Maturing System Competencies to Engineer a Better World

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***Abstract*—Creating a better world requires a systems thinking mindset that incorporates conflicting ideas, sees the world through multiple perspectives, anticipates the impact of systems in use over time and space, and can reliably adjust for the dynamic influences of an uncertain future. Global engineers of the future need to understand the foundations of systems theory and science, and be exposed to challenges that help them mature their knowledge, skills, abilities, and attitudes (competencies) about applying a systems approach. To this end, this paper will report on various efforts to understand the essential systems related competencies that all engineers should develop, the level of proficiency attained by today's engineers in these competencies based on their current level of experience (measured in years), the proposed level of proficiency needed to achieve the goals of peace engineering, and the current gap. The paper will close with recommendations for maturing system related competencies in engineering around the world to close the systems gap and achieve a better world through peace engineering.**

Keywords—systems thinking, systems mindset, systems competencies, systems theory, systems science

I. Introduction

We live in an increasingly complex and interconnected global world where, according to the World Economic Forum, extreme weather events, natural disasters, weapons of mass destruction, cyberattacks, failure of climate-change mitigation and adaption, data fraud or theft, and water crises, comprise the top five global risks based on likelihood or impact [1]. Global challenges to support sustainability of people and the planet have been issued by the National Academy of Engineering (NAE) [2] and the United Nations (UN) [3]. Engineers and scientists continue to serve a pivotal role in meeting these systemic-driven global risks and challenges. Yet, a deep knowledge of systems-based theory and practice is required to develop global solutions that address the challenges while minimizing the impact of unintended negative consequences that could, given the uncertainty of multiple futures, lead to world-wide social, political, economic, or planetary instability.

This work will review and apply systems competencies related research to the goals of peace engineering: prosperity, sustainability, social equity, entrepreneurship, transparency, community voice and engagement, and a culture of quality [4]. The work will identify gaps in systems related knowledge, perspectives, and practice and recommend and give examples of research and educational initiatives that engineering and scientific communities can embrace to bridge the systems gap.

II. Systems Definitions

A. Systems Engineering

Per the International Council on Systems Engineering (INCOSE): "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems…" [5]. When developing system solutions, systems engineers work in concert with team members and stakeholders (those invested in the system solution) to define and develop an optimal system concept, architecture, and design that fulfills the original need over the life cycle of the system. Systems engineers decompose the system design into the design elements that engineers from each discipline can design to and then orchestrate the integration of those elements into an overall working system. Systems engineers are traditionally responsible for the overall system effectiveness, including affordability and performance, once the system is put into operation. However, as systems expand to include socio-political aspects, the role of the systems engineer continues to broaden as does the role of every engineer, scientist, and stakeholder involved with the system. Most industries and domains today practice the principles of systems engineering although they may use different terminology for their approach and implementation.

B. Systems Thinking

In its simplest form, systems thinking is critical thinking guided by systems theory. As the field of systems theory evolves to address the complexity and emergent properties of engineered and socio-political systems, so too do approaches in systems thinking. Systems thinkers have reliable foresight about system behavior and system impact across multiple futures and environments. For this to be true, systems thinkers need a deep understanding of the intra- and inter-relationships of systems. This ability, in turn, requires the ability to view the system through multiple perspectives, to be comfortable holding what appears to be conflicting ideas about the system, to complement critical thinking with abstract thinking, and to understand the system holistically while also understanding the details that drive the behavior and impact of the system at any place within the system and at any point in time. When dealing with deterministic systems where uncertainty lives outside the system design, multiple perspectives are often defined as different views of the system including an operational view, functional view, physical view, and systems view. However, with systems involving human behavior and the uncertainty of multiple futures, additional views of the system behavior and impact are essential to deal with social, political, technological, and economically feasible factors.

C. Systems Competencies

Systems competencies address the knowledge, skills, behaviors, and attitudes that support effective systems thinking. While these competencies are traditionally associated with fields such as systems science, systems engineering, and systems dynamics, they are foundational to the development of systems savvy engineers, scientists, and stakeholders across domains and disciplines to support the development of effective system solutions to global risks and challenges. Examples of recommended competencies from various institutions will be covered in the next section.

