Engineering for a Changing World: Future of Engineering Practice, Research, & Education

Pawan Shakdwipee, Vishnu Inani, Naveen Shakdwipee

Abstract — **An array of powerful forces, including demographics, globalization, and rapidly evolving technologies, is driving profound changes in the role of engineering in society. The changing technology needs of a global knowledge economy are challenging the nature of engineering practice, demanding far broader skills than simply the mastery of scientific and technological disciplines. The growing awareness of the importance of technological innovation to economic competitiveness and national security is demanding a new priority for basic engineering research. The nonlinear nature of the flow of knowledge between fundamental research and engineering application, the highly interdisciplinary nature of new technologies, and the impact of cyber infrastructure demand new paradigms in engineering research and development.**

Index Terms— **Engineering, Research, Higher education, Technological Innovation**

I. Introduction

Engineering is the application of scientific, economic, social, and practical knowledge, in order to design, build, and maintain structures, machines, devices, systems, materials and processes. It may encompass using insights to conceive, model and scale an appropriate solution to a problem or objective. The discipline of engineering is extremely broad, and encompasses a range of more specialized fields of engineering, each with a more specific emphasis on particular areas of technology and types of application. Powerful forces, including demographics, globalization, and rapidly evolving technologies are driving profound changes in the role of engineering in society. The purpose of this study is to pull together the principal findings and recommendations of the various reports concerning the profession of engineering, the technology and innovation needs of the nation, and the role played by human and intellectual capital. It is clear that our nation faces the very real prospect of losing its engineering competence in an era in which technological innovation is key to economic competitiveness, national security, and social well being.

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(A). Engineering Practice

The implications of a technology-driven global economy for engineering practice are particularly profound. The globalization of markets requires engineers capable of working in and with different cultures and knowledgeable about global markets. New perspectives are needed in building competitive enterprises as the distinction between competition and collaboration blurs. The rapid evolution of high-quality engineering services in developing nations with significantly lower labor costs, such as India, China, and Eastern Europe, raises serious questions about the global viability of the United States engineer, who must now produce several times the value-added to justify wage differentials. Both new technologies (e.g., info-bio-nano) and the complex mega systems problems arising in contemporary society require highly interdisciplinary engineering teams characterized by broad intellectual span rather than focused practice within the traditional disciplines. As technological innovation plays an ever more critical role in sustaining the nation's economic prosperity, security, and social well-being, engineering practice will be challenged to shift from traditional problem solving and design skills toward more innovative solutions imbedded in an array of social, environmental, cultural, and ethical issues.

(B). Engineering Research

There is increasing recognition that leadership in technological innovation is key to the nation's prosperity and security in a hypercompetitive, global, knowledge- driven economy (Council on Competitiveness, 2003). While our American culture, based upon a highly diverse population, democratic values, free-market practices, and a stable legal and regulatory environment, provides an unusually fertile environment for technological innovation and entrepreneurial activity, history has shown that significant federal and private investments are necessary to produce the ingredients essential for innovation to flourish: new knowledge (research), human capital (education), infrastructure (e.g., physical, cyber), and policies (e.g., tax, property).

(C). Engineering Education

The current paradigm for engineering education, e.g., an undergraduate degree in a particular engineering discipline, occasionally augmented with workplace training through internships or co-op experiences and perhaps further graduate or professional studies, seems increasingly suspect in an era in which the shelf life of taught knowledge has declined to a few years.

There have long been calls for engineering to take a more formal approach to lifelong learning, much as have other professions such as medicine in which the rapid expansion of the knowledge base has overwhelmed the traditional educational process. Yet such a shift to graduate- level requirements for entry into the engineering profession has also long been resisted both by students and employers. Moreover, it has long been apparent that current engineering science-dominated curricula needs to be broadened considerably if students are to have the opportunity to learn the innovation and entrepreneurial skills so essential for our nation's economic welfare and security, yet this too has been resisted, this time by engineering educators.

(D). The Purpose of the Study

The purpose of this study is to pull together the principal findings and recommendations of these various reports concerning engineering, the technology and innovation needs of the nation, and the role played by human and intellectual capital, into an analysis of the changing nature of engineering practice, research, and education. More specifically, it considers the implications for engineering from several perspectives: i) as a discipline (similar to physics or mathematics), possibly taking its place among the "liberal arts" characterizing a 21st-century technology-driven society; ii) as a profession addressing both the urgent needs and grand challenges facing our society; iii) as a knowledge base supporting innovation, entrepreneurship, and value creation in a knowledge economy; and iv) as a diverse educational system necessary to produce the engineers and engineering research critical to national prosperity and security.

