



INCOSE Perspectives on Engineering 21st Century Systems

International Council on Systems Engineering (INCOSE) is the international professional society promoting application of an interdisciplinary systems approach to enable the realization of successful systems

Engineering 21st century systems depends upon the robustness and effectiveness of engineering practice, and systems engineering is evolving to address the increasing complexity inherent in these systems. The perspectives in this paper are offered as a catalyst for further development of a detailed vision to guide INCOSE and the worldwide systems community to pursue the most promising paths for advancing systems engineering research and practice.

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GLOBAL ENGINEERING ENVIRONMENT

The global engineering environment of this century demands a deeper understanding of national and cultural policies, economies, laws, priorities, and preferences. There is a growing need to address integrated multiculturalism, and to apply systems perspectives and solutions toward addressing the key global challenges of sustainable development, including: world peace and international security, management of natural resources, health systems, and many others.



The International Space Station is the largest and most complex international scientific project in history. Led by the United States, it draws upon the scientific and technological resources of 16 nations: Canada, Japan, Russia, 11 nations of the European Space Agency and Brazil. (photo credit: NASA, with permission)

- Within the context of this global engineering environment and the challenges we face, engineering efforts must increasingly consider the social and ecological impacts of decisions and actions.
- There will be continued growth in international cooperation/merging of defense, information technology, communication, transportation, energy, and many other sectors whereby international extended enterprises will develop systems of unprecedented size and complexity.
- The need for natural resources will be greater than ever, and conflicts may increase related to the opportunities to discover, develop, and deploy these productively for the betterment of humankind on a worldwide basis.
- Changing demographics in population (e.g., a longer lifespan) will influence investments in, and desirable characteristics and capabilities of certain products and systems, as well as the global workforce itself.
- Global terrorist threats will increase the potential instability in economies and will drive the need for counter-terrorist systems, such as the need for sophisticated detection devices and information-fusion technologies. International security will be a major focus, including issues such as border control, surveillance/protection of public places, and detection of potential threats across the globe and identification of appropriate responses.
- Expansion of free trade regions will ease flow of capital resources and open new global markets. Cross investments, mergers and trans-national cooperative ventures will continue to dominate business strategies. Continued cost pressures for gaining competitive advantages on national, regional and global scales will force efficiencies, and return on investment pressures.
- The procurement and operations of systems will experience transitions in multiple dimensions. Government procurement, on an international basis, will increasingly involve commercial products/suppliers. We will see changes in privatization of government operations/systems, as well as government acquisition/operation of previously private systems (e.g., US airport security).
- There will be a further expansion of distributed worldwide production capabilities with associated sharing of resources and specializations for increased efficiency. Globalization will not, however, eliminate the need for and/or the desirability of regional specialization in activities in which a given region has or can develop competitive advantage.

FUTURE SYSTEMS

The global engineering environment drives a new worldview – *systems of systems*. Evolving needs, new approaches, and advances in technology are influencing the characteristics and the capabilities of emerging and future systems, which are increasingly evolutionary and adaptive in nature.



The Central Artery/Tunnel Project's Operations Control Center (OCC) in South Boston contains the most advanced electronic traffic monitoring and incident response system in the world. (photo credit: Massachusetts Turnpike Authority, with permission)

- Systems of all types will continue to become more complex in their composition, capabilities, and interfaces. There will be a **significant increase in "super systems"**, such as Air Traffic Control Systems and Intelligent Transportation, requiring large teams and infrastructures to produce and support.
- Systems developed by **large national and international enterprises** will dominate commercial and defense partnerships. Many systems, including warfare systems, will be driven by the **network-centric paradigm**.
- This continuing **aggregation of systems of systems will drive the need to network new and existing systems**, and the need to effectively implement continuous technology updates throughout the system lifecycle. Considerations of the long-range impacts and supportability will be increasingly important. Global information management and networks of networks will continue to grow
- Systems will **evolve over their lifecycle and must be designed to accommodate new technologies** as they become available for use. For example, biomedical technology will be increasingly important to improving health/quality of life and to counter bio-terrorist threats. Systems engineering will need to address the complex adaptive issues and opportunities leading toward self-healing systems. There will be robust reengineering and remanufacturing of obsolete systems, moving beyond simple reuse.
- Engineering projects will require **less component development and more systems integration** of off-the-shelf products. Product family approaches will grow in importance in both commercial and defense industries. Technology change will continue to accelerate rapidly, and will be both continuous and disruptive. There will be a **convergence of "soft" and "hard" sciences** with increased collaboration by diverse specialists.
- There will be more **complex interaction of multiple advanced technologies, and embedded intelligence** that will allow further automation of complex products and processes. Systems will involve integration of natural systems with human-made products/systems, with the **human/system interface becoming highly sophisticated and complex**. Software and hardware will become increasingly intelligent and adaptable, enabled by faster/better computer technologies and interfaces.
- Products and systems will include **virtual devices with multiple sensory inputs**. Genetic engineering, robotics, micro/nano technologies, neuro-technologies, and improved human/system interfaces become integral. Artificial intelligence, virtual reality, adaptive systems, sensors for condition monitoring, robotics, and other technologies will enable new capabilities.
- **Transportation, environment, defense, and security** will be key areas in the years ahead. Systems opportunities include **anti-terrorism/conflict resolution, environmental science, resource management, healthcare, education, energy, and others**. There will be systems challenges driven by major disparities between the "haves" and "have-nots", within and across nations, and lack of opportunity and societal advancement that stems from that.
- **Systems opportunities will also stem from the need for general upgrading** of new military paradigms, infrastructure replacements, and the exploration of and expansion to space and deep sea.

