Building the Systems Engineering Workforce of the Future
Education, Training and Development of System Engineers

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The demand is growing enormously for engineering talent, especially engineers who can steer the development and operation of large, complex systems composed of mechanical, electrical, biologic, software, human, environmental and societal elements. These engineers must be able to integrate technical as well as programmatic issues across the many disciplines making up the systems of today and of the future. Systems Engineering (SE) is a discipline, performed by System Engineers (SEs), that addresses the engineering, processes, techniques and viewpoints while solving systems issues.

This paper, a complement to the Systems Engineering Vision 2035 (https://www.incose.org/sevision) is intended to provide a sense of the educational and on-the-job training environment influencing the required skills of the SE workforce and also to provide guidance as to how this workforce can be developed and nurtured by an enterprise. In doing so, the paper is predictive in looking ahead 10 to 15 years. It also offers some approaches that learning institutions, as well as enterprises, can take to provide the academic underpinnings and continuing education necessary to develop and nurture the SE workforce of the future.

Contents:

1.0 Global Needs for Systems Engineering

2.0 What are Enterprises demanding of their Systems Engineers?

3.0 What is shaping the Systems Engineering Workforce of the Future?

4.0 What are the Key Characteristics of a Highly Regarded Systems Engineer?
   4.1 Competency Models
      4.1.1 INCOSE
      4.1.2 NASA/JPL

5.0 Systems Engineering Education, Development and Training by 2035
   5.1 Formal Schools and Universities Learning Challenges
      5.1.1 Primary and Secondary Education
      5.1.2 University and Postgraduate Education
1.0 Global Needs for Systems Engineering

The place of Systems Engineering in our society will grow with future social systems complexity growth, and the need for holistic but simple solutions. The ability to reduce complexity will in part depend upon systems analysis, architecting, and engineering and holistic approaches which take into account all relevant disciplines, such as economics, science, environment, law and most always engineering for advancing end-to-end solutions. The following three quotes reinforce this view.

1. Fruehwald and Poeppel (Ref 1) characterize the 21st Century challenge as “Complexity and Reduction.” This is particularly true in view of the sheer infinite and continuously growing knowledge access for all citizens, incl. of course scientist and engineers, where advances depend upon selecting, applying and integrating information to create innovation.

2. In his book entitled 21 Lessons for the 21st Century, (Ref 2), Y. N. Harari wrote:

   “To develop a future educational offer for the coming generations is more difficult today when compared to the past, since the prospective technologic manipulation of body, brain and soul evades the certainty of being. Overcome is the trade of schools to “stuff” their pupils with information. The 21st century offers, independent from schools, information in abundance. Today one needs the ability to interpret information, differentiate between important and incidental facts, and to develop a realistic view of the world from the many information sources.”

   “Of fundamental importance for the future will be to cope with change. Not only new ideas and products are important, but also the ability to re-invent oneself.”
The United Nations Sustainable Development Goals (SDG) (Ref 3) number four addresses fundamental human and societal needs. Most of the UN SDGs require holistic system approaches and well-educated SEs to support their implementation. They are hence an extra motivation for competent systems analysis and engineering education.

In a follow-up world conference, UNESCO expanded on the educational theme number four and passed the Brussels declaration, (Ref 4) stating: “Ensure inclusive and equitable quality education and promote life-long learning opportunities for all.”

An engineering-focused view of societal goals, termed “Grand Challenges for Engineering.” has been taken by the United States National Academy of Engineering (NAE). These challenges provide a roadmap for how engineering can contribute to the welfare of the planet and the world’s population (Ref 5)

![Figure 1.1 UN Sustainable Development Goals (SDGs) highlight quality and continuous education as highly relevant to the achievement of many other goals.](image1)

![Figure 1.2 NAE Grand Challenges for Engineering](image2)
In order to promote education that is positioned to move forward with the grand challenges, the NAE has defined the Grand Challenges Scholars Program (GCRP) and the key competencies that are being sought, which applies very well to the SE of the future.

<table>
<thead>
<tr>
<th>Talent Competency</th>
<th>• mentored research/creative experience on a Grand Challenge-like topic</th>
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<tbody>
<tr>
<td>Multidisciplinary Competency</td>
<td>• understanding multi-disciplinarity of engineering systems solutions developed through personal engagement</td>
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<tr>
<td>Viable Business/Entrepreneurship Competency</td>
<td>• understanding, preferably developed through experience, of the necessity of a viable business model for solution implementation</td>
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<tr>
<td>Multicultural Competency</td>
<td>understanding different cultures, preferably through multicultural experiences, to ensure cultural acceptance of proposed engineering solutions</td>
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<tr>
<td>Social Consciousness Competency</td>
<td>understanding that engineering solutions should primarily serve people and society reflecting social consciousness</td>
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2.0 What are Enterprises Demanding of Their Systems Engineering Workforce?

