although INCOSE's Model-Based Enterprise Capabilities Matrix was written to support organization capabilities and their ability to adopt MBSE at an organizational level, this initiative was able to extract individual competencies needed for systems engineers who are practicing MBSE. These competencies were written at a level that all extracted competencies could map to existing courses since one of the main focuses of the Master of Engineering and Graduate Certificate program is MBSE. The result is that reading the competencies taught by course, and then taking all the competencies in totality, this program reveals itself to be a Systems Engineering program focused more on analytics, modeling, and simulation skills and competencies. The program was thus named Master of Engineering in Advanced Systems Engineering due to the highly analytical nature of the program and need for a higher level of analytical knowledge and skills to achieve these competencies. In the future, the program will consider how new competency frameworks for Digital Engineering will affect and drive future curriculum directions and changes in systems engineering.

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Appendix 1. Extracted and Relevant CPS Competencies from NASEM [1].

CPS Competency Category, University-Defined	**CPS Competency Extracted from Report by UConn**
Computer and Network Security	Can model, predict, and prevent computer and network attacks exploiting physical properties of computation (e.g., time, temperature, radiation).
Computer Architecture	Can design and operate computer architecture for CPS.
CPS Architecture	Can design and operate networks of sensors, actuators, and distributed computation.
Embedded and Real-Time Systems Architecture	Can design systems that compute reliably and timely with noisy sensor data over wired and wireless networks
Feedback Control	Can conduct modeling practices for physical and computational processes of CPS.
Feedback Control	Can design techniques for stability, safety, liveness, and other specifications for CPS
Feedback Control	Can implement design techniques for stability, safety, liveness, and other specifications for CPS on hardware.
Formal Methods	Can develop and update formal models of computation including discrete and analog computation.
Formal Methods	Can develop and update formal specifications and verification methods for CPS designs and CPS systems.
Hybrid Systems	Can conduct modeling, verification, and control of systems containing discrete and continuous components of hybrid systems.
Inference under Uncertainty	Can describe and characterize uncertainty, statistical inference, detection, and estimation in models and analyze their effects on CPS behavior.
Machine Learning	Can apply machine learning methods and practices to the design and operation of CPS.
Medical Embedded Systems	Can model medical embedded systems for CPS.
Modeling from Data	Can create and update CPS models using real-time operating data.
Networked Control Systems Architecture	Can determine the impact of delays, packet collisions, and protocols on performance of networked control systems.
Networked Control Systems Architecture	Can model and implement control over wired and wireless networks.
Robotics and Mechatronics	Can apply principles of mechatronics and robotics to the design and operation of CPS.

CPS Competency Category, University-Defined	**CPS Competency Extracted from Report by UConn**
Sensor Networks	Can define and model sensor networks for CPS.
Signal Processing	Can design and operate digital signal processing on hardware and software
Signal Processing	Can design and operate digital signal processing over networks.
Systems Engineering	Can apply systems engineering methods and principles to the design and operation of CPS.
Systems Thinking and Meta Modeling	Can apply knowledge of how CPS methods integrate at the large, meta system level.

Appendix 2. Relevant and Extracted Competencies from
Applied Mathematics at the U.S. Department of Energy Report,
Lawrence Livermore National Laboratory [22]

