# Transforming the Practice of Engineering for Large Complex Systems

**Inter-Agency Working Group on the Engineering of Complex Systems**

**Executive Summary**: The complexity of engineered systems has swelled in the last several decades, and this trend is likely to continue for the foreseeable future. While projects are becoming more complex, current engineering practice has largely evolved from a top-down approach that is the legacy of past successes. A fundamental rethinking of engineering methodologies is urgently needed if our nation is to ensure that the large complex systems critical to our national security, economy, and quality of life are resilient in the face of natural disasters, creative adversaries, and an unforeseeable future. In June 2012, an Inter-Agency Working Group (IAWG) on Engineering Complex Systems convened to explore these issues from the perspectives of several government agencies that represent diverse missions. The IAWG seeks to stimulate a dialogue that will help usher the engineering community toward the next generation of research and practice.

**55 million without power, 11 deaths, and an estimated cost of $6 billion**. The biggest blackout in American history began without warning. August 14, 2003 was a typically hot summer day in the northeastern United States, with millions of homes and businesses relying on air conditioning to meet critical cooling needs. The demand for electric power was high. The Cleveland-Akron area of Ohio had been hot for days, and two local power generation units were offline for routine repairs and maintenance. Shortly after noon, a software tool that provides situational awareness of the system went offline for nearly four hours due to a combination of bad data and human error. During those hot, sunny hours, several high-voltage power transmission lines sagged and came into contact with overgrown trees, causing short circuits. With an incomplete understanding of what was taking place across the system, utility operators were unable to respond effectively to these and other real-time conditions, including the loss of another power generation unit and a software bug at a utility company. The failures in Ohio began to ripple throughout the system, and within a 15-minute period shortly after 4 o'clock the problem cascaded through Michigan, Pennsylvania, New York, Ontario, and New Jersey. The result was 55 million people without power, 11 deaths, an estimated cost of $6 billion, and disruptions affecting small and large business from hospitals to military facilities.

**The complexity of engineered systems has swelled in the last several decades**. All indications point toward this trend continuing for the foreseeable future. As a result of the revolution in information technology and the adoption of new models for partnerships, governance, and financing, systems in areas such as defense, aerospace, health care, and civil infrastructure (transportation, electric power, and water supply systems, for example) have escalated dramatically in scale and interconnectivity. As with the Northeast blackout, these systems all have mechanical, cyber, and human dimensions. The interactions of these dimensions present challenges ranging from sheer size to interoperability across multiple engineered systems and organizational boundaries.

These interactions have led to increasing complexity. A system may be considered complex if it is not mathematically predictable within reasonable constraints of time, computational power, and existing modeling tools. The interactions that can take place within a complex system cannot be fully imagined or defined based on an understanding of its constituent elements. This makes it impossible to fully test such a system in a traditional manner. Beyond the unpredictable behaviors of these systems, the inability to fully understand and envision them during their design phase usually leads to significant cost and schedule overruns in the development and operation phases.

The difficulty of anticipating these interactions is further complicated because systems often face changing requirements throughout their life cycles. The F/A-18 aircraft, which had its first flight in

1978, was initially designed to serve the U.S. Navy on aircraft carriers for sorties averaging 90 minutes. Its useful life was to be roughly 15 years, including 3000 flight hours. When Switzerland decided to purchase the aircraft in the mid-1990s, its requirements were different. The Swiss F/A-18 was to be a land-based interceptor that would fly sorties averaging 40 minutes. The aircraft's useful life was extended to 30 years, including 5000 flight hours. These new requirements for greater durability demanded a significant redesign effort. In order to address the increased fatigue to the airframe that would result from 2000 additional flight hours, the Swiss redesign called for building the center barrel of the aircraft from titanium rather than aluminum. Because of the complexity of the F/A-18, this relatively small change had the unintended consequences of increasing the weight of the aircraft and shifting the center of gravity. This required changes to the flight control software and manufacturing processes, raising the cost per aircraft by roughly $10 million.

As governments around the world seek to stretch constrained resources through collaboration on complex systems such as the International Space Station (ISS), there is an increasing need to address these types of challenges. In the case of the ISS, the partners have had to adapt to a more ambitious operational model than its designers envisioned, a greater variety of spacecraft docking with the station, and a more difficult orbital debris environment than existed when it was designed. None of the partner governments could have afforded the full investment alone, and none could have kept the station continuously manned over more than a decade.

**While projects are becoming more complex, current engineering practice has evolved from a top-down approach** that enabled the development of our entire present-day physical infrastructure, ground and air transportation systems, and telecommunication networks. This approach, involves reducing a system to its constituent components and computing the performance capabilities and material properties of each component using existing knowledge or scientific theories. The behavior of the entire system is then inferred from the behavior of, and the interactions among, its components. This process can be useful for analyzing large systems such as computers, but it is inadequate and potentially even counter-productive for highly networked systems affected by variables such as the number of decision-makers, culture, and organizational practice, which fall outside traditional engineering concerns. The success of this “components-first, interactions-later” approach can encourage many engineers to focus exclusively on a single component or technical discipline of a system, and to marginalize both nonlinear, unpredictable technical interactions such as those experienced with the F/A-18 and complex social interactions such as incentives and governance.

A fundamental rethinking of engineering methodologies is urgently needed if our nation is to ensure that the large complex systems critical to our national security, economy and quality of life are resilient in the face of natural disasters, creative adversaries, and an unforeseeable future. This transformation of engineering calls for not only a deeper understanding of systems and the scenarios in which they operate, but also for capitalizing on knowledge from interdependent fields such as the social sciences and humanities. A reexamination and reconstruction of engineering practices from the roots upward—from initial research to system disposal—will yield important discoveries that are often found only at the intersection of existing disciplines. Bridging the gap between the natural and social sciences and synthesizing the knowledge and practices of both is essential, as is taking advantage of the rapid advances in computing power available. Today is a watershed moment for engineering that calls for a fundamental transformation of its practice.