D. Peace Engineering

"… define Peace Engineering as the intentional application of systemic-level thinking of science and engineering principles to directly promote and support conditions for peace." [4]. This definition directly calls for concepts, principles, and practices that have matured through the systems sciences and systems engineering, and the associated progress in systems thinking across these and related systems fields.

III. Systems Competency Research

A. NASA Systems Competencies and Relevant Findings

In 2008, thirty seven systems competencies were identified by the National Aeronautics and Space Administration (NASA) in collaboration with industry to form a foundational set of system competencies required for effective systems engineering. The initial eight systems competencies leading to the definition of a system design solution, early in the system life cycle, consist of [6]:

1) ***Form Mission Needs Statement:*** Accurately define need, basis for need, and success criteria for the system in the current and future environments.
2) ***Describe System Environments:*** Understand and describe expected system environment including inherent constraints and required design guidelines.
3) ***Perform Trade Studies:*** Compare and contrast systems models and solutions and identify a well-balanced (cost, schedule, technical, quality, etc.) solution.
4) ***Create System Architectures:*** Develop and communicate multiple system views, and external and internal interfaces (through functional decomposition).
5) ***Define/Manage Stakeholder Expectations:*** Identify relevant stakeholders and their expectations; manage these expectations throughout the system life cycle.
6) ***Define Technical [System] Requirements:*** Translate stakeholder expectations and related design constraints to system requirements and performance measures.
7) ***Logically Decompose System:*** Decompose the system into design elements and derive and allocate design requirements, resolving inherent conflicts.
8) ***Define System Design Solution:*** Define, analyze, and select the 'best' system alternative and create a full design description for the system design solution.

In response to a survey supporting dissertation research [7], engineers (n=109) enrolled in the School of Systems of Enterprises courses through the Stevens Institute of Technology during the spring semester of 2010 provided responses on their self-perceived level of knowledge in systems competencies using the scale shown in Table I.

TABLE I. PERCEIVED LEVEL OF SYSTEMS KNOWLEDGE SCALE[7]

Scale	Perceived Level of Systems Knowledge
1	Little to no systems knowledge
2	Basic level of systems knowledge
3	Between Basic and Intermediate
4	Intermediate level of systems knowledge
5	Between Intermediate and Expert

As shown in Fig. 1 for the sample set surveyed, proficiency in early systems life cycle competencies increased as one gains professional experience. However, even after thirty years of experience, engineers on average only achieved a self-perceived intermediate level of knowledge across the set of eight systems competencies.

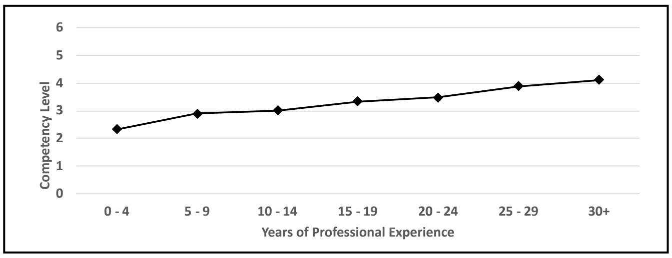

Fig. 1. Average of Early System Life Cycle Competency Levels by Years of Experience [7]

As systems become more impactful around the world, and the negative unintended consequences of these systems have a wider impact on the sustainability of the planet and the future of the human race, lead engineers across all disciplines need to mature proficiencies in systems competencies to the expert level. However, this data on the system competencies supporting the development of the system design solution (prior to design, build, and deployment) indicates an average systems knowledge between basic and intermediate (based on n=109 samples) for the engineers surveyed; and the attainment of expert level for only a small portion of engineers.

