Reforming civil engineering education given the challenges related to infrastructure engineering and management

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Abstract

In this paper, the authors review and evaluate some of the pressing specific problems that we face as a society and that have been traditionally entrusted to civil and environmental engineers. There is ample evidence that the state-of-the practice is not sufficiently qualified to address daunting problems related to the safe and efficient performance of infrastructures with the current approaches to feasibility analysis, financing, design, construction, operation, protection, inspection, maintenance and renewal. Especially, the concerns related to protecting infrastructures against hazards have been further emphasized in relation to homeland security. Properly educated and trained civil engineers are in fact essential as coordinators of multi-disciplinary teams responsible for addressing such large system of systems problems and integrators of related technology. The research and education strategy needs, and the need for new paradigms to help change the status quo of civil engineering education and research are discussed. A multi-disciplinary research and education initiative that will be "field-centered, i.e. grounded on the reality of actual operating infrastructures, is formulated. Such an approach to civil engineering education and research is defended as essential to assure the graduates will be qualified to address our current problems with the engineering and management of infrastructure systems.

INTRODUCTION: EDUCATION REFORM

Since the 1990's, a number of important summits, workshops, conferences and NSF initiatives focused on engineering education in general, civil and environmental engineering in particular (e.g. the 1985, 1990 and 1995 Civil Engineering Education Conferences organized by ASCE, the 1994 ASCE/NSF Workshop on Civil Engineering Education, the 1994 NSF Workshop on Restructuring Engineering Education, the 1995 NSF Workshop on Systemic Engineering Education Reform, the 1997 NSF Engineering Education Innovators' Conference, 1999 ASEE/IEEE Frontiers in Education Conference, 2000 MIT Colloquium on the Future of Civil and Environmental Engineering (http://web.mit.edu/civenv/www/colloquium.html), amongst many others). In a thought-provoking trilogy "Engineering Education Reform: A Trilogy," Splitt (2002) discusses "Environmentally Smart Engineering Education, The Challenge to Change, and, "Systemic Engineering Education Reform: A Grand Challenge." In a subsequent paper, Splitt (2003) offers an overview of the seminal events since the late 1980's that have resulted in the current consensus on the need for a new paradigm for engineering education.

In his seminal paper (http://www.nae.edu/nae/bridgecom.nsf/weblinks/NAEW-4NHMKV?OpenDocument) "The Urgency of Engineering Education Reform," Wulf (2001) describes the engineer: "*Science is analytic - it strives to understand nature, what is. Engineering is synthetic - it strives to create what can be. My favorite operational definition of engineering is "design under constraint." Engineering is creating, designing what can be, but it is constrained by nature, by cost, by concerns of safety, reliability, environmental impact, manufacturability, maintainability, and many other...*"

Wulf further indicates "*incorporating a set of new fundamentals into the engineering curriculum and encouraging faculty to practice their craft are among the steps needed to bring engineering education into the 21st century. Growing global competition and the subsequent restructuring of industry, the shift from defense to civilian work, the use of new materials and biological processes, and the explosion of information technology - both as part of the process of engineering and as part of its product - have dramatically and irreversibly changed how engineers work. If anything, the pace of this change is accelerating. Although there are exceptions, in general, engineering education has not kept up with this changing environment……Most obviously; we need to focus on curriculum, pedagogy, and diversity… We need to question whether the B.S. should be the first professional degree. We need to scrutinize the current system of faculty rewards. We need to seriously consider the need for formalized lifelong learning, the adequacy of student preparation in grades K-12, and the importance of technological literacy in the general population.*"

The Engineer of 2020 report from Phase I of a NAE initiative on engineering education (NAE, 2004) (http://www.nae.edu/nae/engeducom.nsf/weblinks/MCAA-5L3MNK?OpenDocument), *"centers on an effort to envision the future and to use that knowledge to attempt to predict the roles that engineers will play in the future. While of interest in itself, the exercise is also intended to provide a framework that will be used in subsequent work to position engineering education in the United States for what lies ahead, rather than waiting for time to pass and then trying to respond.*