As systems become more multidisciplinary, digital, and smarter, enterprises will need to attract and retain a diverse workforce, with an extensive variety of skills, to support or apply rapidly changing technologies and shifting stakeholder demands. This workforce will need to provide not only broad and focused technical and business competencies, but also engineering talent to architect, integrate and coordinate the system of interest to a specific business. In order to be successful in the next decade, enterprises, regardless of engineering discipline focus, will need to actualize the workforce imperatives described in Figure 2.1 (Source: Incose SE Vision)

**The Enterprise Environment**

- **GLOBALIZATION AND DIVERSITY**
  Enterprises will continue to move toward greater globalization, embracing diversity, innovation, and new collaboration methods in search of competitive efficiencies.

- **SUSTAINABILITY ETHICS**
  Sustainability will become a key attribute of the enterprise culture and products. Enterprises will need to develop a positive ethical identity to attract and retain customers as well as employees.

- **SYSTEMS THINKING**
  Demand for an enterprise culture of systems thinking will grow to address issues of product, production, and organizational complexity. Dispersed, multi-disciplinary teams will generate collective systems views supported by digital tools.

- **ANTICIPATION OF TECHNOLOGY**
  Successful enterprises of the future will anticipate and rapidly embrace new technologies. It will not simply be sufficient to wait for a technology to prove itself in the market. A systems perspective will be critical to understand the technologies that will be most significant to the enterprise.

- **SUPPLY CHAIN INTEGRATION**
  Modern supply chains will depend upon layers of systems-cognizant subcontractors who can deal astutely with functionality trade-offs and risk decisions. Coherence of software among all project partners will be critical for seamless and trusted exchange of digital products and intellectual property.

- **ENTERPRISE INTELLIGENCE, DECISION MAKING, AND LEARNING**
  Enterprises will need to protect product and process know-how, while at the same time creating an internal learning environment in which the workforce can easily access and take advantage of the enterprise intellectual assets. Enterprises will need to be flexible and sufficiently adaptable to react quickly.

- **AUTOMATION AND DIGITAL TRANSFORMATION**
  Digital transformation of the enterprise will increase reliance on quantitative decision making, streamlined development processes, and automation. Software robots will complement physical robots in the quest for ever greater product and service quality as well as reductions in the cost of production.

*Figure 2.1 Enterprise of the Future Workforce Imperatives*
The Japanese Society 5.0 strategy characterizes important workforce developments as follows:

**Society 5.0**

...recognizes that information will be readily available to the workforce via digital search, and much routine work will be accomplished by robots and AI, so training must concentrate on human skills, leadership, endurance, reading and comprehension. Education systems must support this workforce transition by breaking down the traditional barriers between STEM and social science/humanities curricula. (Ref 6)

The World Economic Forum, in its *Future of Jobs Report 2020* (Ref 7), predicts the top ten skills of 2025, below. Even though the time horizon for this prediction is 2025, these skills represent an important path to 2035 as well.
In order to meet the imperatives described above, enterprises will need highly competent systems analysis and SE talent. Holistic “end-to-end” life-cycle approaches, taking business, environmental, engineering and social components into account will be necessary. Thus, demand will grow substantially for systems thinkers, systems analysts, systems architects and SEs. SE interfaces with product life-cycle, project management and business functions will grow in importance. SE leadership and project management, representing technical and program authority, will need to be highly complementary and cross-trained. As a result of these broad integrative roles, senior SEs will increasingly form a pipeline of leadership within government and industry enterprises.

3.0 What Is Shaping the Systems Engineering Workforce of the Future?

Some key trends impacting the SE workforce of 2035 are:

Systems (engineering) tasks, functions and career paths will be more diverse, reflecting complexity growth and the multidisciplinary composition of current and future systems.

Tools and methods will be largely digital and comprehensively integrated across the enterprise and within supply chains. Mid and late-career SEs will be challenged to adapt to these more comprehensive approaches.

Capabilities in modeling, simulation and working in virtual environments will strongly affect industrial efficiency and competition.

The ability to digitally architect, design, analyze and implement the systems of the future will be required to retain competitiveness.

Foundational techniques such as statistics, risk analysis, and decision theory will be applied to systems analysis as quantitative assessments of system behaviors become more important, better understood and applied.

The ability to form, train, integrate and lead teams focused on systems development will become increasingly important.

