WIP: Convergent Systems Engineering: A Modular, Agile Master's Program for Multi-Scale Systems

Jon Wade
Mechanical and Aerospace Engineering
University of California, San Diego
La Jolla, California, US
jpwade@ucsd.edu

Hyoduk Shin
Rady School of Management
University of California, San Diego
La Jolla, California, US
hdshin@ucsd.edu

Richard Gessner
Electrical and Computer Engineering
University of California, San Diego
La Jolla, California, US
rgessner@ucsd.edu

***Abstract*—This work in progress innovative practice paper describes a novel curriculum and pedagogy used in a systems engineering graduate program that provides ethical, innovative and sustainable solutions to important, complex societal problems using convergent transdisciplinary, collaborative, team-based approaches. Convergent engineering approaches have been applied to the program itself to foster collective learning through iterative rapid integration and testing in real world scenarios. This paper presents the motivation, approach, program, pedagogy, and curriculum for the Convergent Systems Engineering master program which supports three major systems scales from products and services, to the enterprise, and finally global value supply chains.**

Keywords—Systems Engineering education, Systems Engineering graduate programs, Systems Engineering curricula and pedagogy, agile education, value supply chains, ethical sustainability

I. Background

A. *Systems Engineering at Multiple Scales*

The global community is calling for more attention to how systems can positively contribute to our social condition and natural environment, advancing our quality of life. This is evidenced by major movements in social, technical, and financial organizations. Large and often complex engineered systems are key to addressing systems that satisfy physical, psychological, economic, and cultural needs. These systems must be embedded in the prevailing social, physical, psychological, economic, and cultural environment, and the technologies applied to system solutions must be tailored to the relevant local or regional capabilities and resources. Full life-cycle analyses and safe, robust, and sustainable implementation approaches, along with stable governance environments and the communication of their effects in engineering design solutions, are enablers for successful system solutions. A systems-oriented approach is needed to solve the planet's grand challenges, which are systemic in nature [1].

Systems Engineering has been defined as, "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [2]." As such, systems engineering approaches can be applied to many different systems scales. We believe that significant complex systems scales are: products and services, the enterprise, and value supply chain networks.

Traditionally, systems engineering has been applied to products and services in which the human user or operator was only considered as an afterthought. Increasingly, humans are closely involved with the operation of the system, not only as individuals, but as social units. While most think about people using systems, many complex systems (such as the smart grid, or smart cities) are actually a combination of computers, machines and people all working together to achieve the goals of the systems. Cyber-physical social systems (CPSS) are systems that integrate computing, physical assets, and human networks over the lifecycle from concept to deployment and evolution.

Enterprises are organizations that typically are responsible for the development and/or operation of a variety of products and services. The systems engineering approaches can be used to enable enterprises to better respond to the challenges of globally distributed operations in complex, highly dynamic, event-driven environment. An integrated perspective that merges the views of management and engineering communities is increasingly recognized as one of the cornerstones of a successful approach to enterprise complexity.

Supply chains have been defined as, "the flow of all information, products, materials, and funds between different stages of creating and selling a product to the end-user. The concept of the supply chain comes from an operational management perspective. Every step in the process—including creating a good or service, manufacturing it, transporting it to a place of sale, and selling it—is part of a company's supply chain [3]." These flows are shown in Figure 1. The Value Supply Chain (VSC) combines the supply chain and value chain concepts to include their impact on the sustainability of society, the environment, and economies. Practices in disposal, circular supply chain operations, and labor, and the sustainability of each, are in the scope of the VSC, dramatically expanding their design complexity beyond the traditionally narrow view and highlighting the need to apply System Engineering to design and implement them optimally.

