Enhancing Engineering Productivity

Douglass Post and Richard Kendall

he high level of technological innovation required for a strong national economy and defense is only achievable with a highly productive engineering workforce. In this country, the widely reported decline in the number of US students graduating in STEM disciplines strongly suggests that the US lead in innovation could be in jeopardy.¹ Changing demographics in the US engineering workforce exacerbate this situation: many of the most highly skilled engineers in the US defense community are rapidly approaching retirement age, and replacing their skills is a huge challenge.

This impact can be ameliorated by increasing engineering workforce productivity. Driven by US national defense needs^{2,3} in the 1940s and 1950s, computers were initially developed to increase the productivity of scientists and mathematicians engaged in decryption and cryptography, the design and testing of nuclear weapons, the computation of artillery firing tables, the design and testing of aerospace systems—including the Apollo Program—and many other defense related programs. The adoption of PCs and workstations in the 1980s and 1990s accelerated office and engineering productivity via word processors, spreadsheets, business enterprise data processing, and computer-aided design systems. More recently, sophisticated engineering tools such as Matlab (www. mathworks.com) and Nastran, (www.mscsoftware.com/product/msc-nastran) as well as multi-physics "linked" tools such as ANSYS (www.ansys.com) and Comsol (www. comsol.com), have continued to increase engineering workforce productivity. However, the exponential growth in the computing power of laptops and small clusters that has sustained the growth of this productivity is slowing down and saturating.⁴

Fortunately, help is on the way. The confluence of the growing power of supercomputers and the development and deployment of multi-effect, science-based computational engineering software applications (tools) is beginning to give us the ability—for the first time in human history—to make accurate predictions of the performance of many complex, full-scale systems. For instance, the US Department of Defense High Performance Computing Modernization Program engineering application HPCMP CREATE-Kestrel can accurately predict the flight performance of a fixed-wing jet aircraft, including the aerodynamics, structural dynamics, propulsion, control, and other effects that determine the flight characteristics (http://aem.eng.ua.edu/files/2015/01/ David-McDaniel-flyer.pdf). Similarly, Goodyear's tire design tool treats all the major effects that determine tire performance for modern vehicles.⁵ Engineers now use validated tools like Kestrel and the Goodyear tire design tool to design and analyze fixedand rotary-winged aircraft and modern complex tires, ships, complex antenna systems, ground vehicles, nuclear reactors, and many other complex systems. New tools are continually being developed for many other systems.

Going Virtual

All of these tools enable the construction and testing of virtual prototypes, thereby reducing the requirements for live tests and providing design decision data much earlier than previously achievable. Design engineers can develop optimized designs quickly as "virtual prototypes" and test them with multi-physics analysis tools early in the product development phase, even at the beginning of conceptual design and requirements definition. Design flaws, integration problems, and performance shortfalls can be detected and fixed before metal has been cut, thus avoiding time-consuming and costly rework. A classic example of the advantages of this paradigm for product development comes from Goodyear.⁵ In 2003, Goodyear Tire began serious use of a set of multiphysics high-performance computing tools that could create virtual prototypes for complex, multi-tread, multi-layer tires and analyze and accurately predict their performance (tread wear, hydroplaning, low rolling resistance, and so on) prior to live testing. These tools enabled Goodyear to reduce its time to market by a factor of four, increase its innovation rate from 10 new products a year to more than 60, and reduce its testing costs by 60 percent (http://investor.goodyear.com/annuals.cfm).

Computational engineering design tools not only simulate a complex physical system's performance, their use can also simulate the product development process itself. By working on simulated design projects, engineers have the ability to gain extensive and wide-ranging work experience by participating in many, rather than just a few, design and development projects over the course of their career. Many large industries focus on a few major projects at any given time—for example, the design and product development of major airplanes, such as the Boeing 787, take nine or more years. For an engineering career that might span 35 years, an engineer can expect to be part of around four major projects. For military aircraft systems, the product development cycle time can take 25 years or more, which translates to just two projects over the course of a career. This undoubtedly overstates the severity of the problem, but the fact remains that having fewer major design projects reduces an engineer's ability to gain a wide range of work experience.

In this environment, it's difficult to get the kind of experience that engineers in the 1970s got when the product development cycle was closer to five years, enabling engineers to work on many more projects over their career. With computational tools to create and "test" virtual prototypes, engineers can develop, test, and optimize many different designs. This gives them feedback on how well their designs work and helps them develop the experience they need to advance their professional careers by giving them additional opportunities to grow their expertise and confidence.