SYSTEMS ENGINEERING EVOLUTION

Systems engineering is evolving as a **broader and more multi-faceted field**, as the problems and challenges of this century are solved better by systems approaches, rather than through application of technology alone. **Systems engineering grows in importance** to match stakeholder needs and desires with systems functionality and behaviors in order to ensure that systems "not only do things right but do the right things." Systems engineering now encompasses and combines **elements of many diverse fields and practices**: operations research, cybernetics, modeling and simulation, decision analysis, program/project management, requirements management, industrial engineering, risk management, logistics, product development, manufacturing, test, verification and validation, business systems engineering, economic systems analysis, and others.



Systems engineering is essential to successfully design, develop, and sustain the highly complex systems of the 21st century. (photo credit: INCOSE)

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- There is a critical need to ensure that **systems engineering focus is broad, increasingly embracing “non-technical” parameters** with focus on complete life cycles, value streams, return on investment, real options, risk management, and competitiveness of products. Systems, more than ever, will need to effectively accommodate technology, politics, economics, people, culture, environment, geography, and other factors.
- Systems Engineering has subsequently developed into an overarching mature discipline enabling the identification of system architectures, trade-offs among competing concerns, and integration across and between many specialty engineering, scientific, organizational, and related disciplines pursuing the **objective of achieving competitive products, processes, and services**. Further development and harmonization of the engineering approaches, standards, practices, and education is important to successfully solve the significant engineering challenges of this century.
- Many serious problems we now confront are **generic systems problems**, and not uniquely and only component and materials problems. We face **system-of-systems architecting, development, and management issues that are increasingly global and overarching** and involve interdisciplinary team efforts.
- In the 21st century, engineering involves **greater emphasis on increasingly complex systems of all types**: technological, human, and organizational. Increasing globalization, aggressive competition, expanded outsourcing, constantly changing needs and requirements, a distributed industrial base, and dwindling natural resources are just some of the challenges faced.
- Enterprises performing engineering must also keep pace with the times, and there **must be corresponding changes in the profession and practice of engineering**. Engineers will need to follow technological advancements to stay in tune with shorter technological and engineering knowledge update cycles.
- Systems engineering must **encompass architecting, design, development, and sustainment**, recognizing that the future brings opportunities and increased complexity and associated needs for evolution and adaptation as societies and businesses become increasingly inter-twined.
- As knowledge expands, engineering specialists will need to take a deeper and narrower focus, while the **systems engineer will need to cover an even broader perspective**. The near term effect (already taking place) is that we will have two (or more) layers of system engineers. At one end will be externally focused systems engineers that necessarily deal with such issues as definition of requirements, architecting and integration, and associated operational test and evaluation. At the other end, there will be domain system engineers who deal with “internals” of specific technological systems.

SYSTEMS ENGINEERING PRACTICE

There will be growing recognition that the **enterprise and its programs are all systems**, with focus on **lean efficient businesses and extended enterprises**. Means of collaboration will evolve with increased teamwork, distance collaboration, and telecommuting, with appropriate methods and tools to enable these. **Computerization of the development process** will continue to evolve, enabled by advances in methodologies and tools.



The engineering development environment will provide the capability for increased prototyping, modeling, simulation, and experimentation. As an example, Draper Laboratory's Rapid Prototyping Center allows engineers to create and evaluate concept models and functional prototypes early in the design process. (photo credit: *The Charles Stark Draper Laboratory, Inc., with permission*)

- International standards **harmonization** will be essential for interdisciplinary collaboration. Standards for architecting and interface definition are critical to development of robust systems and supporting the development environment. **Capability models serve as an enabler for the evolution and integration of an enterprise** from a process perspective.
- Measurement science will move further beyond planning and management focus, to offering a truly **predictive capability**. There will be greater attention to non-traditional methods of representing and analyzing **emergent and adaptive**

behavior. Methodologies and enabling technologies for **quantitatively predicting system behavior** will evolve.

