The Current State and Future Needs of Systems Engineering Education: A Proposed Curriculum

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Thomas J. Gwilliam
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Technical Project Team Members
Salem Keleta
Maggie Salomonsky
Vinay Vangala
Mia Varghese

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

William Scherer, Department of Systems Engineering

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Thomas J. Gwilliam, Salem T. Keleta, Maggie D. Salomonsky, Vinay V. Vangala, Mia E. Varghese, Matthew W. Burkett, William T. Scherer, *Member, IEEE*

Abstract— **Since the first use of the term "systems engineering" in the 1940's, the discipline has progressed significantly as the complexity of systems and the development of technology continue to increase. This paper examines the current state and evolution of systems engineering and systems engineering education. The paper first identifies the current state of systems engineering by recognizing systems engineers' roles, responsibilities, and expectations. Following the current state of systems engineering, the changes needed are addressed through multiple frameworks and skill sets that will be critical to the evolving industry. The paper also explores the future of systems education focusing on content, content delivery, cost, and student cooperation. The analysis suggests that universities could adjust their curriculum to better align with the demands of the industry. The paper concludes with an overview of potential solutions designed to meet the needs of systems engineers by preparing them for the growing and multifaceted industry demands of the future.**

I. Introduction

According to the International Council on Systems Engineering (INCOSE), Systems Engineering (SE) is 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" [1]. NASA explains further how the discipline seeks a "safe and balanced design in the face of opposing interests and multiple, sometimes conflicting constraints" [2]. With this discipline being so fundamental to launching successful systems, it is vital to develop a holistic understanding of how this area of study interacts within education and the workforce, and where the practice is headed in the future.

II. What is a systems engineer?

a. A. *Definition and Early History*

A systems engineer is "generally responsible for the overall planning, design, testing, and production of today's automatic and semi-automatic systems" [3]. As this generalized description encapsulates much of the traditional obligations of a systems engineer, the role of a systems engineer has evolved over time, altering the necessary skill set for individuals within differing organizations. Early systems engineers in the mid to late 20th century focused on identifying problems and finding optimal solutions. This naturally transitioned to a more defined focus on processes and process optimization. This new identity of a systems engineer uses the systems engineering framework and approach to realize conceptual solutions given the physical constraints of their respective problems. The system's life-cycle process is critical in implementing successful solutions, especially as complex solutions become increasingly digital in the age of technology. Satisfying the users, or what is often referred to as validating the correct system, is just as critical as making sure the engineered system satisfies the technological specifications. This enables verification that the system is correct [4].

b. B. *Roles in Systems Engineering*

Systems engineering is a broad field allowing systems engineers to be tasked with different responsibilities and job titles. Some roles that would fall under systems engineering include [5]:

- Systems analyst: confirms the designed system will meet requirements
- Test engineer: plans and implements the system verification and validation program
- Systems engineer: serves as the proactive troubleshooter and systems designer who is responsible for creating the high-level system architecture and design.

Additionally, systems engineers work closely with project managers and design engineers to ensure the product meets the requirements and stays within the program schedule and cost [6]. While systems engineers are trained for and assigned many responsibilities, the necessary traits and skills of systems engineers will continue to evolve.

c. C. *Changes in Requirements for Systems Engineers*

The complexity of systems and the market need for system engineers is evolving with technology. Systems engineering has grown from the traditional approach to integrating more aspects and skillsets to reflect the expanding needs of the industry. Through research conducted on Evidence-Based Systems Engineering, a framework was developed that combines scientific knowledge with data analytics to produce evidence to make systems engineering decisions [7]. As systems engineering integrates more analytical skill sets, systems engineers will need to incorporate these skill

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M. W. Burkett (mwb5x@virginia.edu).
T. J. Gwilliam (e-mail: tg4znf@virginia.edu).
S. T. Keleta (e-mail: stk4mqg@virginia.edu).
M.D. Salomonsky (e-mail: ms4azb@virginia.edu).
W. T. Scherer (e-mail: wts@virginia.edu).
V. V. Vangala. (e-mail: vvv8mgv@virginia.edu).
M. E. Varghese (e-mail: mev5qf@virginia.edu).

sets to be successful as the aspects to maintain their value in the evolving optimization space. In addition to analytical skills, the workforce is looking for engineers who have been exposed to and understand innovation and entrepreneurial activities as it's critical for the growth of corporations [8]. Furthermore, additional skills such as Model-Based Systems Engineering (MBSE) are growing to become a critical aspect of systems engineering [9]. MBSE, which uses modeling to support systems requirements, is becoming increasingly important in several industries, especially those with complex systems like manufacturing and supply-chain-oriented businesses.