Many large industries that produce complex systems are evolving into systems integrators. Much, if not most, of the technical product design and development is often outsourced to suppliers. The integrator needs engineers to oversee and manage the process of procuring and integrating components from suppliers into the system. These engineers must be knowledgeable and experienced and possess considerable technical judgment. But companies frequently, out of necessity, hire engineers who are early in their careers and haven't had time to acquire the skills, judgment, and confidence they need to be successful. The use of simulated design environments for training can accelerate the acquisition of such abilities, and it can also help with recruiting and retention. Engineers who start their first job expect to do "real" engineering that allows them to grow and mature their engineering and professional skills. If placed in a program management or procurement job that doesn't allow them to increase those skills, they often become dissatisfied and leave. The combination of technical work on a real project, combined with program management experience and participation in virtual design and development projects, can facilitate career growth, resulting in much greater job satisfaction and retention, as well as helping them improve their technical skills and their effectiveness as program managers.

Changing Demographics

The age distribution in many engineering organizations is bi-modal: most engineers are very senior and nearing retirement or are very young and inexperienced. These organizations need to cope with the imminent loss of the institutional knowledge and experience that resides in their senior engineering staff and rapidly transfer it from senior to junior staff. The use of a simulated design and product development process helps senior engineers mentor many more junior engineers in the early stage of their careers than they could in a conventional project. Catalogues of real and candidate designs can be constructed, analyzed, and stored. Guided by a senior engineer, junior staff can use computational tools to analyze these designs and discuss the results with their mentor. Then they can develop their own designs, use the tools for analysis, and discuss them with their mentor. During our careers, we've seen one senior engineer train more than 10 engineers over the course of a year or two. The "graduates" of the simulated design and product development "school" eventually became a disproportionately large fraction of the leading engineers in that organization, and this training paradigm was gradually adopted across the board.

This paradigm also enables greater product innovation. In the traditional conceptual design process, an engineer usually constructs a few candidate designs and then iteratively refines those designs with a series of detailed analyses. This process is laborious and allows exploration of only a few design concepts. With computational physics-based conceptual design tools, thousands of options can be developed and assessed using low-fidelity analysis tools to weed out infeasible designs and identify the feasible ones. It's similar to Darwinian "natural selection." The low-fidelity tools are used to identify and eliminate the "less fit" designs—only the "fittest" designs survive. Variations of these "fittest" designs are developed and then subjected to the "natural selection" process. Once a final generation of "fittest" design options has been identified, more accurate high-fidelity tools can validate the choices made on the basis of low-fidelity analyses.

f course, there are caveats. These tools are based on mathematical models of nature. They aren't nature, so they must be extensively verified and validated. Final predictions must be confirmed with live tests. These tools help to focus testing to make it more effective. This can reduce the amount of testing required, but doesn't replace testing. Quantitative knowledge of the uncertainties in the calculated results is needed to guide decisions. The codes must be used by experienced and knowledgeable subject matter experts because these tools aren't black boxes. It's all too easy for an inexperienced or careless user to get a faulty answer. However, in the hands of a skilled and knowledgeable engineer, these tools can greatly magnify productivity, just as the computers and decryption algorithms at Bletchley Park increased by many orders of magnitude⁶ the speed, number, and fidelity of the decryptions that the British Ultra staff made of intercepted German military radio messages encrypted with Enigma machines. The importance of the workforce productivity enhancement provided by the tools and computers is described in the following quotation: "Sir Harry Hinsley, Bletchley Park veteran and official historian of British Intelligence in World War II, made a similar assessment about Ultra (the decryption work being done at Bletchley Park), saying that it shortened the war 'by not less than two years and probably by four years'; and that, in the absence of Ultra, it is uncertain how the war would have ended."⁷

References

- 1. N. Augustine et al., *Rising above the Gathering Storm, Revisited: Rapidly Approaching Category 5*, Nat'l Academies Press, 2010.
- 2. G. Dyson, Turing's Cathedral, Vintage, 2012.
- 3. L. Weiss, *America Inc., Innovation and Enterprise in the National Security State*, Cornell Univ. Press, 2014.
- 4. S. Fuller and L. Millett, *The Future of Computing Performance*, Nat'l Academies Press, 2011.
- L.K. Miller, "Simulation-Based Engineering for Industrial Competitive Advantage," Computing in Science & Eng., vol. 12, no. 3, 2010, pp. 14–21.
- 6. Andrew Hodges, Alan Turning: The Enigma, Princeton Univ. Press, 2014.
- H. Hinsley, "The Influence of ULTRA in the Second World War," transcript of a lecture, Cambridge Univ., 19 Oct. 1993.