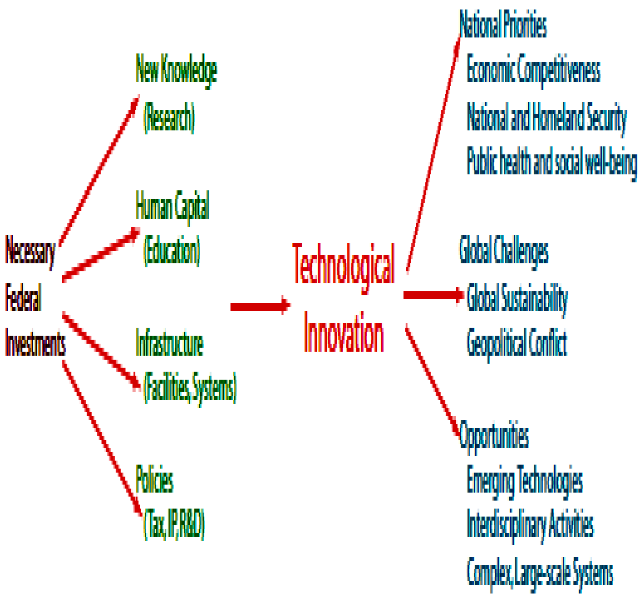

Figure 1. The role of technological innovation in the knowledge economy.

(E). Technological Innovation

Many nations are investing heavily in the foundations of modern innovation systems, including research facilities and infrastructure and a strong technical workforce. Unfortunately, the United States has failed to give such investments the priority they deserve in recent years. The changing nature of the international Economy, characterized by intense competition coexisting with broad-based collaboration and global supply chains and, underscores long-standing weaknesses in the nation's investment in the key ingredients of technological innovation: new knowledge (research), human capital (education), and infrastructure (educational institutions, laboratories, cyber infrastructure).

II. A Time of Challenge, Opportunity, and Responsibility

It is certainly true that many of the characteristics of our nation that have made the United States such a leader in innovation and economic renewal remain strong: a dynamic free society that is continually renewed through immigration; the quality of American intellectual property protection and the most flexible labor laws in the world, the best regulated and most efficient capital markets in the world for taking new ideas and turning them into products and services, open trade and open borders (at least relative to most other nations), and universities and research laboratories that are the envy of the world. If all of this remained in place, strong and healthy, the United States would continue to remain prosperous and secure, even in the face of an intensely competitive global knowledge economy. We would continue to churn out the knowledge workers, the ideas and innovation, and the products and services (even if partially outsourced) that would dominate the global marketplace.

Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, natural and man-made materials and the forces of nature for the benefit of human kind. Engineers are persons who, by reason of their special knowledge and use of mathematical, physical, and engineering sciences and the principles and methods of engineering analysis and design, acquired by education and experience, are qualified to practice engineering.

In a more general sense, engineers are problem solvers, creators of ideas and concepts, builders of devices, structures, and systems. They apply their knowledge of science and technology to meet the needs of society, to solve its problems, and to pave the way for its future progress. The intellectual activities of engineering are heavily based on synthesis, design, and innovation through the integration of knowledge. But engineering is more than an intellectual discipline like physics or chemistry. It is also a vocation characterized by great diversity. For example, most engineering students would likely describe their career interests in terms of their engineering major, e.g., civil engineering, mechanical engineering, electrical engineering, industrial engineering, or one of a growing array of engineering specialties (e.g., aerospace, agricultural, architectural, atmospheric, automotive, biomedical, computer, environmental, manufacturing, materials, metallurgical, mining, nuclear, petroleum, sanitary, system, and transportation). Yet as graduates move into engineering practice, they are more likely to define their occupation in terms of specific roles and activities, e.g., product design, manufacturing engineering, systems engineering, research and development, construction engineering, project management, operations engineering, testing, sales and marketing, management, consulting, and teaching (academe).

(A). The Knowledge Base for Engineering

Key to the ability of engineers to develop the products, systems, and services that are essential to national security, public health, and the economic competitiveness of the nation's business and industry is the knowledge base created by engineering research. The new knowledge generated through research drives technological innovation–the transformation of knowledge into products, processes, and services–which, in turn, is critical to competitiveness, long-term productivity growth, and the generation of wealth.