Competency Category	**Competency Statement**
Computationally tractable approximations through modeling	Can develop and use approaches for deriving computationally tractable approximations to systems that are formulated in very high dimensional spaces, such as those arising in quantum mechanics.
Computationally tractable approximations through modeling	Can develop and use systematic mathematical approaches for constructing nonlinear empirical models informed by physics principles, possibly including physically imposed constraints;
Computationally tractable approximations through modeling	Can develop and use mathematically rigorous frameworks and efficient, robust numerical methods for data assimilation into models of complex systems that are informed by numerical analysis- based error estimates for simulations and statistics-based error estimates for the assimilated data.
Large scale meta systems	Can perform modeling and analysis to design and predict operating characteristics for a complex system.
Large scale meta systems	Can perform modeling and analysis to design and predict when changing meta system conditions cause system failures.
Large scale meta systems	Can perform modeling and analysis of a large stochastic system and simulate to understand performance based upon technical performance measures.
Large scale meta systems	Can decompose complex systems into canonical subsystems to design and predict system behavior and elucidating the coupling between components.
Large scale meta systems	Can optimize a complex system to meet stakeholder requirements and best engineering practice standards.
Large scale meta systems	Can perform modeling and analysis to quantify cost, schedule, and technical risk.
Manage design change through modeling and introducing new data types	Can modify a model of a complex system to introduce new data types and formats.
Manage design change through modeling and introducing new technology	Can perform modeling and analysis to design and predict the effects of introducing a new technology into a current complex system.
Multi-physics, multiscale modeling, numerical modeling, model scalability	Can develop analytical and computational approaches needed to understand and model the behavior of complex multi-physics, and multiscale phenomena.

Competency Category	Competency Statement
Multi-physics, multiscale modeling, numerical modeling, model scalability	Can develop and use methodologies for representing behavior at fine scales in models for the system at larger scales.
Multi-physics, multiscale modeling, numerical modeling, model scalability	Can develop and use the corresponding analytical tools and computational approaches needed to quantify the impact of the fidelity of finer-scale models on large-scale dynamics.
Multi-physics, multiscale modeling, numerical modeling, model scalability	Can develop and use algorithmic techniques appropriate for emerging computer architectures for simulating multi-physics and multiscale processes with quantifiable fidelity.
Multi-physics, multiscale modeling, numerical modeling, model scalability	Can develop and analyze numerical methods for hybrid models that couple continuum and discrete processes and determine how changes in the discrete variables affect the accuracy of the continuum part of the model.
Uncertainty quantification and modeling	Can perform modeling and analysis to design and predict uncertainty in behavior in a complex system.
Uncertainty quantification and modeling	Can perform modeling and analysis to design and predict optimal size and location of hardware sensing devices in a remote sensing network.
Uncertainty quantification and modeling	Can conduct sensitivity analysis for a complex system using a model.
Uncertainty quantification and modeling	Can quantify uncertainty in a complex system using a model.
Uncertainty quantification and modeling	Can apply mathematical inversion methods to optimize a complex system.
Uncertainty quantification and modeling	Can develop and use systematic methodologies for the estimation of system parameters, constitutive relations and uncertainties based on data;
Use of experimental data and numerical analysis	Can incorporate observational and experimental data to model and simulate a complex system.
Use of experimental data and numerical analysis	Can develop sound, computationally feasible strategies and methods for the collection, organization, statistical analysis, and use of data associated with complex systems.
Use of experimental data and numerical analysis	Can quantify the effects of uncertainty and numerical simulation error on predictions using complex models and when fitting complex models to observations.
Analyze and model materials and processes	Can perform modeling and analysis to design and predict structural support or containment for a complex system.
Analyze and model materials and processes	Can perform modeling and analysis to determine optimal properties of materials based upon historical material and process data.

Appendix 3. Relevant and Extracted Competencies from
the INCOSE Systems Engineering Competency Framework [22]