In its conclusion, *"The engineer of 2020 will be faced with myriad challenges, creating offensive and defensive solutions at the macro- and micro-scales in preparation for possible dramatic changes in the world. Engineers will be expected to anticipate and prepare for potential catastrophes such as biological terrorism; water and food contamination; infrastructure damage to roads, bridges, buildings, and the electricity grid; and communications breakdown in the Internet, telephony, radio, and television. Engineers will be asked to create solutions that minimize the risk of complete failure and at the same time prepare backup solutions that enable rapid recovery, reconstruction, and deployment. In short, they will face problems qualitatively similar to those they already face today. To solve the new problems, however, they can be expected to create an array of new and possibly revolutionary tools and technologies. These will embody the core knowledge and skills that will support effective engineering education and a sense of engineering professionalism in the new century. The challenge for the profession and engineering education is to ensure that the core knowledge advances in information technology, nanoscience, biotechnology, materials science, photonics and other areas yet to be discovered are delivered to engineering students so they can leverage them to achieve inter-disciplinary solutions to engineering problems in their engineering practice. The rapidly changing nature of modern knowledge and technology will demand, even more so than today, that engineers so educated must embrace continuing education as a career development strategy with the same fervor that continuous improvement has been embraced by the manufacturing community."*

In their seminal paper on civil engineering education, (Sack, et al, 2000) indicate: *"Civil engineering, the oldest engineering discipline, is facing unprecedented challenges. The world we live in today is vastly different from that of fifty years ago. Information technology has become ubiquitous in our society; new technologies are emerging, and learning paradigms and cognitive psychology are pointing the way to more effective education. Students are searching for an educational experience that prepares them for a variety of jobs, yet the curriculum and educational paradigm for civil engineers remains virtually unchanged over the past half century. Civil engineering technicians are serving in positions that would have been filled by civil engineering graduates in the past, and other professionals are filling some executive positions that had been reserved for civil engineers. New civil engineering graduates have the lowest engineering starting salaries, and the civil engineer has the bottom median salary of all fields of engineering. There is a clarion call to recruit, retain and reward women, minorities and the physically challenged into the profession. It is time to reinvent the educational system so that we can begin to educate tomorrow's civil systems integrators."*

STATE OF ENGINEERING/CIVIL ENGINEERING EDUCATION

As a result of a decade of initiatives and activities focused on engineering education, we have a better appreciation of the drivers for reform in engineering education, as well as additional issues related specifically to civil engineering education, research, and practice. To gain a perspective of the direct stakeholders of engineering/civil engineering education that share data with ASEE and that are Abet-accredited, we refer to "The Year in Numbers (ASEE, 2004, http://asee.org/about/publications/profiles/upload/2004ProfileIntro2.pdf)." 2004 ASEE data indicates 24,000 FT engineering faculty in North America with 3,340 of them in civil engineering. The total number of undergraduate students that were enrolled in engineering/civil engineering programs in North America was (rounded) 400,000/47,000. The engineering/civil engineering bachelors degrees awarded in 2004 were 73,000/8,000. Around 40,000/3,750 and 6,600/650 MS and PhD degrees were awarded in engineering and civil engineering, respectively in 2004. More than 240 academic programs offered a Bachelors or Masters in civil and/or environmental engineering, and more than 125 also offered a PhD degree in civil engineering. We note the existence of over 40 construction technology programs. According to the Carnegie Foundation for the Advancement of Teaching, there were 111 Doctoral Universities, 88 Research I

universities and 37 Research II universities in 1994, for a total of 236, but we note that a number of these did not offer a civil engineering degree, and there were others that did not offer an Abet-accredited civil engineering degree.

Given the above numbers, we expect considerable variation in the breadth, depth and quality (to be defined) in the knowledge and skills offered to future engineers, the quality in the delivery, and the validation of the outcomes, between various programs depending on many organizational, geographical, social and economical parameters. The landmark Boyer Commission Report (1998) evaluated the state of the broader undergraduate education, and articulated the distinctions of research universities. They formulated criteria for undergraduate education that, while providing the essential features of general education, introduces students to inquiry-based learning. The ASCE's Body of Knowledge (1994) and the ABET Criteria (1994) for Accrediting Engineering Programs provide the guidelines shaping the state of civil engineering education offered by the programs interested in accreditation. In their paper discussing "ASCE's Raise the Bar Initiative: Accreditation-Related Barriers and Critical Issues," Smerdon et al (2003) indicate that *"The conditions and broad requirements of engineering practice are rapidly changing – and they will change even more in the future. Moreover, engineering education is also changing, perhaps more rapidly than ever before. To its credit, ABET in the last decade has made substantive changes in accreditation procedures for engineering programs. The change from focusing evaluations on input measures to an outcomes based approach with much more flexibility is in line with total quality improvement concepts. The fact that each program to be accredited must have detailed published educational objectives that are consistent with the mission of the institution provides potential for variations in the programs and no longer are engineering education programs necessarily in lock step. Differences and uniqueness in individual programs are valued."*