When assessing the skills of systems engineers in industries, MITRE Systems Engineering Competency Model created five categories [10]:

2. Enterprise Perspective; comprehension viewpoint, innovative approaches, foster stakeholder relationships
3. Systems Engineering Life Cycle; traditional systems engineering processes, such as design and development, systems implementations, and test and evaluation
4. Systems Engineering Planning and Management Systems; planning and managing the systems engineering activities such as risk management and logistics
5. Systems Engineering Technical Specialities; systems engineers working with specialty engineering in different disciplines such as human-centered engineering, modeling and simulation, cost/benefit analysis
6. Collaboration and Individual Characteristics; collaboration skills and communication as systems engineers need to be able to articulate and express their vision to other teams and disciplines

As systems engineers enter the workforce, the skills needed have progressed past the traditional systems life-cycle process. These skills need to be incorporated into the future of higher education systems engineering curricula because the demands of systems engineers will continue to develop as systems become more complex.

Many systems engineers find themselves in organizations that commonly focus on adjacent engineering disciplines. As the complexity of civil, mechanical, and chemical engineering systems necessitates greater overarching system management, graduates of both undergraduate and graduate SE programs often find themselves focused on optimizing processes surrounding other disciplines in a managerial capacity [11]. While employment opportunities around project management, project development, consulting, and design are common, the generalizable nature of the SE skill set offers a massive value to almost any company or firm. Education and curricula must be aligned to the needs of industry in order to best prepare SE graduates for the roles they could take on.

III. Methodology

The current state of content for systems engineering does not meet the evolving business and technological needs of today. With an analysis of current programs, there is still a need for product development and innovation in coursework. There is also a need for a new method of content delivery, which in the future will likely be hybrid. With growing hybrid learning demands and evolving SE content, the systems engineering curriculum must be modified to meet these needs and prepare students for a new workforce.

a. A. Landscape of Systems Engineering Content

The content of Systems Engineering (SE) education has been undergoing debate since the early 1970s and is still being debated today over what is included in its curriculum, what topics are most relevant, and what the best combination of technical and managerial lessons is for the modern age [12]. Ideally, SE simultaneously permeates a multitude of disciplines while attacking the forefront of technology development. Considering that technology is an ever-expanding field in and of itself, maintaining an accurate and innovative curriculum for the intersection of business and technology is of utmost importance [13]. However, current systems engineering programs lack in their implementation of an entrepreneurial mindset, even considering its importance [14].

Research by Brown and Scherer (2000) grouped systems engineering programs into one of four major content categories: systems analysis and design, industrial/manufacturing engineering, traditional control systems, and control systems among other topics [15]. While thorough for the state of the profession at the time, current systems engineering programs have not adapted to workplace changes, making it easy to group them into one of these decades-old categories, with a major focus of current systems engineering programs on analytics, preparing current students to be consultants or data analysts. A proposed reference framework for systems engineering aligns closely with the current state of systems engineering education content, with a foundation in math and statistics, an introduction to general systems engineering, core courses in modeling and design, and the opportunity for specialization courses in topics such as software engineering and finance [16]. These general ideas can also be described as various "flavors" of systems engineering: systems thinking, mathematical analysis, engineering component - whole relationships, and engineering deployment processes. Unfortunately, most programs today, even while following some or all of these flavors, still contain major gaps in topics such as system resilience and topics within optimization [17].

Other studies cite gaps between industry and academia in even the most basic topics, such as systems analysis [18]. As stated more succinctly in a proposal for a portal connecting academia and industry, "our education systems are not capable of evolving at the rate necessary to meet the challenges presented by rapidly changing technology" [19]. Systems engineering education content is currently an artifact of the past separated from industry and adapting far too slowly to the new industrial revolution.

b. B. Landscape of Systems Engineering Content Delivery

Current content delivery tactics aid students in understanding the “interoperability” of systems analysis, due to the nature of its broad applications [20]. However, such interoperability becomes subject to future threats if systems are not robust enough to mitigate threats, such as data breaches. “Social network analysis” helps students to understand responsible and robust ways of maintaining interoperable systems.