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
1	CORE SE Principles	Lifecycles	Identifies different lifecycle types (e.g., waterfall, Vee, incremental, iterative, spiral) and summarizes the key characteristics of each.	AWARENESS	2.7
2	CORE SE Principles	Lifecycles	Explains why selection of lifecycle is important when developing a system solution.	AWARENESS	2.7
3	CORE SE Principles	Lifecycles	Explains why it is necessary to define an appropriate lifecycle process model and the key steps involved.	AWARENESS	2.7
4	CORE SE Principles	Lifecycles	Explains why differing engineering approaches are required in different lifecycle phases and provides examples.	AWARENESS	2.3
5	CORE SE Principles	Lifecycles	Describes the key characteristics of differing lifecycles and how these relate to the system lifecycle.	AWARENESS	2.3
6	CORE SE Principles	Lifecycles	Describes systems engineering lifecycle processes.	SUPERVISED PRACTITIONER	2.3
7	CORE SE Principles	Lifecycles	Assists in lifecycle definition activities at system or system element level.	SUPERVISED PRACTITIONER	2.7
8	CORE SE Principles	Lifecycles	Describes the system lifecycle in which they are working on their project.	SUPERVISED PRACTITIONER	2.7
9	CORE SE Principles	Lifecycles	Identifies the systems engineering lifecycle processes in place on their project.	SUPERVISED PRACTITIONER	2.0
10	CORE SE Principles	Lifecycles	Identifies the advantages and disadvantages of different types of systems lifecycle and where each might be used advantageously.	SUPERVISED PRACTITIONER	2.3
74	CORE SE Principles	Lifecycles	Explains why it is important to consider future lifecycle stages in the current stage, with examples.	SUPERVISED PRACTITIONER	2.7
29	CORE SE Principles	Capability Engineering	Describes and illustrates the difficulties of translating capability needs of the wider system into system requirements.	AWARENESS	2.3

ID	COMP CATE-GORY	COM. AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
31	CORE SE Principles	Capability Engineering	Explains the concept of capability and how the use of capabilities to characterize systems can prove beneficial.	AWARENESS	2.3
32	CORE SE Principles	Capability Engineering	Explains how capability requirements can be satisfied by integrating several systems.	AWARENESS	2.3
33	CORE SE Principles	Capability Engineering	Explains how super system capability needs impact on the development of each system that contributes to the capability.	AWARENESS	2.7
30	CORE SE Principles	Capability Engineering	Assists in technology planning required to provide capability.	SUPERVISED PRACTITIONER	2.0
34	CORE SE Principles	Capability Engineering	Identifies, with guidance, capability issues from the wider system which will affect the design of a system of interest.	SUPERVISED PRACTITIONER	2.0
35	CORE SE Principles	Capability Engineering	Describes different elements that make up capability within own project, with examples.	SUPERVISED PRACTITIONER	2.7
61	CORE SE Principles	Capability Engineering	Describes the environment and the capability outcome required in own project.	SUPERVISED PRACTITIONER	2.3
36	CORE SE Principles	Critical Thinking	Explains why conclusions and arguments made by others may be based upon incomplete, potentially erroneous or inadequate information, with examples.	AWARENESS	2.3
37	CORE SE Principles	Critical Thinking	Explains why assumptions are important and why there is a need to ensure that they are based upon sound information.	AWARENESS	2.0
38	CORE SE Principles	Critical Thinking	Explains the relationship between assumptions and risk and why assumptions need to be validated.	AWARENESS	2.0
39	CORE SE Principles	Critical Thinking	Explains how own perception of arguments from others may be biased and how this can be recognized.	AWARENESS	2.0
118	CORE SE Principles	Critical Thinking	Explains why ideas, arguments and solutions need to be critically evaluated.	AWARENESS	2.3
42	CORE SE Principles	General Engineering	Explains why probability and statistics are both relevant to engineering, with examples.	AWARENESS	2.0