B. NAE Grand Challenge Scholars Competencies

The 2008 NAE Grand Challenges vision is for: "Continuation of life on the planet, making our world more sustainable, secure, healthy, and joyful" [8]. The Grand Challenges Scholar program was introduced one year after the fourteen global grand challenges to extend undergraduate engineering education to the global community, requiring students to achieve the following five competencies [8]:

1) ***Talent Competency:*** *mentored research / creative experience on a Grand Challenge-like topic*

2) ***Multidisciplinary competency:*** *understanding multidisciplinary of engineering system solutions, developed through personal engagement*

3) ***Viable Business / Entrepreneurship competency:*** *understanding, preferably developed through experience, of the necessity of a viable business model for solution implementation*

4) ***Multicultural competency:*** *understanding different cultures, preferably through multicultural experiences, to ensure cultural acceptance of proposed engineering solutions*

5) ***Social consciousness competency:*** *understanding that the engineering solutions should primarily serve people and society reflecting social consciousness*

While these competencies align to systems competencies required for effective systems engineering (see Fig. 1), the multidisciplinary competency as defined above, directly maps to a primary systems competency required by all systems engineers.

C. ASEE Transforming Undergraduate Engineering Education Relevant Findings: Industry and Students

The American Society of Engineering Education (ASEE) completed a series of four workshops to transform the undergraduate engineering experience, each workshop with an emphasis on different stakeholders (industry, students, women, and professional societies). Findings relevant to systems competencies were identified from the first and second report.

The first workshop incorporated findings from industry and called out 15 high priority Knowledge, Skills, and Abilities (KSAs) which are similar to KSAs required for effective systems engineering (see Fig. 2). With respect to systems engineering, the Transforming Undergraduate Engineering Education (TUEE) Phase I report specifically states under KSA 4: Systems integration (knowledge) that: "All technical challenges and designs are generally at the systems level, so students need to be introduced to systems engineering early in their undergraduate programs" [9]. The report refers to the importance of the capstone experience and the need to partner with industry for providing authentic systems integration experiences. The report also calls out the need for KSA 24: Systems thinking (skill), and emphasizes that "all problems are generally system problems" [9]. The majority of the workshop participants also found a large gap between the very important need to "Synthesize engineering, business and societal perspectives to design systems and processes" in ten years (2023), and the ability of engineering educators to address this need (rated by the majority as fair).

In the second workshop report, students highlighted the need for systems thinking across the engineering curriculum. The report states: "Students urged that schools address systems thinking in more depth, incorporating it earlier into labs and capstones" [10]. Students stated that a general understanding of systems thinking is missing and that everyone needs to look beyond their own discipline [10].

D. INCOSE Academic Council Capstone Framework

INCOSE's vision is "A better world through a systems approach" [5]. As the academic arm of INCOSE, the INCOSE Academic Council sponsors workshops, panels, papers and related activities through participating universities and educational conferences such as the ASEE annual conference and for the first time this year, the International Federation of Engineering Education Societies (IFEES).

One INCOSE sponsored ASEE workshop provided in 2015 focused on integrating systems engineering into undergraduate education and asked the twenty-seven participating engineering educators to select the top three missing areas of systems knowledge in engineering education based on their experience. The voting revealed the top gaps of systems knowledge as:

1) Systems thinking related to interdependencies, interactions, interfaces, and relationships, including among multi-disciplines (81%)

2) System modeling (26%)

3) Trade-off and decision analysis; and problem analysis including goals and objectives, needs statement, and requirements elicitation (22%)

4) Requirements analysis; and understanding complexity as part of systems science and fundamentals (19%)

Note that systems thinking was identified as a systems competency gap in engineering education by over four-fifths of the participating undergraduate engineering education faculty.

Another INCOSE workshop held at George Mason University in May of 2016 focused on approaches for integrating systems engineering knowledge and skills into engineering education programs in the first year and through the capstone experience, and associated implementation obstacles.