One reason for the ease with which technology threats can overwhelm current systems is that current teaching practices are not evolving at the rate necessary to match the technology industry. Digital transformation, or “digital disruption”, causes vulnerabilities in the technology space if users, instructors, and students do not practice responsible social network analysis, and thus understand the factors causing such vulnerabilities [12]. In the educational space, the capabilities, desires, and needs of users must be transparently discussed [21].

c. C. Evaluation of Current Programs

The need for a hybrid cohort model with education in product innovation and entrepreneurship is not satisfied through current market offerings. Looking at 11 Masters in Systems Engineering (or adjacent concentrations) program offerings in the Mid-Atlantic Region (Table 1) revealed the following commonalities amongst some or all programs:

- A standardized structure of a set of core courses developed to provide a baseline understanding of systems concepts and practices supplemented with 3 - 5 more specialized elective track course offerings.
- A high degree of modeling-focused course offerings as well as a frequent emphasis on data analysis.
- A common thread of management-oriented skill set building.
- Utilization of a part-time/limited engagement structure in which students can determine the timeline of the program by varying the courses taken per semester leading to a disjointed class graduation size and ranging program durations. Furthermore, it is recognized that this structure limits the available interaction between students as the involvement of a student at any given point may be different from others.
- Highly volatile tuition cost range with all in tuition between less than $10,000 to over $60,000, with a typical program costing within the $30,000 - $40,000 range. This variation in the tuition was frequently correlated with the course structure as the online format likely required a reduced operational cost.
- Company partnership programs and subsidized relationships to drive engagement and enrollment within the program.
- Typical credit hour requirements are characterized by 30 - 36 credit hours at a 3-4 credit hour commitment per course.

While the part-time structure is promising, there still exists a need for a larger focus on product innovation and entrepreneurship, along with a cohort-based model to develop skills of collaboration and social competence. None of the flagship Mid-Atlantic programs address these pain points, making them unsatisfactory in preparing students to contribute as professional systems engineers.

	Under $40k Tuition?	Hybrid?	Complete in Less than a Year?	Cohort Model?
George Washington University	×			
Johns Hopkins University		×		
George Mason University		×	×	
Georgia Institute of Technology	×		×	
Colorado State University	×	×	×	
Stevens Institute of Technology		×		
Cornell University	×		×	
University of Maryland Global Campus	×			
Old Dominion University	×			
University of Michigan	×	×		
Virginia Polytechnic Institute and State University	×			

Table 1. Comparison of Systems Graduate Programs

d. D. Future of Systems Education Content

The needs of the modern systems engineer now include entrepreneurship and the expertise to manage the product development and innovation process. In *Systems Engineering in the Fourth Industrial Revolution*, the authors state that “this holistic perspective to entrepreneurship initiatives requires an integrated systematic approach… carefully planning the way under a systemic concept may vastly increase the chances for the success of an entrepreneurship” [22]. Further, the authors discuss systems engineering in the current industrial revolution as being malleable, with concepts being applied to “life cycle characteristics” and “evolutionary properties of current technologies,” two major components of analysis and management of the product development lifecycle [22]. A 2016 study supports this stating that “in the current context of increasing time-to-market pressure, innovation has been identified as the major factor of competitiveness," and that a dynamic model within a systems engineering framework can manage an effective product innovation process [23]. This progression of the role of the modern systems engineer is natural - product development and innovation is a system in and of itself, requiring the management and analysis of multiple moving parts to create a final deliverable. *Digital Entrepreneurship: What is New if Anything?* takes this further and calls for the need for ecosystem understanding in entrepreneurship with major obstacles often residing in a misunderstanding of the system in which the new product is entering [24]. As such, it is clear that another current role played by the modern systems engineer is yet again not addressed in major systems engineering curricula. All of this goes to show the importance of the systems engineering methodology in product development, an idea that is analyzed deeply in *Designing Complex Products with Systems Engineering Processes and Techniques*, a testimonial to the success of developing a product from a systems point of view, a need for the modern systems engineer [25].