Many enterprises are entering into programs to more completely automate ideation, design, realization, operations and logistical support processes, along with business and human capital functions interactions. These enterprise-level “Digital Transformation” demands require a further alignment of the SE workforce and their education. In addition to essential domain competencies in the product ecosystem of an enterprise, strong digital competences in systems analysis, engineering and development are required.
While it may be felt that systems-orientated engineering competencies are only needed in large enterprises, in fact, these competencies are needed at all layers of system composition. Engineering enterprises exist at many different scales, from large systems integrators developing power plants, space vehicles, transportation infrastructure, etc., to small enterprises that produce either limited-scope end products, or components that feed the supply chain of the large integrators. SEs are needed at almost all levels of the supply chain comprising prime contractors, original equipment manufacturers (OEMs) and sub-tier suppliers. For example, a construction firm designing an office building needs specialty domain systems competencies for heating, air conditioning, security, waste management, and other subsystems. Subsystem engineering enterprises must deal with hardware and software design while being part of an interdependent, broader supply chain. Today’s aircraft, automobile, and most infrastructure projects depend upon competent layers of subsystem subcontractors who can deal with relevant system issues of functionality, design tradeoffs, and risk.

SEs need to integrate knowledge across many different fields, requiring engineers with sound domain as well as system competencies. Moreover, they work at many different component and equipment levels (tiers) of a system as illustrated by two examples from the automotive and infrastructure fields in Figure 3.2. SEs develop different background and domain specializations as they work in different subsystems. These subsystem competencies are necessary throughout the supply chain of today’s complex system products. Broader system integration functions are most often filled with SEs who progress through their careers from the cadre of more specialized domain and subsystem engineers.
Complex systems applications will continue and grow e. g. in the fields of energy, mobility, communications networks, aerospace, smart cities, biological and health systems, and large construction and infrastructure projects. Enterprises will require interdisciplinary systems team competencies to analyze, evaluate, plan, and execute these systems within environmental, regulatory, programmatic and socially acceptable boundaries. The growth of applications in these and other fields has led to a high demand for competent and well-trained SEs. In part this is also due to, and complementary to, the trend of deep and narrow engineering specializations in “high-tech” industries or institutional organizations. Such specialization is leading to higher fragmentation of design work and the need for better end-to-end system-wide integration to ensure added value.

The trends towards increasing automation and autonomy, ever more sophisticated digital ecosystems, rapidly changing technologies, and the need for cyber-secure and trusted systems have further fueled the need for SE competencies. Increasing data, the growing availability of AI, self-learning capabilities, modeling, simulation, and virtual environments are catapulting systems analysis, SE and data analytics into the forefront of many social and industrial undertakings.

The above trends have also led to a recognition that next to SE also strong domain competences are needed.
Examples for domain competences along with SE competences are:

| Data Analytics | IT, AI, machine learning, software, cloud computing and systems analysis. |
| Complex Process Plants | e.g. for chemical production, require solid fluid dynamics, thermal and logistics knowledge combined with process, controls, and design competencies. |
| Communication and Energy Networks | electrical, advanced electronics, control, operations, and communications engineering along with systems analysis expertise. |
| Automated or Autonomous Systems | such as automobiles, or harbor/airfield logistics require skills in IT, software, sensors, communication, cyber security, design for safety, security and social science skills. |
| Small Medical or Smart Home Devices | such as blood pressure or temperature measurement equipment's require skills in sensor, IT, software, and communication fields. |

The examples above illustrate the need for well-educated traditional discipline engineers with deep technical domain expertise but with ever broader systems competencies.

These examples reinforce the fact that integration competencies are needed for small and large systems as well as small and large enterprises, since complexity increases are affecting most all system, social, financial or industrial products of today. The key question is how educational institutions, training providers and enterprises can ensure that such workforce competencies will become readily available.

Systems are becoming more software intensive, requiring substantial software architecting and programming competencies of SEs. In turn, software engineers need to expand their systems competencies and viewpoints in order to field robust “end-to-end” systems containing hardware, software, firmware and other elements. In fact, with software increasingly being used to define
system behaviors, software engineers are often a project’s de facto SEs. Software is much more than just coding. Software engineers are often in the driver’s seat when it comes to interpreting stakeholder needs, forming system behaviors, ensuring durable operation and services, and providing successful user experiences. Additionally, the growing need for trusted, resilient, and secure systems solutions in many industrial fields require that SEs have basic competences for designing safe, (cyber) secure, trustworthy and dependable (hardware and software) solutions for most all future systems.

Project management and SE disciplines have become highly interdependent. Hence both need to have the basic competencies of each other’s discipline to facilitate effective interaction. Since SEs almost always work in teams and need to lead both small and large teams, either functionally or hierarchically, social and leadership skills are a mandatory competence for their acceptance and effectiveness.

4.0 What are the Key Characteristics of a highly regarded System Engineer?

Enterprises that have a long history of excellence in SE have developed profiles of their most regarded SEs. These profiles capture and codify employee behaviors sought and nurtured in career management, succession planning and project assignment.