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
43	CORE SE Principles	General Engineering	Explains why uncertainty is an important factor in engineering and explains how it might arise from many sources.	AWARENESS	2.0
106	CORE SE Principles	General Engineering	Explains what an engineered system is and recognizes examples of engineered systems which are physical, software and socio-technical systems or combinations thereof.	AWARENESS	2.3
107	CORE SE Principles	General Engineering	Explains why analytical methods and sound judgement are central to engineering decisions.	AWARENESS	1.3
44	CORE SE Principles	General Engineering	Considers the nature and effect of variation in engineering tasks.	SUPERVISED PRACTITIONER	1.3
45	CORE SE Principles	General Engineering	Applies scientific and mathematical knowledge when performing engineering tasks.	SUPERVISED PRACTITIONER	1.3
17	CORE SE Principles	Systems Modeling and Analysis	Explains why system representations are required and the benefits they can bring to developments.	AWARENESS	2.0
18	CORE SE Principles	Systems Modeling and Analysis	Describes the scope and limitations of models and simulations, including definition, implementation, and analysis.	AWARENESS	1.7
19	CORE SE Principles	Systems Modeling and Analysis	Describes different types of modeling and simulation and provides examples.	AWARENESS	1.7
20	CORE SE Principles	Systems Modeling and Analysis	Explains how the purpose of modeling and simulation affects the approach taken.	AWARENESS	1.7
21	CORE SE Principles	Systems Modeling and Analysis	Explains the relevance of outputs from systems modeling and analysis, and how these relate to overall system development.	AWARENESS	1.3
22	CORE SE Principles	Systems Modeling and Analysis	Explains the difference between modeling and simulation.	AWARENESS	1.7
23	CORE SE Principles	Systems Modeling and Analysis	Describes a variety of system analysis techniques which can be used to derive information about a system.	AWARENESS	2.0
94	CORE SE Principles	Systems Modeling and Analysis	Explains why functional analysis and modeling is important in Systems Engineering.	AWARENESS	1.7

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24	CORE SE Principles	Systems Modeling and Analysis	Explains why models and simulations have a limit of valid use, and the risks of using models and simulations outside those limits.	SUPERVISED PRACTITIONER	1.7
25	CORE SE Principles	Systems Modeling and Analysis	Explains why models are developed for a specific purpose or use and provides examples.	SUPERVISED PRACTITIONER	1.7
26	CORE SE Principles	Systems Modeling and Analysis	Uses modeling and simulation tools and techniques to represent a system or system element.	SUPERVISED PRACTITIONER	1.7
27	CORE SE Principles	Systems Modeling and Analysis	Interprets and uses outcomes of modeling and analysis, with guidance.	SUPERVISED PRACTITIONER	1.7
28	CORE SE Principles	Systems Modeling and Analysis	Contributes to the model development and interpretation activities.	SUPERVISED PRACTITIONER	2.0
14	SE Management	Decision Management	Identifies the systems engineering situations where a structured decision is and is not appropriate.	AWARENESS	2.7
99	SE Management	Decision Management	Describes the relevance of comparative techniques (e.g., trade studies, make/ buy, etc.) to assist decision processes.	AWARENESS	2.0
100	SE Management	Decision Management	Explains why there is a need to select a preferred solution.	AWARENESS	2.3
101	SE Management	Decision Management	Assists with selection of decision criteria and performance parameters.	SUPERVISED PRACTITIONER	1.7
102	SE Management	Decision Management	Assists with the selection of tools and techniques for the decision process and provides examples of different tools and techniques.	SUPERVISED PRACTITIONER	2.0
103	SE Management	Decision Management	Assists with decision trade studies and records results.	SUPERVISED PRACTITIONER	2.0
12	SE Management	Risk and Opportunity Management	Describes the distinction between risk, issue, opportunity and can provide examples of each.	AWARENESS	2.3
13	SE Management	Risk and Opportunity Management	Lists key factors associated with good risk management and why these factors are important.	AWARENESS	2.3