As a result of the workshop, outcomes for the capstone experience were defined by industry and academia participants in terms of systems competencies, in the following eight areas:

- **Interpersonal skills:** ability to negotiate, communicate effectively, adapt, manage conflict, and understand multi-team dynamics with a 'can do' resilient attitude

- **System design / model / analysis:** designs with uncertainty, deals with complexity; understands unintended consequences, interdependencies, control and feedback mechanisms; performs systems modeling and tradeoffs; understands software and optimal system architecture process

- **Systems engineering process:** defines the right problem, understands mission / stakeholder / system requirements, develops broad solution space, applies fitness for use, considers total systems life cycle
- **Thinking / perspectives:** has engineering vision, values systems engineering, applies systems and critical thinking
- **Professional skills:** applies systems engineering and project management, has business acumen, leads effectively, manages risk and opportunity, understands decision-making process
- **Adaptive / lifelong learning:** has basic math, programming, engineering, systems engineering knowledge and skills; has broad engineering knowledge and skills; learns from experience; is a self-learner and an adaptive learner
- **Cross-cultural skills:** maintains and ethical perspective, maintains global awareness, understands societal and cultural impact
- **Specialty engineering:** considers human factors and human systems integration, considers sustainability, understands decision analysis theory

The team developed the capstone framework in Fig. 2.

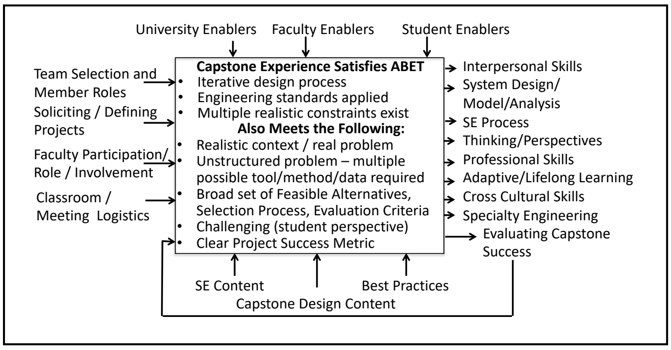

Fig. 2. Integrating Systems Competencies via the Capstone Experience

IV. Bridging The Systems Gap

A. SE Vision 2025

INCOSE has defined the global context for systems engineering and addressed the current and future states in the Systems Engineering Vision 2025 [11]. The future vision calls for a broadening of systems engineering applications across domains and to support policy, and the transformation of systems engineering. This transformation 1) shores up the foundations of systems engineering, 2) incorporates a value driven process and a fully integrated toolset, 3) broadens the roles and competencies of systems engineers to address increasing diversity, complexity, and expanded breadth and depth of future systems, and 4) requires resilient systems that integrate engineering, construction, science, maintenance, management views into the system architecture [14].

This future state of the vision requires lifelong training and education not only for systems engineers, but for all engineers. The vision proposes a body of systems engineering foundations that is defined and taught consistently across academia; and that systems thinking is taught at all levels of education around the world [14]. The vision also acknowledges the importance of global recognition of the value of a systems approach which leads to the understanding, belief in, and use of systems related principles, concepts, and practices.

B. Systems Research

From October 2016 through October 2017, the INCOSE Academic Council organized a series of three workshops that focused on areas of systems research required to close the systems education gap. The team's approach comprised of selecting and evaluating global grand challenges that are systemic in nature, defining systems engineering capabilities required to address the selected grand challenges, and identifying gaps in the current systems engineering capabilities for future research. The team selecting four grand challenges for analysis: access to clean water, access to healthcare, access to education, and security and safety. While key problems, research threads. current systems research gaps and suggested topics for future systems research were identified for all four grand challenges, there were three common themes that emerged across all four grand challenges [12,13]:

- *Understand the human element in developing the system and the deployed system.*
- *Determine the role of systems engineering in developing self-adaptive, evolving, and self-sustaining systems.*
- *Determine the role of systems engineering in human factors by researching models of long-term socio-technical systems to address culture- and value-based decisions.*

The nature of the findings indicate that similar common areas of systems related research applies to other global challenges such as peace engineering and the pursuit of world peace. This research would extend to the roles of engineers, scientists, and others in the design, development, and deployment of these far reaching and impactful systems.

C. Systems Education Pathway

As concluded through various research efforts from various institutions and professional societies, systems education in concert with the current reductionist view (breaking the problem into parts) is needed at the onset of one's education. A notional pathway to mature systems education over time is shown in Table II [14].