4.1 Competency Models

SE competency models can form the core evaluation framework, above and beyond applicable technical acumen, for an enterprise’s SE training and development program. It can also be used to inform curricula development for more formal SE educational institutions. Competency models tend to focus on behaviors, soft skills and thinking approaches, and are meant to complement assessments of technical competency. Two examples follow.

4.1.1 INCOSE

The International Council on Systems Engineering (INCOSE) Competency Framework provides a set of 36 competencies for SE within a tailorable framework that provides guidance for practitioners and stakeholders to identify knowledge, skills, abilities and behaviors crucial to SE effectiveness. (Ref 9)

4.1 2 NASA/Jet Propulsion Laboratory
In 2005 a study was conducted at NASA’s Jet Propulsion Laboratory (JPL) to determine the behavioral competencies of high performing SEs. These behaviors were used to formulate training programs, as well as guide career and succession planning. The behaviors have broad applicability for SEs, regardless of industry domain. An abridged version of the behaviors identified by the study are:

- **Leadership**
  - Influences Others
  - Works Well with a Team
  - Trusts Others
  - Communicates a Vision and Technical Steps Needed to Reach Implementation
  - Mentors and Coaches

- **Attitudes and Attributes**
  - Possesses Self-Confidence
  - Has an Objective and Comprehensive View of the Job
  - Is Intellectually Curious
  - Manages Change

- **Communication**
  - Advances Ideas
  - Communicates through Storytelling and Analogies
  - Listens Effectively and Translates Information

- **Problem Solving and Systems Thinking**
  - Uses Critical Thinking
  - Manages Risk
  - Exhibits Proper Paranoia -- an abiding focus on what might go wrong

The study made the following overall observations: “The... systems engineers studied typically view the system or subsystem as a non-linear web of connects or disconnects to be solved. They have the ability to view the big picture, zoom in to pin-point the disconnect, and then zoom back out to the big picture, while at the same time looking at the interrelationships and patterns in the system or design. They have a high degree of curiosity mixed with self-confidence and persistence and are achievement-oriented. They may describe themselves as having extraordinary physical insight to see the connections and interrelationships between what they are doing and the world around them. They are drawn to the challenge of solving complex problems and are creative in the midst of numerous constraints.”
5.0 Systems Engineering Education, Development and Training by 2035

This chapter describes what SE education could look like in the mid 2030s in response to the global and enterprise environments and needs described in the sections above. It describes the educational demands for schools, universities, training organizations and enterprises, while offering solutions for the associated educational paths. Keeping students and enterprise workforces current with evolving demands of the future is a major challenge!

The growing worldwide demand for SEs in many application domains exceeds the available supply. For many reasons, most practicing SEs do not have a formal SE education but learned on the job. It will be common by 2035 for enterprises to have internal training programs to keep their workforces “a jour” or further develop them.

5.1 Formal Schools and Universities Learning Challenges

Formal education from elementary school through post-graduate education has an important role to play in preparing engineers for careers as SEs. An increasing number of universities and training providers teach SE, but the number of students is small when compared to other engineering disciplines and the market demand. Various guidelines for curricula harmonization and competence categorizations have recently been defined as part of international efforts to broadly stimulate SE education. New programs have been initiated to attract students to the study of SE. The significance of systems thinking is also increasingly being recognized and taught in other disciplines.

5.1.1 Primary and Secondary Education

A key mission of primary and secondary education is to teach the fundamental skills necessary to function as an adult in contemporary society, which we can refer to as “21st Century skills.” While the specific skills deemed to be “21st Century skills” may be defined differently from person to person, place to place, or school to school, the term does reflect a general, if somewhat loose and shifting, consensus. The following list provides a brief illustrative overview of the knowledge, skills, work habits, and character traits commonly associated with 21st Century skills (Ref 10)

- Critical thinking, problem solving, reasoning, analysis, interpretation, synthesizing information
- Research skills and practices, interrogative questioning
- Creativity, artistry, curiosity, imagination, innovation, personal expression
Perseverance, self-direction, planning, self-discipline, adaptability, initiative
- Oral and written communication, public speaking and presenting, listening
- Leadership, teamwork, collaboration, cooperation, facility in using virtual workspaces
- Information and communication technology (ICT) literacy, media and internet literacy, data interpretation and analysis, computer programming
- Civic, ethical, and social-justice literacy
- Economic and financial literacy, entrepreneurialism
- Global awareness, multicultural literacy, humanitarianism
- Scientific literacy and reasoning, the scientific method
- Environmental and conservation literacy, ecosystems understanding
- Health and wellness literacy, including nutrition, diet, exercise, and public health and safety

The following observations from the same reference above (with slight modifications) provide representative arguments that can be made in support of teaching 21st Century skills:

In today’s world, information and knowledge are increasing at such an “astronomical rate” that no one can learn everything about every subject. What may appear true today could be proven to be false tomorrow, and the jobs that students will get after they graduate may not yet exist. For this reason, students need to be taught how to process, parse, and use information, and they need adaptable skills they can apply in all areas of life—just teaching them ideas and facts, without teaching them how to use them in real-life settings, is no longer enough.