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
11	SE Technical Processes	Design For…	Identifies analytical techniques and describes the importance of design integrity, legislation, whole life costs and customer satisfaction.	AWARENESS	2.7
15	SE Technical Processes	Requirements Definition	Identifies major stakeholders and their needs.	AWARENESS	2.0
16	SE Technical Processes	Requirements Definition	Identifies all stakeholders and their sphere of influence.	SUPERVISED PRACTITIONER	1.3
40	SE Technical Processes	Design For…	Explains why there is a need to accommodate the requirements of all lifecycle stages when determining a solution.	AWARENESS	2.7
41	SE Technical Processes	Design For…	Explains why it is important to integrate design specialties into the solution and how this can be a potential source of conflict with requirements.	AWARENESS	2.7
46	SE Technical Processes	Operation and Support	Explains why a system, product or service needs to be supported during operation and provides examples.	AWARENESS	2.3
47	SE Technical Processes	Operation and Support	Describes the difference between preventive and corrective maintenance	AWARENESS	2.0
48	SE Technical Processes	Operation and Support	Explains why it is necessary to address failures, parts obsolescence, and evolving user requirements during system operation.	AWARENESS	2.3
49	SE Technical Processes	Operation and Support	Lists the different levels of repair capability and describes the characteristics of each.	AWARENESS	2.7
50	SE Technical Processes	Requirements Definition	Describes different types of requirements (e.g., functional, nonfunctional, business etc.).	AWARENESS	2.0
51	SE Technical Processes	Requirements Definition	Explains why there is a need for good quality requirements.	AWARENESS	1.7
52	SE Technical Processes	Requirements Definition	Explains why managing requirements throughout the lifecycle is important.	AWARENESS	2.0
53	SE Technical Processes	Requirements Definition	Explains why there is a need to manage all types of requirements.	AWARENESS	2.0

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54	SE Technical Processes	Requirements Definition	Describes the characteristics of good quality requirements and provides examples.	SUPERVISED PRACTITIONER	2.0
55	SE Technical Processes	Requirements Definition	Describes different mechanisms used to gather requirements.	SUPERVISED PRACTITIONER	2.7
56	SE Technical Processes	Requirements Definition	Explains why there is a need for traceability in the requirements process.	SUPERVISED PRACTITIONER	1.3
57	SE Technical Processes	Requirements Definition	Assists with establishment of acceptance criteria for requirements.	SUPERVISED PRACTITIONER	2.3
58	SE Technical Processes	Requirements Definition	Identifies potential requirement conflicts within the requirement set.	SUPERVISED PRACTITIONER	1.3
59	SE Technical Processes	Requirements Definition	Explains how requirements affect design and vice versa and provides examples.	SUPERVISED PRACTITIONER	2.0
60	SE Technical Processes	Requirements Definition	Assists with the establishment and maintenance of requirements traceability information.	SUPERVISED PRACTITIONER	2.7
80	SE Technical Processes	System Architecting	Describes the process and key artifacts of functional analysis.	AWARENESS	2.3
81	SE Technical Processes	System Architecting	Explains why there is a need for functional models of the system.	AWARENESS	2.3
82	SE Technical Processes	System Architecting	Explains how outputs from functional analysis relate to the overall system design and provides examples.	AWARENESS	2.3
83	SE Technical Processes	System Architecting	Uses appropriate tools and techniques to conduct functional analysis.	SUPERVISED PRACTITIONER	1.7
84	SE Technical Processes	System Architecting	Describes the principles of architectural design and its role within the lifecycle.	AWARENESS	2.0
85	SE Technical Processes	System Architecting	Describes different types of architecture and provides examples.	AWARENESS	1.3
86	SE Technical Processes	System Architecting	Explains why architectural decisions can constrain and limit future use and evolution and provides examples.	AWARENESS	2.0
87	SE Technical Processes	System Architecting	Explains why there is a need to explore alternative and innovative ways of satisfying the requirements.	AWARENESS	2.0