The translation of these needs to curricular implementation is addressed in *Modern Systems Engineering Education in the Context of the Formation of Professional Competencies*, where it is identified that professional competency in engineering is fostered through a classroom environment focused on personal and social competence [26]. The key trend identified is a focus on relationships, indicating that the modern systems engineering curriculum translates better to the workforce if taught in a hands-on and collaborative manner. Specifically relating to product development, Wu and Chen identify that a company can only stay competitive with a focus on the development of new products, and that a curriculum focusing on product development with "pedagogical approaches of experiential learning and constructivist learning [is] effective for teaching innovation management [and] project management" [27]. Employing that pedagogy in a systems engineering curriculum can create systems engineers who bridge the gap between business and engineering as new product development becomes increasingly technical. This idea of employing traditional business concepts and mindsets to systems engineering will unlock new curricula that better prepare systems engineers for the evolving needs of the workforce. *Industrial and Systems Engineering Education and Entrepreneurial Mindset: A Systematic Literature Review* brings up this idea further, stating that "there is natural synergy and overlap between [entrepreneurial mindset] and ISE," and that it must be added to SE curricula in order to better prepare students for the current workforce demands [14].

The effectiveness of this pedagogy has been tested in smaller quantities. In *The Effect of Entrepreneurial Mindset, Work Environment on Employees' Work Performance*, it was found that an entrepreneurial mindset is significantly correlated to work performance, with independent thinking fostering more success in the workplace [28]. In another study, computer systems engineers exposed to entrepreneurial and innovation-based activities were able to grasp the concepts presented [25]. The need for a product innovation and entrepreneurship-focused curriculum is apparent, and the future of systems engineering education relies on successfully implementing those topics to prepare students for the interpersonal nature of their applications in the workplace.

E. Future of Systems Education Content Delivery

Future SE education must also innovate in regards to content delivery. The features of SE learning crucial to its core are approaches to team dynamics and communication while problem-solving [29]. However, there still remain areas in need of their own innovation, such as the industry accuracy of new SE content, overall program affordability, growing hybrid learning demands, and the rapidly growing need to understand modern decision-making technology [30]. Nonetheless, students who graduate with a SE degree are unique amongst general engineering students due to the central relevance their education has for social competency. Social competence involves the students' level of sociability, debate mediation, and overall team workability [26]. Systems engineering focuses a pillar of its education on building these skills and, for this reason, is considered a "transdisciplinary discipline" [31]. Predictably successful future SE programs highlight the need for cohort-style learning environments, where smaller, close networks of students can engage intensively in projects together. With this framework, future SE graduates can master teamwork capabilities, as well as create tight bonds with their peers for future professional networks [26]. The importance of a capstone project as a culmination of the work is also showcased in successful programs [32].

Balancing the financial and quality considerations of a SE degree are important design considerations for administrators of SE programs [33]. With the modern online education sphere rapidly decreasing accessibility costs, maintaining accurate, innovative, and affordable degrees becomes a new priority for universities. Luckily, trends indicate that concerns about the financial burden of SE degrees become offset after graduation by graduates' salary increases, personal technology advancement, acquired professional experience, and the overall ability to move at the pace of globalization [29]. The cost versus quality debate for SE has large thanks to give to its efficient administrative systems, a historically indicative metric for student performance after graduation [34]. These systems not only seek efficient administrators but also critique the level of experience its faculty bring into the classroom. A 2014 study found that successful engineering programs were not comprised of faculty who came exclusively from either industry or academia. This finding was a product of both groups being unaware of the other's experience "rhythms" due to limited exposure to domains beyond their own [35]. Overcoming this divide through intentional overlap in the classroom accommodates the necessary administrative counsel for the next generation of systems engineers. As such, modern systems engineering education must not teach "straight out of the industrial trenches" [35], but strike a respectable balance between both academia and industry knowledge.

The tradeoff conversation extends to the pros and cons of online versus in-person content delivery. It has become apparent after the COVID-19 pandemic that hybrid education platforms are the future of education [36]. There are a multitude of positive features to hybrid education, especially the fact that it supports competitive graduate programs [35]. Some of these positive features include:

- webcasting specialist keynote speakers to lecture for SE students who otherwise are unable to be physically present;
- adapting to individualized course delivery;
- reconstructing the program setting to match the industrial “non-linear scaffolding” of SE to its classroom atmosphere [29].