Given the widespread availability of information today, students no longer need teachers to lecture them on simple facts because that information is readily available—and often in more engaging formats than a typical classroom lecture. For this reason, educators should use in-school time to teach students how to find, interpret, and use information.

Schools need to adapt and develop new ways of teaching and learning that reflect a changing world. The purpose of school should be to prepare students for success after graduation. Therefore schools need to prioritize the knowledge and skills that will be in the greatest demand, such as those skills deemed to be most important by college professors and employers. Teaching students to perform well in school or on a test is no longer sufficient.
By 2035 systems thinking will be embedded in early education to complement learning in sciences, technology, engineering, and mathematics. Early school education will develop systems thinking and team skills to create multidisciplinary solutions that respond to pre-defined problems and constraints. Later education will teach basic systems engineering concepts, such as soliciting and understanding stakeholder needs, developing requirements, identifying, and evaluating conceptual alternatives before arriving at a solution and digital system design. These concepts will stress full life cycle impacts while understanding and validating sources of data.

Students will need to be motivated to acquire the requisite mathematical, scientific, IT, and social knowledge to support systems analyses and decision-making. For this motivation, teaching and mentoring will be practical, based on real-world experiences with hands-on projects, in cooperation with regional industries, when possible.

A “teach the teacher” program will ensure the proper teacher, advisor, and mentor resources are in place to connect learning activities with practical workforce skills. Teachers will have access to the latest technology and applications to provide engaging learning experiences that motivate learning math, science and engineering. Enabling technology will motivate teachers to more effectively create and execute individualized education plans.

At both primary and secondary levels, innovations in educational technology will enhance models of learning. Students will use digital technology in learning and developing fluency in programming languages beginning at an early age. Interactions between and among educators and students will be substantially enriched through digital technologies.
Generation Z (those born between 1997 and 2012) will be the first generation of students “living their lives largely digital.” Knowledge will be publicly available, challenging educational institutions to guide students beyond the basic competencies of their selected study direction to find and critically evaluate, adopt and assess the trustworthiness of the relevant information.

5.1.2 University and Postgraduate Education

Universities are destined for substantial change. The Organization for Economic Co-operation and Development (OECD), the World Economic Forum, the global Engineering Deans Council, along with others, are calling for a profound change in the university-level engineering education sector. Their call is for fast-paced initiatives to enhance curricula for key enabling technologies, that should include manufacturing and processes. They foresee a major shift in higher education’s responsibility and purpose. They also envision a move towards:

- socially relevant engineering curricula that offer students more choice,
- integrating engineering knowledge with humanities, economics and social sciences in the form of interdisciplinary learning and education.

Fig 5.4 Industry 4.0 Major Elements
Two initiatives of the past few years (Industry 4.0 (Ref 11) and Society 5.0 (Ref 6) already mentioned in section 2.0) have set new goals and visions for our social and industrial developments and will shape future education needs. Industry 4.0, a German Academy of Technology initiative, characterizes the fourth industrial phase, which we are transitioning towards, as one of “cyber physical systems”. It envisions the need for the integration of automation, big data, autonomy, augmented reality and other specialties which too often are constrained to a stovepipe environment (Figure 5.4).

University curricula for SE need to adapt to such changing industrial and societal demands. Industry 4.0, Society 5.0, advanced technologies, the “Digital Transformation” and evolving virtual environments (sometimes also referred to “metaverse”) will substantially change demands for university engineering education. Interdisciplinary and IT competencies, as well as personal and professional skills, will enable students to cope with new demands and a changing society.

SE will diversify along specific needs by various stakeholders into different specialties, such as systems research engineer, systems analyst, systems architect, front-end innovator, ideation specialist, systems integrator, systems manufacturing and services systems engineer, or digital “model curator.” Postgraduate education programs are and will continue to be critical in supporting such in-depth SE specializations.

New generations of students “live their lives largely digital”. Lectures and course deliveries will continue to shift towards being available in the classroom, and virtually for self-study. Online and in situ learning will complement each other. But these will in no way eliminate the requirement of intense team interactions around practical capstone system projects.

Balancing domain and multidisciplinary education will be just one of the challenges for university-level education. Engineering, social and science programs, e.g. business, computer science, electrical and mechanical engineering, management, social sciences, etc. will increasingly include systems-oriented courses, especially focused on systems thinking and end-to-end systems analysis. Broadening curricula will advance the skills of decision makers as systems thinkers.