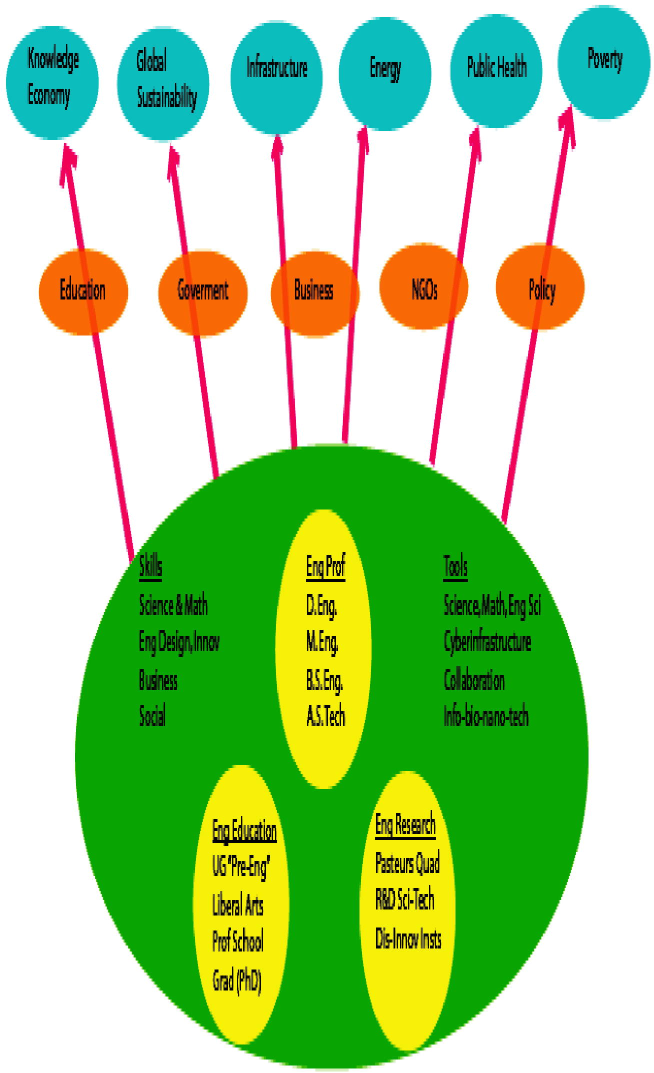

Figure 2 : The Grand Challenges of 21st Century Engineering.

Engineers take new and existing knowledge and make it useful, typically generating new knowledge in the process. Without engineering research, innovation, especially groundbreaking innovation that creates new industries and transforms old ones, simply does not happen. Applying technological advances to achieve global sustainability will require significant investment, creativity, and technical competence. Advances in nanotechnologies, biotechnologies, new materials, and information and communication technologies may lead to solutions to difficult environmental, health, and security challenges, but their development and application will require significant investments of money and effort in engineering research.

(B). Engineering Education and Training

What key skills and competencies are needed by today's engineers? Certainly sufficient mastery of the basic tools of science and mathematics to address technological problems. In fact, ABET (once an abbreviation for the Accreditation Board for Engineering and Technology but now only an acronym for the accreditation agency) sets the following objective for engineering degree programs:

"Students should gain an ability to apply knowledge of mathematics, science, and engineering; to design and conduct experiments as well as to analyze and interpret data; to function on multidisciplinary teams; and to communicate effectively."

More specifically, today's ABET's Engineering Criteria includes, among other elements, requirements which stress the importance of an engineering graduate's ability to:

* Apply knowledge of science, mathematics, and engineering
* Design and conduct experiments and analyze data
* Design a system, component, or process to meet desired needs
* Function on multi-disciplinary teams
* Identify, formulate, and solve engineering problems
* Understand professional and ethical responsibility
* Communicate effectively
* Understand the impact of engineering solutions in a global/social context
* Engage in life-long learning
* Exhibit a knowledge of contemporary issues
* Use the techniques, skills, and modern engineering tools necessary for engineering practice.

Engineers have a collective responsibility to improve the lives of people around the world.

The world is becoming a place in which the human population (which now numbers more than six billion) is becoming more crowded, more consuming, more polluting, more connected, and in many ways less diverse than at any time in history. The question now arises whether it is possible to satisfy the needs of a population that is growing exponentially while preserving the carrying capacity of our ecosystems and biological and cultural diversity. A related question is what should be done now and in the near future to ensure that the basic needs for water, sanitation, nutrition, health, safety, and meaningful work are fulfilled for all humans. These commitments were defined as the "Millennium Development Goals" by the United Nations General Assembly on September 18, 2000 (United Nations Development Programme, 2003).