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
88	SE Technical Processes	System Architecting	Uses a governing process and appropriate tools to manage and control their own system architectural design activities.	SUPERVISED PRACTITIONER	1.7
89	SE Technical Processes	System Architecting	Uses analysis techniques to support architectural design process.	SUPERVISED PRACTITIONER	2.0
90	SE Technical Processes	System Architecting	Interprets an architectural design.	SUPERVISED PRACTITIONER	2.0
91	SE Technical Processes	System Architecting	Contributes candidate concepts (no matter how radical).	SUPERVISED PRACTITIONER	1.3
92	SE Technical Processes	System Architecting	Assists with the assessment of the feasibility of concepts.	SUPERVISED PRACTITIONER	2.0
93	SE Technical Processes	System Architecting	Contributes to system architectural design activities.	SUPERVISED PRACTITIONER	1.3
104	SE Technical Processes	Design For…	Identifies the relationships between the integration of specialisms within their project and provides examples.	SUPERVISED PRACTITIONER	2.0
105	SE Technical Processes	Design For…	Assists with trade studies which determine and characterize specialty characteristics of proposed solutions.	SUPERVISED PRACTITIONER	2.3
108	SE Technical Processes	System Architecting	Contributes to alternative architectural designs that are traceable to the requirements	SUPERVISED PRACTITIONER	2.0
109	SE Technical Processes	System Architecting	Explains why alternative discipline technologies can be used to satisfy the same requirement and provides examples.	AWARENESS	2.3
110	SE Technical Processes	System Architecting	Assists with the architectural design trade-offs.	SUPERVISED PRACTITIONER	1.3
113	SE Technical Processes	Interfaces	Explains why there is a need for interface definition and management and its impact on the integrity of the system solution.	AWARENESS	2.3
114	SE Technical Processes	Interfaces	Identifies and describes possible sources of complexity in interface definition and management.	AWARENESS	2.0
115	SE Technical Processes	Interfaces	Identifies and defines simple interfaces.	SUPERVISED PRACTITIONER	2.0

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
119	SE Technical Processes	Integration	Explains why integration is important and how it confirms the system design, architecture and interfaces.	AWARENESS	2.0
120	SE Technical Processes	Integration	Explains why it is important to integrate the system in a logical sequence.	AWARENESS	2.3
121	SE Technical Processes	Integration	Explains why planning and management of systems integration is necessary.	AWARENESS	2.3
122	SE Technical Processes	Integration	Describes the relationship between integration and verification.	AWARENESS	2.0
123	SE Technical Processes	Integration	Assists with the identification of an integration environment.	SUPERVISED PRACTITIONER	2.0
124	SE Technical Processes	Requirements Definition	Describes the relationship between requirements and acceptance.	AWARENESS	1.7
125	SE Technical Processes	Transition	Explains why there is a need to carry out transition to operation, how it is performed and the benefits a controlled transition to operation brings.	AWARNESS	2.0
126	SE Technical Processes	Transition	Lists the type of activities and work products required for transition to operation and provides examples.	AWARNESS	2.3
127	SE Technical Processes	Validation	Explains what validation is, the purpose of validation and why validation is important.	AWARENESS	1.7
128	SE Technical Processes	Validation	Explains why there is a need for early planning for validation.	AWARENESS	1.0
129	SE Technical Processes	Validation	Describes the relationship between validation, verification, qualification, certification, and acceptance.	AWARENESS	2.0
130	SE Technical Processes	Validation	Describes the relationship between traceability and validation.	AWARENESS	2.0
131	SE Technical Processes	Validation	Explains why customer and communications both need to reflect the terminology of the customer or end user.	SUPERVISED PRACTITIONER	1.0
132	SE Technical Processes	Verification	Explains what verification is, the purpose of verification and why verification against the system requirements is important.	AWARENESS	1.0

ID	COMP CATE-GORY	COMP AREA	EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE	Two COMPETENCY LEVELS	Rank 1 = very important 2 = important 3 = not that important
133	SE Technical Processes	Verification	Explains why there is a need to verify the system in a logical sequence.	AWARENESS	1.7
134	SE Technical Processes	Verification	Explains why planning for system verification is necessary.	AWARENESS	1.0
135	SE Technical Processes	Verification	Describes how traceability can be used to establish whether a system meets requirements.	AWARENESS	2.0
136	SE Technical Processes	Verification	Describes the relationship between verification, validation, qualification, certification, and acceptance.	AWARENESS	2.0
137	SE Technical Processes	Verification	Uses verification to establish whether a system meets requirements.	SUPERVISED PRACTITIONER	1.3

Appendix 4. Relevant and Extracted Competencies from the
INCOSE Model-Based Enterprise Capabilities Matrix [23]

INCOSE MBSE Management Competency. Can Perform MBSE Management Practices for a Real-World Problem.