Postgraduate education programs will provide the SEs of 2035 broad multidisciplinary learning opportunities. These will include, in addition to sound scientific and technical education, socio-technical leadership and entrepreneurship programs to enable engineers to cope with non-deterministic complex systems that span a broad range of applications and involve large teams as well as a large industrial supply chain. SE curricula specifically will expand to include socio-
political and soft skills. These curricula will also feature broad digital modeling, simulation, virtualization, and tools skills, incorporating modern processes and methods.

In addition to the discipline training characteristic of traditional departments and colleges, universities must also play a central role in teaching the foundational elements of systems analysis. Techniques such as risk assessment, applied probability and statistics, operations research, decision theory, complexity theory, formal software verification, reliability, modeling and simulation, and analysis of alternatives are important tools for well-rounded SEs to understand emerging behaviors and probability of system success. These skills are necessary to work with technical specialists and project/program management in understanding, avoiding, and mitigating risk.

Closer university-industry collaboration will create a more “fluid transfer” from university to industry or government agencies and vice versa. Early exchanges and dialogue between academia and industry, regarding domain and systems curricula, will become the norm. Practical industry support to university teaching or mentoring will expand to achieve a “real life” insight and fluid transfer of graduates and motivate students for seeking industry employment.

University-level education will be a catalyst in the shift from traditional “design-build-test” to “analyze-model-simulate-build” approaches by introducing students to new processes and techniques. This will often include new industry processes such as “agile,” concurrent, or “iterative” SE to cope with or improve emergent behaviors which are difficult to characterize during early definition and design phases as well as model-based project reviews. The use of high fidelity modeling and simulation coupled with digital twins will enable students to more effectively experiment and understand how engineering decisions and tradeoffs are made and implemented. Similar processes and techniques will be applied to understanding operations design and operations/maintenance/servicing impacts.

Instructional methods will predominantly be guided by problem definition, finding suitable solutions, and cultivating team productivity. For instructional problem sets to be application oriented, universities will frequently collaborate with industry in addressing real-world needs.

Educators will learn to reinvent themselves; to un-learn and re-learn continuously along their careers. An element of life-long learning is the ability to recognize that some knowledge continues to be superseded by new science and that consequently the need to let go of outdated knowledge becomes part of the continuous learning process.

All of the above have substantial impact upon the educational needs and career path for SEs of the future. School and university education along with training enterprises need to set the stage and support the need for a continuous development of the engineering and especially the SE
workforce. The following section introduces various options and examples for such developments.

5.2 Career Progression and On-The-Job Training

Most practicing SEs do not have a formal SE education but learned it on the job. The reason for this is that it is absolutely necessary for SEs to first establish knowledge in a specific domain and then to build on that knowledge while expanding the breadth of expertise. So SEs generally enter the workplace in a specialized field, then develop into a limited systems area and gradually advance to system architect, chief engineer, project manager, or enterprise management. It is this career progression that provides SEs with the broad perspective needed to carry out the role as a lead engineer.

For early and mid-career SEs, certain roles within a system life cycle can provide a greater training opportunity than others. System validation provides insight into how a design actually meets its intended objective and how individual design decisions either support or detract from customer satisfaction. Integration and testing allows an engineer to experience first-hand the results of making subsystems work together and identify the root causes of failures associated with independent subsystem viewpoints and implementations. Operations experience allows an engineer to personally experience the end result of architecture and design decisions made in the very early phases of a project and make connections that can be applied in later design assignments. These integrative roles are invaluable to the development of high-performing SEs and therefore, enterprises pursuing career path experiences for developing SEs would do well to place a priority on these opportunities.

The growth of engineers from specialist to SEs is well illustrated by the “T Model of Systems Engineering Skills” in Figure 5.4. The basic underlying idea is that engineers are in the first instance educated in a special discipline, e.g. mechanical, electrical, physics, bio, controls, or other. Some develop further within the knowledge and skills base of their disciplines. Others want to understand more and more about other “neighboring” disciplines, thereby developing an ability to analyze issues across several disciplines. They are then on their way towards becoming SEs. The more they learn about other (engineering) disciplines and the more they are capable of interacting with a multitude of engineering and programmatic disciplines (schedule, cost, finance, planning, leadership, markets, etc.), the more they grow to become senior SEs or system architects.
Subject matter expert and management careers traditionally develop in parallel. The usual enterprise promotion and career progression criteria is dominated by size of budget and extent of staff supervision responsibilities. Some modern organizations have created parallel expert career promotion tracks. This implies that senior specialists in important technical or administrative domains can have separate career paths and remuneration progressions, at least up to certain levels in a hierarchy. Advancements to Chief Engineer, Chief Architect or CTO typically exist along this path.