A review of the ABET criteria reveals that these are indeed highly broad and flexible guidelines as opposed to minimum standards or specifications. These guidelines permit extensive flexibility related to curriculum and the implementation of a curriculum. The Abet Accreditation Policy and Procedure Manual (2004) outlines the self-study report and the on-site visit that will help Abet reach its evaluation. The Manual indicates a need for *"Clearly stated expectations for learning and student achievement appropriate to the mission and educational objectives of the institution and program. Academic policies relating to student, such as admissions, probation, dismissal, grievances, and graduation requirements must be fair, equitable, and published"*. It follows that Abet's procedures, similar to its criteria, are directed towards ensuring some minimum standards for education and aim at meeting the perceived needs of the current state-of-the-practice as opposed to societal needs of the future. Finally, we note that in the ASCE's Body of Knowledge (2004), in addition to the Abet criteria (a)-(k), additional educational outcomes have been proposed.

The ASCE's Body of Knowledge indicates*: "Relative to today's basic programs, the outcomes collectively prescribe a substantially greater depth and breadth of knowledge, skills, and attitudes required of an individual aspiring to the practice of civil engineering at the professional level (licensure) in the 21st century. The 15 outcomes include and begin with the 11outcomes of the Accreditation Board for Engineering and Technology (ABET) and prescribe more technical depth and additional breadth. The 21st century civil engineer must demonstrate:*

1. an ability to apply knowledge of mathematics, science and engineering.
2. an ability to design and conduct experiments, as well as analyze and interpret data.
3. an ability to design a system, component or process to meet desired needs.
4. an ability to function on multi-disciplinary teams.
5. an ability to identify, formulate and solve engineering problems.
6. an understanding of professional and ethical responsibility.
7. an ability to communicate effectively.
8. the broad education necessary to understand the impact of engineering solutions in a global and societal context.
9. a recognition of the need for, and an ability to engage in, life-long learning.
10. a knowledge of contemporary issues.
11. an ability to understand the techniques, skills, and modern engineering tools necessary for engineering practice.
12. an ability to apply knowledge in a specialized area related to civil engineering.
13. an understanding of the elements of project management, construction, and asset management.

14. an understanding of business and public policy and administration fundamentals.
15. an understanding of the role of the leader and leadership principles and attitudes.

We note the ranking instruments such as the well-known US News and World Report (www.usnews.com) as well as the 1995 ranking of the PhD programs by NAS, with a recent follow-up study of program ranking criteria (Assessing Research-Doctorate Programs: A Methodology Study, NAE Press, 2004). These ranking instruments indicate significant differences in both objective and subjective quality ranking indices of the first, second and third tier programs, even when we consider only the Abet certified programs. Further, considerable differences exist between even the relative ranking of Research I universities. Clearly, neither the criteria for being designated as a "Research University", nor Abet criteria, and not even the additional ASCE outcomes are sufficient for assuring the quality of the graduates from a program. While all these referenced criteria serve as valuable guidelines, it is up to the programs to leverage these guidelines to ascertain the quality of their product. In fact, there are a number of very highly rated programs graduating very successful civil engineers that do not desire to be Abet accredited.

The 2004 NAS follow-up study (Assessing, 2004) pointed to the advantages and disadvantages of various ranking approaches, identified some limitations of the US News and World Report rankings, and, recommended that NAS itself should continue ranking doctorate programs. It is interesting that although NAS and US News and World Report are explicit about their ranking criteria, just the criteria do not reveal the complexity of cause-and-effect relationships within a university system of systems that impact ranking. For example, some academic administrators may not recognize the need for consistently emphasizing the important values, choosing the right policies and adopting appropriate strategies before any tactics may succeed in advancing the quality of a program and eventually its ranking. It is the writer's experience that academic quality is as complex a concept as Zen. It is very difficult to fully understand and accomplish this concept especially if the value system within a university does not explicitly encourage its pursuit as the primary goal of any academic career. The landmark Boyer Commission Report (1998) articulated this quite well.