- Advances in computing power and experimentation methods will enable **high value experimentation throughout the engineering lifecycle**, with particular focus in early concept phase, thereby enabling design alternatives to be explored and decisions made with low risk and minimal costs.
- There will be **more prototyping of increasingly complex - and therefore hard to predict systems**, with sophisticated simulations. Methods to explore alternative roadmaps and **assess constraints/impacts from other systems** in a system-of-systems will become increasingly important.
- Systems engineering will involve increased use of **model-based techniques and processes**. There will be an evolution from isolated specialty views of system information into a truly model-based integrated development infrastructure. A rejoining of software and systems modeling interests around an evolving variation on current UML is leading to important integration effect where software and hardware engineers communicate much better than at present.
- **Development will be driven by modeling and simulation and seamless "cradle to grave" databanks** in an interactive environment where artificial boundaries between hardware, software and human systems will gradually become more transparent and ideally disappear.
- Standards and methods will better address the exploratory efforts that precede establishment of initial operational requirements and subsequent technological specifications. New techniques and tools will provide a structured approach to enable better understandings and to support predictions of **how changes in the world result in an evolutionary need for changes in the initially instantiated operational requirements** and associated system specifications.
- Automated tools used by all practitioners involved in an engineering effort will become seamless and easier to use. The **development environment will give organizations ability to save time and money** by exporting engineering information around the world, throughout supplier chains, and over networks in computer interpretable form. Supportability tools will be integrated from the start to ensure the total systems solution meets needs of all stakeholders. Higher quality and more extensive trade-off studies will be essential to reduce cost and time to market.
- The engineering of systems will involve strong collaboration and teamwork, and we will see the evolution of the approaches, methods, and tools to drive high levels of effectiveness of a diverse multidiscipline team.

EDUCATION & RESEARCH

As systems engineering and other engineering disciplines continue to evolve to meet the challenges of this new century, there must be **associated enabling changes in engineering education**. Engineering schools will have a broader multi-disciplinary focus and evolve to highly integrated, collaborate organizations rather than a cooperative of individual academic departments. Education will become a more integral and continuous part of the “professional lifecycle” of every engineer and will take place in many different venues.



Design competitions provide an excellent educational experience for student teams. Shown in the photo above is a view of the RoboCup 2003 International Robotics Competition (*photo credit: Patrick Riley, with permission*).

- All engineers will be **educated as problem solvers** with knowledge of systems engineering, human behavior, geo-political models, laws, and ethics. Engineers will be **educated to design for “what are you trying to accomplish”, to have a higher tolerance for change, and be able to design for the “promises of technology”**. More attention will be directed at long-term, hard-soft problems of engineering, for example ill-structured problem solving, architecture, integration, realistic decision assessment, and risk management.
- “Conventional” engineering education will be facilitated by **improved distance education, on-demand/just-in-time training, and extensive use of simulation technologies**. Engineers will develop skills needed for effective participation in larger more diverse multi-discipline teams.
- Undergraduate engineering programs will evolve to more systems-centered disciplinary programs, teaching approaches needed to engineer a complete system. At the graduate level we will see innovative, interdisciplinary programs. Increasingly, universities will have capstone projects with significant complexity, presenting management and technology challenges for student teams.
- There will be a **growing number of international competitions** hosted by professional societies and other engineering groups for designing airplanes, robotics, race cars and other systems to foster innovative research as well as providing a learning activity that emulates real world experiences.
- **Design laboratories will be needed to promote and fund research** and also provide educational opportunities that advance students from novice/apprentice to journeyman/master status.
- Universities and their extensions will be clearing houses for education and training products created and owned by the universities. More **corporate universities will be formed** through teaming with traditional universities. Certification and certificate programs will increase driven by industry demand. There will second degree postgraduate programs in systems engineering, to complement the master level degree in an engineering specialization.
- Systems engineering education will experience a **convergence in curricula** and increase in shared knowledge assets, while allowing flexibility to retain unique value of a given university. This convergence in curricula will be at all levels including post-graduate programs and certificate programs, and will be enabled by increased dialogue and formalization.
- **Collaboration in education and research between government, industry and academia** will increase. There will be a better understanding of what constitutes systems research, and funds available from companies and government to undertake it. Outstanding universities will couple practical and theoretical research, to achieve innovative breakthroughs through research project synergies.