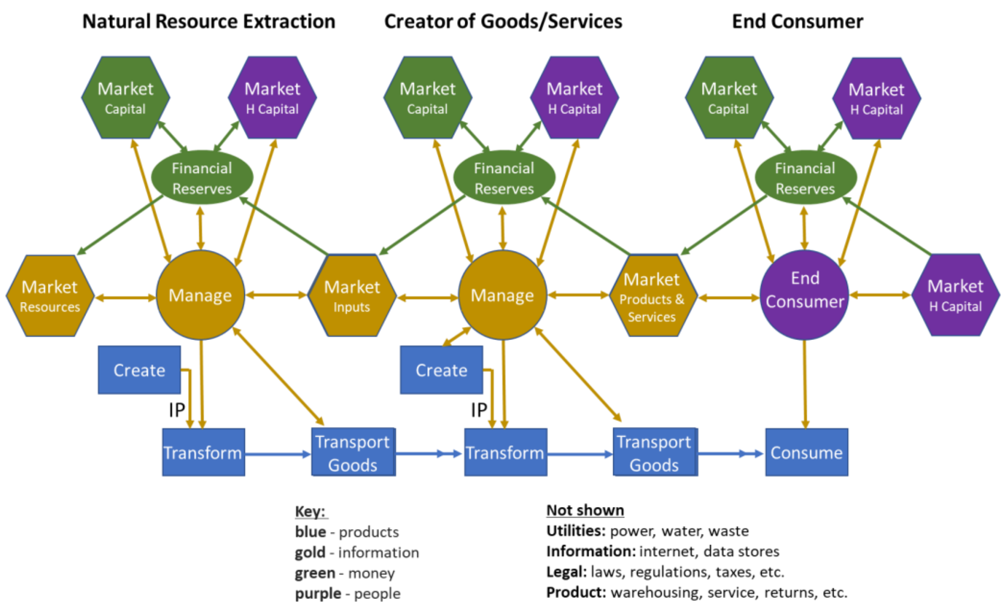

Fig. 1. Value Supply Chain

B. *Vision & Mission*

Systems Engineering (SE) education is challenged to address the technical leadership needs posed by rapidly changing technology epitomized by Industry 5.0, digital transformation and the rapid advances of AI/ML [4]. In 2018 the Jacobs School of Engineering's Systems Engineering Visioning Committee was formed to develop a Jacobs School vision for an educational program to educate systems engineering leaders for the 21st century. In preparing this White Paper, numerous faculty members representing all six engineering departments talked to more than a hundred industry executives, surveyed hundreds of students and evaluated systems engineering programs at our competing universities. As a result of those efforts, a white paper was produced which described the Jacobs School's commitment to launching a systems engineering program based on convergent principles designed to prepare our graduates to be leaders and innovators in tomorrow's rapidly advancing, and globally connected organizations. At the heart of our systems engineering program will be a focus on closed-loop system design deeply leveraging AI/ML and data science built to constantly evolve and improve.

Our Vision:

To provide ethical, innovative and sustainable solutions to important, complex societal problems using transdisciplinary, collaborative, team-based approaches to foster collective learning through iterative rapid integration and testing in real world scenarios.

In December 1983, the United Nations created an independent organization, the Brundtland Commission, to focus on environmental and developmental problems and solutions. The resulting Brundtland Report [5] defined sustainability as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The three main pillars of sustainable development include economic growth, environmental protection, and social equality. The challenge becomes how to ethically balance these three factors. We call this balance, Ethical Sustainability. This is the focus of our research and education mission.

Our Education Mission:

To educate students locally and globally to be effective future systems leaders, supporting the vision, while using the classroom as a laboratory to both validate systems research, and utilize it to revolutionize the practice of education.

We expect that graduates of our educational program will lead the engineering and operation of ethically sustainable products, services, and supply chains. This is being accomplished through convergent research and education with the development of modeling and simulation tools, design methodologies, course curricula, and pedagogy. The classroom will be the laboratory for this work. It is our desire to achieve for sustainable systems in Industry 4.0 what was accomplished in the early 1980s that enabled the third industrial revolution for the electronics industry [6].

II. Educational Objectives

A. *Approach & Core Values*

In 2015, the National Academies established the Committee on a Vision for the Future of Center-Based, Multidisciplinary Engineering Research to address the needs of the times. This Committee defined convergent engineering as, "a deeply collaborative, team-based engineering approach for defining and solving important, complex societal problems. All necessary disciplines, skills, and capabilities are combined to address a specific research opportunity. It is distinguished by resolutely using team-research and value-creation best practices to rapidly and efficiently integrate the unique contributions of individual members and develop valuable and innovative solutions for society [7]." This systems approach embraces the complexity of the context and underlying systems that compose products, services, the enterprise, and global supply chains. As such, it is understood that these are not deterministic systems that can be concretely defined, planned, and optimized using traditional Operations Research and Industrial Engineering approaches, but rather require approaches that might be more familiar to scientists, and suitable for non-closed form data analytic and simulation approaches. These are evolving, rather than static systems.