5.3 Continuous Education, the Answer to Advancing Systems Engineering Competencies

Employer-sponsored continuous learning programs, prioritizing practical experiences, will expand. Recognizing that university education can be the first step for graduating SEs, employers have to bridge the transition from university education to industrial practice -- both general and enterprise-specific. Continuing education can focus upon either SE competencies such as evolving methods, technologies, and processes in the fields of digital engineering or non-deterministic systems, but can also include domain-focused competencies such as software, cyber security or AI. In real life, SE career developments will need advancements in domain, technology and systems competencies. Early to mid-career training and education, provided by internal universities or academies, will be focused upon company practices, tailored to the systems, technologies and enterprise specific practices and standards used in an organization. Enterprises will take advantage of complementary formal training programs such as summer
schools, short course offerings, certificate programs, or formal postgraduate programs for systems thinking and analysis.

Enterprise competitiveness requires continuous adaptation of technologies, products, manufacturing, services and processes in ever more rapid cycles. Actively engaging staff in lifelong learning is hence a prerequisite to also mastering the changing SE work challenges and the transition towards digital enterprises. Continuous training and staff development will become indispensable to ensure alignment with: 1) digital transformations and infusion of technologies; and 2) an enterprise’s changing product, supply chain, or mission.

Workplace-based learning programs within an organization’s product, domain, and market environment will continue. They will enable a smooth transition from university education to industrial or government institutions practices. Early to mid-career training and education by internal “academy” and/or external sources, will be focused upon the concerned organization’s practices, up-to-date systems, technologies, engineering developments, and analytical techniques, most often focused upon an organization’s specific practices and standards. In-depth technical training addressing domain-specific plus systems issues will be provided to the practicing and aspiring SEs to move from a discipline-specific into broader SE roles.

In view of the increasing need for life-long learning, commercial SE training providers will continue to grow and serve as “gap fillers” for teaching both broad and deep SE-related subjects. Training houses should have experienced system instructors, who have applied SE in industry or government real-life projects, and can flexibly react to changing enterprise needs, new technologies, or new methodologies. Such enterprises will continue to play a strong role for improving the competencies and skills of the SE community and will complement university and industry postgraduate courses and programs.

Certification programs will increasingly support validation and self-assessment of SE competencies and thus support graduate and postgraduate education initiatives. They can provide benchmarks for knowledge and proficiency assessments along an SEs development path. INCOSE, for example, has three different kinds of certifications for SEs for different stages of developments.

The need for life-long learning and career development is different in various enterprise environments. In small enterprises, on-the-job learning is the predominant method. An engineer entering a company learns by doing and he or she thereby grows into broader knowledge and competencies. Becoming a systems integrator, chief engineer, project manager, system architect, or similar, is frequently supported by internal training efforts and follows evolutionary steps. Whether this approach will suffice in the future depends on the technological and market environment of an enterprise. Figure 5.5 delineates, in an oversimplified manner, the fundamental steps of career development in a small and medium type enterprise (SME).
Due to the diverse and broad domain of SE competencies, university degrees in SE are mostly earned on the master’s or doctoral levels. Postgraduate education in SE and related disciplines will take an increasingly important role. “Real-life” additional learning and training then takes place in specific enterprise environments. Various training steps and career options follow with increasing experience, competence, and responsibility. The growing interaction and interdependency between SE and project management leads to a situation where project managers, especially in high-tech product arenas, more often than in the past, will also have a multidisciplinary SE education. Certifications along the career path can be helpful in creating standards of accomplishments. Flexibility in allowing career path crossovers between these different strings, along with a mentoring pipeline, will go a long way towards ensuring a digital enterprise’s workforce remains eager to advance their competencies and integrate the latest technology and process developments into their career paths.
Life-long education and careers in large and often high-tech industry or government enterprises can take quite diversified avenues. Three example paths are shown in Figure 5.6. What is not shown in these oversimplified examples is that engineering, SE, and project management careers often become intertwined. In actuality, there are many variations possible within the two schemes presented in Figures 5.5 and 5.6. Practical education and training concepts for most enterprises respond to a number of the steps and paths described above and often utilize elements of both examples shown.

### 5.4 An Industrial Example for Postgraduate SE Education and Training: The Airbus Defense and Space Company

A remarkable continuous education and training program for SEs has been developed in the past two decades by Airbus Defense and Space (ADS). This company’s program features various stages of development for SEs in line with the need for growing skills, depth and breadth for them to master broader competencies. Through this program and additional initiatives, ADS has improved their SE competencies and capabilities over the past 20 years. A short description, courtesy of ADS, can serve as a benchmark for continuous learning advancement for SEs.
The Airbus Defence and Space Systems Engineering Learning Path (1 / 2)

Airbus Defence and Space (AD) promotes a set of trainings and programs in Systems Engineering, as well as a Systems Engineering learning path as recommendations for future Systems, Lead and Chief Engineers.

For newcomers in the field of Systems Engineering, many e-learnings are available, providing a first introduction to Systems Engineering.