**In June 2012, an Inter-Agency Working Group (IAWG) on Engineering Complex Systems convened to explore these issues** from the perspectives of several government agencies that represent diverse missions. The National Science Foundation has identified needed research on designing complex engineered systems and pioneered funding research and workshops toward this

end for over two decades. The National Aeronautics and Space Administration (NASA) found it necessary to advance and adopt new model-based systems methodologies for recent missions to Mars. In April 2011, the U.S. Secretary of Defense announced seven science and technology priorities essential to the future of the nation, one of which was Engineered Resilient Systems aimed at transforming engineering environments so that warfighting systems are more resilient and affordable across the acquisition lifecycle. At the National Institute of Standards and Technology, benchmark studies on immense complexities in cyber-physical systems were recently completed. And the Department of Energy is making significant investments in advanced simulation to address a wide range of complex problems, including new modeling capabilities to understand nuclear weapon performance, innovative nuclear reactor design, and performance of a smart energy grid. Through NextGen, the FAA is in the midst of a widespread, transformative change to the complex national airspace and the way we fly. Similarly, the advent of connected vehicles and infrastructure provides an opportunity to transform surface transportation on the nation's highways.

Looking at these challenges through a common lens, the IAWG envisions a future in which large, technologically path-breaking engineering projects are undertaken regularly, are almost always successful, and are routinely accomplished on time and within budget. There is an urgency to achieve this vision because our society increasingly relies on complex systems, and their number is on the rise. They are heavily influenced by factors such as environmental sustainability, highly networked cyber systems, and other drivers of organizational complexity such as project teams distributed across multiple continents and time zones, divergent interests among numerous stakeholders, and geostrategic concerns that can affect international partnerships.

**The IAWG seeks to stimulate a dialogue that will help usher the engineering community toward the next generation of research and practice**. The path forward will redefine how engineers approach both the technical and social challenges of researching, designing, developing, and delivering systems, making it possible to reframe the engineering of complex system in ways that significantly enhance value and effectiveness. The needed transformations must address effectiveness, affordability, timeliness, and adaptability challenges posed by current and future technologically sophisticated systems, through tools and approaches grounded in fundamental scientific and mathematical principles.

Long-term success will require engaging the diverse research communities across all relevant fields (e.g., engineering, social science, business, and law); working with private industry to transform that research into new, transformational advances in engineering practice; and collaborating with the educational community on the development of innovative training techniques to enable a new generation of engineering practitioners and educators. By initiating this crucial interdisciplinary discussion, the IAWG seeks to draw on the collective wisdom of all stakeholders across the engineering enterprise. We believe this transformation represents more than a small step for professional practice—it is a giant leap forward for our future.

## Inter-agency Working Group Meeting Participants:

**Kristen J. Baldwin**
*Principal Deputy, Deputy Assistant Secretary of Defense for Systems Engineering, DOD*

**Paul Collopy, PhD**
*Program Director, Engineering and Systems Design, CMMI, NSF*

**George Hazelrigg, PhD**
*Deputy Division Director, Division of Civil, Mechanical and Manufacturing Innovation (CMMI), NSF*

**Lois Hollan**
*Research Fellow, Potomac Institute for Policy Studies*

**Jeffery P. Holland, PhD**
*Director, US Army Engineer Research and Development Center; Director of Research and Development, US Army Corps of Engineers, DOD*

**Brian Hooper**
*Acting Assistant Deputy Administrator for Systems Engineering & Integration, Office of Defense Programs, NNSA, DOE*

**Albert T. Jones, PhD**
*Scientific Advisor, Systems Integration Division, NIST*

**Scott Lucero**
*Deputy Director of Strategic Initiatives, Office of the Deputy Assistant Secretary of Defense, Systems Engineering, DOD*

**Natesh Manikoth**
*Chief Scientist for NAS System Software, FAA*

**Anna-Maria R. McGowan**
*Senior Advisor for Engineering Complex Systems, NASA Langley Research Center, Aeronautics Research Directorate*

**Steven H. McKnight, PhD**
*Division Director, Division of Civil, Mechanical and Manufacturing Innovation (CMMI), NSF*

**Robert A. Pearce**
*Director for Strategy, Architecture and Analysis, NASA Langley*

**Jonathan Porter, PhD**
*Chief Scientist, Office of Research, Development and Technology Federal Highway Administration*

**David R. Richards**
*Technical Director, Information Technology Laboratory, US Army ERDC, DOD*

**Mike Ryschkewitsch, PhD**
*NASA Chief Engineer, NASA Headquarters*

**Joseph Smith**
*Program Executive for Systems Engineering, Office of the Chief Engineer, NASA Headquarters*

**Vijay Srinivasan, PhD**
*Chief, Systems Integration Division, Engineering Laboratory, NIST*

**Clayton Turner**
*Director, Engineering Directorate, NASA Langley Research Center*

Distribution Statement A – Approved for public release by DOPSR on 11/27/2013; SR Case #14-S-0484 applies. Distribution is unlimited. Concurrence: Department of Energy, Department of Transportation, National Aeronautics and Space Administration.

*The views and conclusions contained in this document are those of the authors and editors, and should not be interpreted as necessarily representing the official policies, either expressed or implied, of any specific US Government agency or the United States Government in general.*