To support the evolutionary nature of the complex systems and the convergent systems approach, our program supports the following core values and practices:

- Openness, transparency, and the willingness and ability to learn quickly which are necessary for the successful evolution of complex adaptive systems. These depend upon an environment of diversity, equity, inclusion, and respect.
- Transdisciplinary, collaborative teams, using agile, model, and data-driven approaches, with rapid, small units of work, focusing on learning with agile Orient-Observe-Decide-Act (OODA) loops.
- Tight coupling between research, education, and practice, using the classroom as a laboratory to test new concepts, research as a classroom to discuss new approaches, and practitioner mentorships to share pragmatic wisdom.
- Focus on the convergence of human and machine decision-making, resulting in augmented intelligence and continually evolving learning systems. Incorporate ethical decision-making in the foundation.
- Open sharing of our research results, technology, educational materials, and pedagogy as a means to rapidly scale the global impact of our work.

B. *Competency Focus Areas*

In UCSD's efforts to best serve their students and sponsors, a survey was created to record the needs of Jacobs School of Engineering's Corporate Affiliate Program (CAP) corporate partners for systems competencies both for engineering new college graduates (NCGs) and early to mid-career engineers (MCEs) who are working in their organizations [8]. Thirty-seven competencies, each with five proficiency level based on INCOSE's Competency Framework [9] were included in this survey. The desired and actual perceived proficiency levels for each competency were noted, along with the resultant gap. The competencies with the top five greatest gaps and desired proficiency levels for NCGs and MCEs are shown in Tables 1 and 2, respectively. These competencies are some of the areas of primary focus in the MAS of Convergent Systems Engineering (CoSE) program.

Table 1. Competencies with Largest Proficiency Gaps for NCGs

Competency	Proficiency Level	Gap
Systems Thinking	2.28	1.24
Ethics & Professionalism	2.78	1.00
Communication	2.39	1.00
Concurrent Engineering	1.50	0.79
Design of Experiments	2.06	0.76
General Engineering	*2.28*	*0.41*

Table 2. Competencies with Largest Proficiency Gaps for MCEs

Competency	Proficiency Level	Gap
Systems Modeling & Analysis	3.65	1.19
Systems Thinking	3.76	1.00
System Architecting	3.44	1.00
Communication	3.65	0.94
Decision Management	3.53	0.94
Facilitation	3.35	0.94
General Engineering	*3.76*	*0.56*

Typical science-based proficiencies are highlighted in red, social sciences in yellow, management in orange, and engineering are blue.

C. *Target Market*

As stated above, the objective of this program is to educate the future leaders who are ready to engage in an international, highly competitive marketplace, and propel their classroom and laboratory learning straight into industry impact in products, services, the enterprise, and value supply chains. As such, we value quality over quantity, and thought leadership over institutionalized thinking. The critical elements of our program are that it is relevant, forward looking, and provides immediate value to practicing professionals. We believe that this can best be accomplished by focusing on both new college graduates with relevant experience, and early- and mid-career professionals in engineering, supply chains or related areas.

As such, this engineering-focused professional degree program is designed for early and mid-career professionals in engineering, supply chain, operations, and industrial engineering roles to step out of the workforce for a short period, receive intense, practical training in supply chain fundamentals and leadership skills, and then return to the workforce at a higher level of responsibility. The program provides organizations of all kinds with engineers and supply chain professionals who are highly trained in both analytical problem solving and transformational leadership.

III. Program, Pedagogy, and Curriculum

A. *Program*

The pioneering Masters of Advanced Studies (MAS) in Architecture-based Enterprise Systems Engineering (AESE) program was created by the Jacobs School of Engineering, in collaboration with the Rady School of Management, to address these issues by educating professional engineers in the processes, structures, and formal methods through which enterprise systems are architected, integrated and made inter-operable. Since its creation, these same approaches and techniques have increasingly been applied on smaller scale products and services, which are the products of the enterprise, and on a broader scale to supply chains which are systems of systems.

In response, the MAE Department is expanding the scope of the existing MAS in AESE program to cover this system space by extending its curricular, pedagogical and administrative framework to support two new specializations: "Cyber-Physical Social Systems" (products and services) and "Value Supply Chains" (systems of systems), while retaining the current AESE degree as a specialization (enterprise). This expanded MAS degree containing all three specializations is entitled "Convergent Systems Engineering". This is accomplished using five of the existing courses in the AESE program as core courses, with four domain specific courses in each of the two new specializations, along with a domain specific capstone project for each. The MAS of CoSE course structure is shown below in Figure 2.