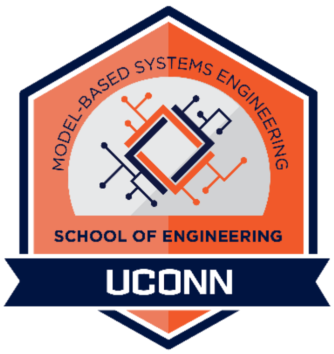
MBSE Management. Can Describe Modeling Roles and Responsibilities.	Fundamental
MBSE Management. Can Describe Knowledge, Skills, and Abilities for MBSE Practitioners.	Fundamental
MBSE Management. Can Develop an MBSE Use Strategy for their Organization.	Intermediate
MBSE Management. Can Conduct Model-Based Verification and Validation.	Intermediate

INCOSE MBSE Modeling Competency. Can perform Model Based Systems Engineering by System Modeling Using a Systems Modeling Language.

Modeling Skills. Can Describe Different Types of Model Languages.	Fundamental
Modeling Skills. Can Describe Different Types of System Modeling Methods.	Fundamental
Modeling Skills. Can Develop a Systems Engineering-Driven Model Plan.	Fundamental
Modeling Skills. Can Define Model Metrics.	Fundamental
Modeling Skills. Can Describe and Apply the Systems Engineering Technical Processes to a Real-World Problem.	Fundamental
Modeling Skills. Can Develop a High-Quality Systems Model Based Upon a Defined Purpose.	Fundamental
Modeling Skills. Can Model Stakeholder Requirements.	Fundamental
Modeling Skills. Can Develop a High-Quality Systems Model Using SysML or Other Standard System Model Language.	Fundamental
Modeling Skills. Can Analyze Systems by Simulation.	Intermediate
Modeling Skills. Can Verify and Validate Models.	Intermediate
Modeling Skills. Can Define and Develop Model Libraries.	Intermediate
Modeling Skills. Can Conduct Model Based Reviews.	Intermediate
Modeling Skills. Can Integrate Models.	Intermediate
Modeling Skills. Can Quantify Model Process Quality.	Intermediate
Modeling Skills. Can Use Existing Models for Analysis Based Upon Different Types of Needs.	Intermediate

Appendix 5. Example Credly Badge and Competencies
for Model-Based Systems Engineering
See UConn SE Badges and Competencies:
https://www.credly.com/organizations/university-of-connecticut/badges

Model-Based Systems Engineering



Earners of the Model Based Systems Engineering Badge have developed skills in the discrete modeling and simulation of cyber-physical systems using a systems engineering approach and can construct high quality systems models using the SysML modeling language and an MBSE tool. They can analyze sensitivity of cyber-physical designs for variability and uncertainty in the context environment and perform verification and validation of requirements, design, systems, and systems models.

Earners of the Model Based Systems Engineering Badge have developed skills in the discrete modeling and simulation of cyber-physical systems using a systems engineering approach and can construct high quality systems models using the SysML modeling language and an MBSE tool. They can analyze sensitivity of cyber-physical designs for variability and uncertainty in the context environment and perform verification and validation of requirements, design, systems, and systems models.

Skills

- Complex System Modeling
- Cyber-Physical Systems
- Manage Design Change
- Meta System Modeling
- Model-Based Systems Engineering
- Model-Based Systems Engineering Management
- Model-Based Systems Engineering Modeling
- SysML
- System Design
- Systems Analysis
- Systems Architecting
- Systems Engineering
- Systems Modeling
- Systems Thinking
- Uncertainty Quantification
- Validation
- Verification

Earning Criteria

- Badge earners complete SE 5001 Model Based Systems Engineering course at the University, which is a hybrid-online graduate course that can be taken from anywhere in the world. Earners can take this graduate course as a matriculated UConn graduate student or as a non-degree graduate student, which does not require admission to the UConn graduate school. Badge holders complete a course-long project and must earn a B- or better on this project to earn the badge.