This growth will create unprecedented demands for energy, food, land, water, transportation, materials, waste disposal, earth moving, health care, environmental cleanup, telecommunication, and infrastructure. The role of engineers will be critical in fulfilling those demands at various scales, ranging from remote small communities to large urban areas (megacities), mostly in the developing world.

For that to occur, engineers must adopt a completely different attitude toward natural and cultural systems and reconsider interactions between engineering disciplines and nontechnical fields. For the past 150 years, engineering practice has been based on a paradigm of controlling nature rather than cooperating with nature. In the control-of-nature paradigm, humans and the natural world are divided, and humans adopt an oppositional, manipulative stance toward nature. Despite this reductionist view of natural systems, this approach led to remarkable engineering achievements during the nineteenth and especially twentieth century's. For instance, civil and environmental engineers have played a critical role in improving the condition of humankind on Earth by improving sanitation, developing water resources, and developing transportation systems. Most engineering achievements of the past were developed without consideration for their social, economic, and environmental impacts on natural systems. Not much attention was paid to minimizing the risk and scale of unplanned or undesirable perturbations in natural systems associated with engineering systems. As we enter the twenty-first century, we must embark on a worldwide transition to a more holistic approach to engineering. This will require: (1) a major paradigm shift from control of nature to participation with nature; (2) an awareness of ecosystems, ecosystems services, and the preservation and restoration of natural capital; and (3) a new mindset of the mutual enhancement of nature and humans that embraces the principles of sustainable development, renewable resources management, appropriate technology.

In addition, engineering educators must take a closer look at how engineering students are being prepared to enter the "real world." Current graduates will be called upon to make decisions in a socio-geo-political environment quite different from that of today. In their lifetimes, engineering students now attending college can expect to see an increase in world population from 6 to 9 or 10 billion people, major global warming phenomena, and major losses in biological and cultural diversity on Earth. An issue of equal importance is the education of engineers interested in addressing problems specific to developing communities. These include water provisioning and purification, sanitation, power production, shelter, site planning, infrastructure, food production and distribution, and communication, among many others. Such problems are not usually addressed in engineering curricula in the United States, however. Thus, our engineers are not educated to address the needs of the most destitute people on our planet, many of them living in industrialized countries

Furthermore, engineers will be critical to addressing the complex problems associated with refugees, displaced populations, and the large-scale movement of populations worldwide resulting from political conflicts, famine, shortages of land, and natural hazards Engineers of the future must be trained to make intelligent decisions that protect and enhance the quality of life on Earth rather than endangering it. They must also make decisions in a professional environment in which they will have to interact with people from both technical and nontechnical disciplines. Preparing engineers to become facilitators of sustainable development, appropriate technology, and social and economic changes is one of the greatest challenges faced by the engineering profession today. Meeting that challenge may provide a unique opportunity for renewing leadership of the U.S. engineering profession as we enter the twenty-first century.

Earth Systems Engineering

In the past five years, a new, promising concept called earth systems engineering (ESE) has emerged as an alternative to the usual way engineering has looked at the world. ESE acknowledges the complexity of world problems and encourages the use of more holistic and systemic tools to address interactions between the anthrosphere (i.e., the part of the environment made and modified by humans and used for their activities) and natural and cultural systems.

ESE is a multidisciplinary (engineering, science, social science, and governance) process of solution development that takes a holistic view of natural and human system interactions. The goal of ESE is to better understand complex, nonlinear systems of global importance and to develop the tools necessary to implement that understanding. ESE acknowledges that, so far, humans have demonstrated a limited understanding of the dynamic interactions between natural and human (non-natural) systems. This is partly attributable to the complexity of the problems at stake. On one hand, natural systems are traditionally nonlinear, chaotic, and open dissipative systems characterized by interconnectedness and self-organization. Small changes in parts of natural systems can have a big impact on their response to disturbances. On the other hand, human (anthropogenic) systems are based on a more predictable Cartesian mindset.

The workshop brought together about 90 industry, government, and university participants from engineering, physical sciences, biological sciences, and social sciences. The overall goals of the workshop were:

(1) to provide an intellectual framework for interdisciplinary exchange; (2) to make recommendations for changes to engineering education, research, and practice that would further the understanding of the interactions between natural and non-natural systems at multiple scales, from local to regional and global; and (3) to create a plan of action to implement the recommendations. More specifically, the

workshop addressed the interactions of natural systems with the built environment. The workshop participants unanimously adopted the following definition of the "engineer of the future":

The engineer of the future applies scientific analysis and holistic synthesis to develop sustainable solutions that integrate social, environmental, cultural, and economic systems.