Senior leaders, such as Michael B. Horn and Heather Staker, note that “blended” and “student-centered” learning is the key to teaching on a large scale, and many institutions agree; virtual learning is not only the future of large-scale education, but it is “critical” to the long-term strategic plan of many high performing universities [37]. Today, educators are not only seen as individuals standing in front of a classroom whiteboard but as people who “reach across time and distance” to educate students in an online, equally engaging, way [29].

With virtual and in-person education amidst one of many equilibriums that modern SE curricula must navigate, the population of enrolling students and their preexisting knowledge is another layer of consideration for redesigns [29]. Aligning curriculum to skills innately possessed by different generations of students is a quality underwritten by the ability for SE programs to adapt to the modern technology and business landscape. This denotes the future industry needs to be demanded of modern SE graduates considering globalization, the rise in “mobile careers,” and the ease that exposure to international cultures has on the modern intersection of technology and business [29].

Future SE education also has emphasis and reliance on technological decision-support systems. These supported decision-making tools allow students to analyze data sets and discover trends otherwise not noticeable with the stand-alone human mind. This phenomenon of human and technology capability is coined as “digital disruption”, where the excessive lean on technology-aided human decision-making is occurring at a rate and magnitude far greater than anything the natural human brain can understand on its own [12]. This era of digital disruption is thus a key influencer for future industry trends and is beneficial to future systems students if, in the classroom, they can grow their familiarity with its technologically supported decision-making tools. These tools help to bridge generational gaps and preferences for certain learning styles [38].

SE education is evolving from the diverse debate over its academic to industrial self-sustainability, as well as its accommodation to the approaching horizon of virtual education and digital disruption. The measure of sustainability that SE holds refers to the replicability of its course quality, such as accuracy, innovation, affordability, and balance of academic and industrial learning [34]. As such, the “long view” of the modern systems engineer demands an education that contributes positively to the universality, development, and reputability of the systems engineering profession [12].

IV. Results

There is still a need for a systems engineering program with a focus in innovation and entrepreneurship. This proposed curriculum and pedagogy is a possible remedy to these issues, designed with a focus on enhancing skills specifically needed in the advancing industry and workforce so that students can become technology leaders in their field.

The proposed curriculum is one idea - targeted toward those who want to build their analytical skills to become better data-driven decision-makers and gain business knowledge to drive innovation. Designed to be finished in one year with a consistent cohort of students completing the curriculum simultaneously and together, the proposed program would offer additional value to the degree through the ability for network development. The content to be provided under the proposed curriculum model would include:

- *Module 1: System and Design* Thinking courses to provide the foundation for systems engineering that will be incorporated into all subsequent coursework and modules.
- *Module 2: Quantitative Methods* provide a foundation in quantitative techniques commonly used in systems analysis and data Science.
- *Module 3: Strategic Innovation* provides the skills, both hard and soft, needed to manage, create, develop, and launch new products.
- *Module 4: Online Electives* utilizes the vast array of online educational offerings to allow for a breadth of program focus and allow students to dive deeper into a domain of interest.
- *Module 5: Integrated Experience* would provide students an opportunity to apply all materials and skillsets learned from the program in real-world engagement.

This proposed structure and modules not only strengthen the skills needed for a systems engineering student but also satisfies product development and leadership needs, unlike other current offerings. Recognizing the opportunities for improvement in aligning educational pursuits with industry readiness needs, this proposed curriculum, or curriculums following similar logic of design, could greatly improve the impact systems education has on post-graduation opportunities and life- long career performance. Furthermore, the proposed program’s hybrid structure offers an in-person experience as well as flexible online opportunities and could host professors and instruction ranging from academia to industry. The unique cohort model features in-person networking and class bonding which would give students the opportunity to participate in the full educational experience and the chance to learn and pursue new and exciting careers.

V. Conclusion

Systems engineering education is forever a function of the needs of the professional sector. The future of systems engineering is increasingly collaborative, with a focus on innovation and product development. By emphasizing these skills in a modern, hybrid and cohort style curriculum, future systems engineers will be better equipped to manage and develop products while bridging the gap between business and engineering.

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