For future Systems Engineers with about 3 years of professional experience, AD recommends the "Systems Engineering Training for Defence and Space (SET4DS)“ program. This is a two weeks training, consisting of lectures on Systems Engineering Fundamentals and a Show Case Project, to practice the content of the lectures.
The Airbus Defence and Space Systems Engineering Learning Path (2 / 2)

At any time, the engineers shall attend individual specialized SE trainings like Processes, Methods and Tools, Technical Topics / Specialty Engineering based on the needs of their project.

For future Systems Engineers with about 7 years of professional experience, AD recommends the "Systems Engineering Qualification (SEQ)" Program, which is an Airbus Defence and Space transversal program consisting of 6 technical modules of one week each and a set of technical online lectures, 3 social skills modules of two days each, a Kick-Off event, a Final Presentation and a real life project that the SEQ students have to execute in parallel. SEQ is a Call for Nomination Program, i.e. the participants have to be nominated by their line manager and HR Business Partner.

After about 10 years of professional experience, the engineer can specialize in one of the Architect Development Paths (ADP):

- Military Aircraft (Mil. A/C) & Unmanned Aerial System (UAS) Architect Development Path: 11 modules of one week each,
- Space Systems Architect Development Path: 7 modules of 3-4 days each.
- System-of-Systems (SoS) Architect Development Path: 2 modules of 3,5 days each,
- Connected Intelligence Architect Development Path, a set of e-learnings and classroom trainings composed individually.

All ADPs are Call for Nomination Programs.

Finally experienced Systems, Lead and Chief Engineers meet in the "Advanced Practices for Systems Engineering" training workshop: a forum to learn and discuss about future trends in Systems Engineering, to see how Systems Engineering is applied in other industries and to discuss topics coming from their own projects.
5.4 Technologies Impacting Systems Engineering Training and Development in the Future (Re-engineering Engineering Education)

“There has never been a better time to be an engineer with special skills or the right education, because these people can use technology to create and capture value. However, there has never been a worse time to be an engineer with only “ordinary” skills and abilities to offer: Employability competition is worldwide. Engineering students all over the globe, computers, virtual assistants and other thinking machines are acquiring these skills and abilities at an extraordinary rate.” —Brynjolfsson and McAffee

New technologies, notably AI, machine learning and digital analysis and design tools, will support early schooling and ease knowledge transmission tasks. Along with these will be advances in the fields of automation and robotics, which will impact work and learning patterns as well as student-teacher cooperation and industrial processes. Immersive virtualizations and machine-brain interactions will become new tools for improving effectiveness and innovation in the engineering world.
6.0 Summary and Conclusions

Systems analysis and engineering competencies, like many others, will need continuous nurturing and career development to ensure that the workforce remains current with technology, tools and methods, regulations, and many other developments. Digital enterprises moreover need a systems approach to unite and correlate the different value streams of their operations and ensure that their business models and products are resilient.

Changing SE development needs apply to industry, educational institutions and government organizations, especially to those involved in high-tech, often complex SE programs or acquisition and supply chain interactions. All need to advance their traditional approaches to cope with the demands of digital enterprises and remain current in 2035. This will require major investments.

Since information will be progressively available in most all fields, education of SEs needs to focus more and more upon “truth of knowledge” and the integration of competencies across various engineering and programmatic domains. SE will continue to evolve and its education will be adapted to respond to changing stakeholder and digital transformation needs of the 2030s.

Key for successful enterprises in the 21st Century are people, their education, knowledge and effectiveness. Ensuring their continued competency development and motivation will be essential to attracting the best employees and retaining them.

7.0 References, Background Reading and Credits

7.1 References


2. Y. N. Harari, “21 Lessons for the 21st Century”


5. NAE Grand Engineering Challenges (http://www.engineeringchallenges.org/challenges.aspx)


12. Brynjolfsson and McAfee (2014), For further reading on sharing tasks between humans and machines see also (WEF_Future_of_jobs_2020.pdf) Figure 21 et al

7.2 Selective Background Reading with Emphasis on Post-Graduate SE Education (Needs additional suggestions coming from the community)

1. MIT System Design and Management Program (https://sdm.mit.edu/)


3. USC – Boeing Engineering Management and Systems Engineering Program (https://emse.mst.edu/boeing/)


7. Airbus Defense and Space: Dr. Uwe Kuehne, Dr. Colin Hamilton, Dr. Stefan Brueggemann – Introducing Agile Methodology into advanced Systems Engineering Training – Regular paper for ERTS 2020, published on HAL Archive


10. ABET criteria and accreditation of Systems Engineering (https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2020-2021)


13. CNN Money survey of 2009 (https://www.money.cnn.com/magazines/moneymag/bestjobs/2009/snapshots/1.html) ranked system engineers from amongst 50 most desirable jobs in America as the number one!

### 7.3 Credits and Thanks

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