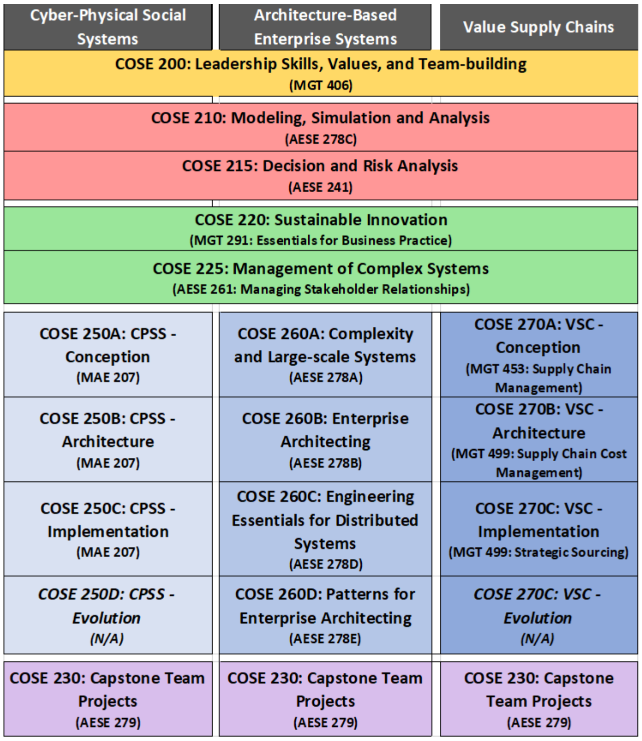

Fig. 2. MAS for Convergent Systems Engineering program courses

B. *Pedagogy*

A critical aspect of the pedagogy of this program is that it supports the convergent engineering values and principles described earlier, namely, 1) Openness, transparency, and the willingness and ability to learn quickly, 2) Transdisciplinary, collaborative teams, using agile, model, and data-driven approaches, with rapid, small units of work, focused on learning, 3) Tight coupling between research, education, and practice, using the classroom as a laboratory to test new concept, and 4) Focus on the convergence of human and machine decision-making, resulting in augmented intelligence and continually evolving learning systems. Incorporate ethical decision-making in the foundation. The program is fundamentally one of collaborative teams, working together using both proven and experimental agile approaches on real-life projects. A team-based keystone program is threaded through the entire program, with each course having both team assignments targeted towards these keystone projects, and individual assignments to ensure that personal skill development.

The program is composed of tightly integrated courses that are sequenced such that a core course is delivered prior to a specialization course which deeply utilizes its competencies. For example, the first course is in Leadership Skill and Team-building which supports the development of the keystone project teams. This is followed by the Sustainable Innovation course which provides a foundational background in systems thinking, sustainability, ethics and innovation. With this, students enter a specialization course in Conception. This is followed by a core course in Modeling, Simulation, and Analysis which provides expertise which is needed in the next specialization course in Architecture. This is followed by a course in Decision and Risk Analysis which supports the following specialization course in Implementation. Finally, a course in the Management of Complex Systems provides the skills necessary in the specialization course of Evolution. The program is completed with a capstone experience which is the conclusion of the key-stone project.

A team-based, participatory approach is used in each of the courses. We follow a 70:20:10 learning model in which we believe about 10% of the learning comes directly from the lecture, 20% from mentoring and classroom interactions, and 70% from project work. Each course follows an agile spiral development process which consists of two hour modules (i.e., sprints) that include a lecture, group work, and class discussion. Typically, each course is composed of approximately 8 - 16 modules. Currently, these modules are completed in four full day sessions, typically on two sets of Friday – Saturdays, from 9am to 6pm. Students can attend in person or online remotely. However, four courses are completed in a four day sequence that must be attended in person. The time to degree is two calendar years for part-time students and one calendar year for full-time students.

C. *Curricula*

The curricula is composed of five core courses, four specialization courses, and keystone/capstone courses which are described below.

1) *Core Courses*

The required five core courses for each specialization are described below.