The workshop participants also recommended the adoption of a transformative model of engineering education and practice for the twenty-first century that (University of Colorado, 2001):

- unleashes the human mind and spirit for creativity and compassion
- expands engineers? professional and personal commitments to include both technical and nontechnical disciplines
- inspires engineers to embrace the principles of sustainable development, renewable resources management, appropriate technology, and systems thinking
- prepares engineers for social, economic, and environmental stewardships

III. Engineering Tomorrow: Needs, Objectives, and Vision

To capitalize on opportunities created by scientific discoveries, the nation must have engineers who can invent new products and services, create new industries and jobs, and generate new wealth. It must generate the new knowledge through engineering research so essential to leadership in technological innovation. And it must educate engineers capable of adapting to the imperatives of an intensely competitive global economy. The changing demands on engineering practice by the global, knowledge-driven economy are perhaps best illustrated by the example of global sourcing. Traditionally, engineering practice has added value through a vertical process, moving linearly through a sequence of activities such as R&D, product development, manufacturing, sales and marketing, and management to develop products, systems, and services.

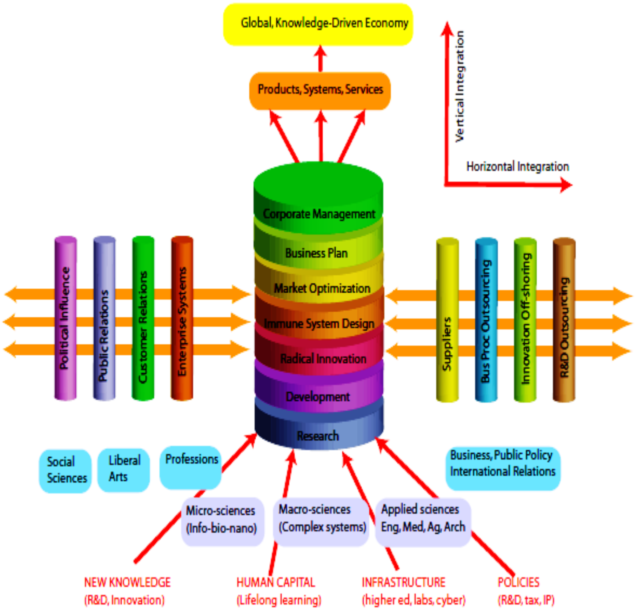

Figure 3 : The Role of 21st Century Engineering

This was built on a strong educational foundation of science, mathematics, and engineering sciences. To understand better the skills and competencies required for 21st-century engineers, consider the possible careers for engineers suggested by Bordogna:

* Sustainable development: avoiding environmental harm; energy / materials efficiency
* Life cycle / infrastructure creation and renewal
* Micro / nanotechnology / micro-electromechanical systems
* Mega systems
* Smart systems
* Multimedia and computer-communications
* Living systems engineering
* Management of technological innovation
* Enterprise transformation

The skill set required for contemporary engineering practice is changing rapidly and will continue to do so even more in the years ahead. Beyond a strong foundation in fundamentals such as science, mathematics, and engineering sciences, engineers require broader skills such as those suggested by Bordogna :

* Engineering science (analysis)
* Systems integration (synthesis)
* Problem formulation as well as problem solving
* Engineering design
* The ability to realize products
* Facility with intelligent technology to enhance creative opportunity
* Ability to manage complexity and uncertainty
* Teamwork (sensitivity in interpersonal relationships)
* Language and multicultural understanding
* Ability to advocate and influence
* Entrepreneurship and decision making
* Knowledge integration, education, and mentoring.

IV. Conclusion

It requires new paradigms for engineering practice, research, and education. The magnitude of the challenges and opportunities facing our nation, the changing demands of achieving prosperity and security in an ever more competitive, global, knowledge-driven world, and the consequences of failing to sustain our engineering leadership demand bold new initiatives. Leadership in engineering will require both commitment to change and investment of time, energy, and resources by the private sector, federal and state governments, and colleges and universities. Bold, transformative initiatives, similar in character and scope to initiatives undertaken in response to earlier times of change and challenge will be necessary for the nation to maintain its leadership in technological innovation. We can no longer afford simply chipping away at the edges of fundamental transformation of the engineering profession and its preparation.

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