TABLE II. SYSTEMS EDUCATION PATHWAY FOR THE GLOBAL ENGINEER (ADAPTED FROM [14])

Systems Education	Thinking / Mindset	Multiple Perspectives	Understand Context
Early years	linear cause and effect; simple patterns	internal / external feedback	relationships of parts and whole
Middle years	non-linear cause and effect; behavior over time; causal loops; system archetypes; complex patterns	ability to identify state and state changes	relates impact of changes in environment to change in familiar behaviors
Teenage years	recognizes system archetypes; generates system models; deduces system behaviors	creates system models with internal and external feedback; multiple states and changes	rigorously analyzes and tests system models for robustness
Young adult	multidisciplinary approach to system model development w/ accurate modeling of interactions, interfaces, and relationships	total life cycle view; multiple design perspectives; optimize solution to right problem	systems theory concepts such as complexity and emergence in system modeling and analysis
Lifelong learning	balance of critically and creatively; individually and cooperatively; expert in holistic thinking	global perspective; balances social, political, economic technical; transdisciplinary	ethical and business norms, global environment across domains; complexity and emergence

D. The Capstone Experience

As previously mentioned, multiple professional societies have suggested the importance of defining capstone or senior projects in engineering education that focus on global risks and challenges.

The United States University Affiliated Research Center for System Engineering (the Systems Engineering Research Center) offers a model for capstone experiences with a capstone marketplace [15].

The NAE offers the Grand Challenges Scholar Program that has 155 universities involved around the world, as of April 2018, representing a three-fold increase over the last year [8].

Many universities and institutions around the world are taking on the grand challenge of sustainability and other grand challenges both in their local regions and in support of global challenges, risks, and goals, and offer opportunities for university capstone projects at both the undergraduate and graduate levels.

E. Global Collaboration

In 2000, the United Nations defined eight Millennium Development Goals (MDGs) to be achieved over a 15-year period as a framework for the world to fight the many dimensions of poverty. In the UN 2015 report on the effort, Ban Ki-moon, General-Secretary of the UN, stated that "The global mobilization behind the Millennium Development Goals has…helped to lift more than one billion people out of extreme poverty, to make inroads against hunger, to enable more girls to attend school than ever before and to protect our planet." [16]. The success of the MDGs was based on global collaborations – including the ability to better identify, monitor, and support impacted communities, although more progress in this area is still needed [16]. The UN's 2030 Agenda for Sustainable Development, developed in 2015, continues and builds on these global collaborations with a new set of 17 sustainable development goals and 169 targets to be achieved over the next 15-year period [3]. Systems integration, the seamless integration of human considerations, timely and accurate data, disparate localized efforts, and all other elements of the system, is key to realizing optimal outcomes towards achieving the sustainable development goals and targets.

V. CONCLUSION

Advancing the ability of engineers to design value-based global-reaching systems that are embraced by cultures around the world requires research in: 1) understanding the role, behaviors, values, and beliefs of the human in the system, 2) modeling long-term socio-technical systems to understand the impact of culture and values on decision-making, and 3) identifying and maturing the competencies needed for engineers and scientists to build effective self-adaptive, self-sustaining, and constantly evolving systems that change with their environment. Similarly, steps to mature systems-based education throughout the lifelong learning process of engineers, scientists, and others is needed to mature the systems thinking skills that are required to effectively design, develop, and deploy globally-based socio-political and technological systems in support of peace engineering. These pursuits require the development of systems-based curriculum for engineers and scientists as well as policy makers and world strategists. Significant progress also requires transdisciplinary collaboration between social scientists, political scientists, data scientists, all kinds of engineers, and the stakeholders involved in building and using the systems designed to address these global risks and challenges. And finally, the global task of peace engineering requires the systems integration of current efforts across the supporting areas to provide emerging value that exceeds the sum of each of the individual efforts currently underway – in support of sustainability of our planet and its resources, the end of poverty and hunger, global solidarity, prosperous and fulfilling lives in harmony with nature, and the fostering of a human race at peace [3].

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