<u>COSE 200: Leadership Skills, Values, and Team-building</u>: Explores how to provide a learning environment for team-building through the understanding of global culture, self and others, while building critical thinking, emotional intelligence and ethical principles, which supports creative collaborative efforts in a diverse, equitable, and inclusive environment.

<u>COSE 220: Sustainable Innovation</u>: Combines the contextual analysis of systems thinking to ensure social, environmental and economic sustainability, with entre/intrapreneurial approaches to innovation to provide the foundations for the conceptualization and engineering of complex systems. The focus is on systemic, ethical sustainability.

<u>COSE 210: Modeling, Simulation, and Analysis</u>: Provides an introduction to the field of modeling and simulation, in both conceptual and physical settings. This considers the complete life-cycle, and explore methodologies related to testing, verification, validation, optimization, and certification, with a central focus on Model-based Systems Engineering (MBSE).

<u>COSE 215: Decision and Risk Analysis:</u> Covers classic concepts of risk analysis, risk metrics, and risk acceptance criteria including qualitative and quantitative methods for risk analysis. The use of artificial intelligence and machine learning methods will be explored to transform the process of risk management and decision-making.

COSE 225: Management of Complex Systems: Enables students to utilize systems concepts to ensure that appropriate data centric tools and agile methodologies are utilized in the formation and management of an effective complex system program. Topics include: computational tools for project coordination and management; real time electronic documentation as a critical design process variable.

2) Specialization Courses

The four specialization courses, in all specializations, are focused on the lifecycle of engineering which is conception, architecture and design, implementation, and evolution. It is only by considering the entire lifecycle that systems can be engineered that are well suited to their purpose and sustainable economically, environmentally, and socially.

As shown in Figure 2, four specialization courses and a keystone project are required for each of the three specializations in addition to the five previously mentioned core courses. While the four specialization courses are different for CPSS, AESE, and VSC they follow a common Conceive, Development, Implement, and Operate (CDIO) approach. The final course is entitled "Evolution" as this is more consistent with the reality of DevOps environment. The specialization courses for CPSS are described below and thematically represent of the course sequences for AESE and VSC.

CoSE 250A: CPSS Conception: Focused on the transformation of opportunity into concept: understanding customers and markets. Students transform the definition of a problem in a technical social context to system concepts, use-case scenarios and technical requirements using a model-based approach.

CoSE 250B: CPSS Architecture: Studies the ways architectures are developed and represented. Involves analysis of well-known architectural types, using case studies as illustrations. Uses a studio approach in the composition of design, best-practices in evaluating architectures with respect to suitability to task, and subsequent improvement..

CoSE 250C: CPSS Implementation: Explores methods for implementing and evaluating systems for correctness, efficiency, performance, scalability, and reliability, including Measures of Effectiveness and Performance. Skills covered include design, inspection, unit-level testing, and integrated system-level analysis, using AI/ML approaches.

CoSE 250D: CPSS Evolution: Focuses on the evolution of a system on three levels: policies, processes and infrastructure to respond to quality issues for the released system; drive the evolution of the system's capabilities based on evolving market needs and enabling technologies; and proactively "disrupt" the market by reframing the opportunity and reinventing the system.

3) Keystone and Capstone Courses

Finally, the keystone experience provides connectivity between all of the skills learned throughout this program, channeling these towards the solution of relevant, complex systems challenges at the desired scale. The real world nature of these challenges motivates the students to pick up and use the kills that will be relevant to their professional career. We are actively partnering with industry to help us define these capstone challenges such that they can serve as test cases for the advancement of the state of the art, blending education with research.

IV. Conclusion

The curriculum have been architected and designed for updates and evolution. The foundational course structure and pedagogy is one that has been proven with over fifteen years of success in the joint Jacobs School of Engineering and Rady School of Management Masters of Advanced Studies (MAS) Architecture-based Enterprise Systems Engineering (AESE) program. This program has been rearchitected to be modular, flexible and provide the ability for core courses to be adapted to the needs of system specializations ranging from products and services, to the entire, and finally to global value supply chains. It is expected that each of these courses will have the flexibility to address the needs of a diverse student population and will evolve over time to meet the changing needs of the market. It is our intention to tightly couple research and education, with the classroom providing a working laboratory for the latest in research results. The expanded MAS of CoSE program has been approved, the core courses are being delivered the academic year of 2023, with a launch of the two new CPSS and VSC specializations planned for the Fall of 2024.

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