- Badge earners can perform MBSE management practices for a real-world problem, can describe modeling roles and responsibilities, can describe knowledge, skills, and abilities for MBSE practitioners, can develop a MBSE use strategy for their organization and can conduct model-based verification and validation. See Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix below.
- Badge earners can perform MBSE by system modeling using a systems modeling language, can describe different types of systems modeling languages and methods, can develop a systems engineering-driven model plan, can define model metrics, can develop a high-quality systems model based upon a defined purpose, can model stakeholder needs, and can develop a high-quality systems model using SysML or other standard language. See Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix below.
- Badge earners can analyze systems by simulation, can verify and validate models, can define and develop model libraries, can conduct model-based reviews, can integrate models, can quantify model process quality, and can use existing models for analysis based upon different types of needs. See Standard [4] INCOSE Model-Based Enterprise Capabilities Matrix below.
- Badge earners can explain why models and simulations have a limit of valid use and explain the risks of fusing models and simulations outside those limits, can explain why models are developed for a specific purpose, can use modeling and simulation tools and techniques to represent a system or system element, can interpret and use outcomes of modeling and analysis, with guidance, and can contribute to the model development and interpretation activities. See Standard [3] INCOSE ISECF below.
- Badge earners can design large-scale meta systems and predict behavior and performance with systems models during early phase design, can perform modeling and analysis to design and predict operating characteristics for a complex system, can perform modeling and

analysis to design and predict when changing meta system conditions cause system failures, See Standard [2] DOE-SIAM below.

- Badge earners can perform modeling and analysis of a stochastic system and simulate it to understand performance based upon performance measures, can decompose complex systems into canonical subsystems to design and predict system behavior and elucidating the coupling between components, can optimize a system to meet stakeholder needs and best engineering practice standards, and can perform modeling and analysis to quantify cost, schedule, and technical risk. See Standard [2] DOE-SIAM below.
- Badge earners can manage design change through system modeling, can perform modeling and analysis to design and predict the effects of introducing a new technology into a current complex system, can modify a model of a complex system to introduce to new data types and formats, can conduct sensitivity analysis for a complex system using a model during early phase design, and can define and quantify uncertainty in systems flows and processes for a systems model. See Standard [2] DOE-SIAM below.
- Badge earners can apply knowledge of how cyber-physical system methods integrate at the large, meta system level, can design and develop cyber-physical system architecture, can develop and update formal specifications for cyber-physical designs and systems, can develop and update verification and validation methods for cyber-physical designs and systems, can apply Systems Engineering methods and principles to the design and operation of a cyber-physical system. See Standard [1] NAE-CPS below.
- Badge holders complete a course-long project consisting of a proposal, midterm and final reports, and systems model artifact. The project consists of creating and developing a systems model that represents the design of a real system using an MBSE tool and a systems modeling language. The model must be defined and simulated to solve a particular problem. The model is simulated to determine if requirements and key performance parameters are met.

Standards

[1] NAE-CPS

A 21st Century Cyber-Physical Systems Education. Committee on 21st Century Cyber-Physical Systems Education; Computer Science and Telecommunications Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine. ISBN 978-0-309-45163-5 | DOI: 10.17226/23686.

[2] DOE-SIAM

SIAM APPLIED MATHEMATICS AT THE U.S. DEPARTMENT OF ENERGY: Past, Present and a View to the Future. A Report by an Independent Panel from the Applied Mathematics Research Community May 2008.

[3] INCOSE-ISECF

INCOSE Model-Based Enterprise Capabilities Matrix 2.0b Draft June 2019 r4. Joe Hale, NASA

[4] INCOSE Model-Based Enterprise Capabilities Matrix

INCOSE Systems Engineering Competency Framework. July 2018. INCOSE Technical Product Reference: INCOSE-TP-2018-002-01.0