MOTIVATION

In system-of-systems problems we expect many possible ranges-of-outcomes when we consider the combinations of large numbers of critical parameters that govern a process ***(civil engineering education)*** and the product coming out of that process (***graduating civil engineer).*** It is therefore quite critical for educational institutions and programs to approach their student selection, the design of their curricula and the delivery of their curricula as a multi-objective optimization problem, clearly formulating all the hard and soft constraints and the goals of education as an optimization problem. Although there can never be a single "most" optimal solution for complex system-of-systems problems, a program can at least rationally identify alternatives, and select and implement a particular solution.

Functioning with a performance-based and not a process-based approach, a program would monitor the outcome over time to make adjustments to its curriculum, syllabi and delivery process. Furthermore, a program may implement its curriculum in a number of ways. Unfortunately, even the best-designed and progressive curriculum can be delivered in an ad hoc manner, analogous to a collection of unrelated short stories, or can be delivered in a manner such as a masterfully integrated epic. It is up to the faculty and administration of a program to work as a close-knit team to design, construct and deliver a curriculum as opposed to just exposing the students to a number of pigeonholed subjects, often forgotten as soon as a Semester or Quarter is over.

In this paper, the authors are motivated to frame the problem of civil engineering education. Most of the issues that govern civil engineering education are common to those governing the broader engineering education; however, we should also recognize that there are clear distinctions between civil and the remaining engineering disciplines that pose additional critical challenges to civil engineering educators. The authors represent private and state-sponsored universities in North America as well as US government agencies. They have been engaged in education, research and professional training of civil engineers at various levels of responsibility for decades.

In addition to being active in the US and Canadian professional societies, during the last several years the authors have focused their collective effort into forming a new international

organization, the International Society for Health Monitoring of Intelligent Infrastructures (ISHMII, 2004). This multidisciplinary, multinational, government-academe-industry partnership has been formed following the recognition that infrastructure systems problems, especially in relation to the operational and structural performance reliability of constructed systems, cannot be fully understood and effectively addressed unless renaissance civil engineers assume the role of "primary care physicians" specialized in the health of "patient" constructed systems, and, ***coordinate, lead and integrate*** multi-disciplinary efforts addressing these infrastructure problems.

While the participation of all engineering, science and art disciplines is essential for effectively addressing problems related to the performance of constructed infrastructures, civil engineers who can integrate the centuries of accumulation of heuristic knowledge on constructed systems together with the emerging technologies and knowledge related to IT, natural systems (water, soil, weather, climate, the environment), biological and micro-scale systems, social and organizational systems and others have to serve as the framers of the problems, and coordinators and integrators of data, information and knowledge. Paradigms and concepts such as systems engineering, risk, reliability and uncertainty, health monitoring, performance based engineering, sustainable engineering, asset management, intelligent systems and others have to be adapted through the leadership of civil engineers to large constructed systems and infrastructures and serve for framing technology development, customizing and integration by multidisciplinary teams. This cannot happen numerically or even by laboratory simulations, but only by properly designed field research on actual operating infrastructures.

A well-designed and properly delivered civil engineering education provides the minimum essential knowledge and skills necessary to ***identify*** (observe, model, simulate, measure, calibrate model), ***understand*** and ***control*** the behaviors of "***large-scale infrastructure systems of systems,***" with interacting human, natural and very large-scale engineered components and sub-systems. The most critical distinction between the systems engineered and managed by civil engineers and many other engineers is the significance of prevailing epistemic uncertainty, and the risks to society that arise due to this uncertainty. Experienced civil engineers have learned to balance epistemic uncertainty and risk levels acceptable to society by leveraging heuristics and by being able to take maximum advantage of sparse data related to very rare events. However, such master engineers are quite rare, and it is a great challenge to help engineers develop such skills by a combination of science and shop-based education and training. A further fundamental issue is that the shop has to be real operating infrastructures and not just a design office or even a construction site.

Given such an essential role critical for the well being of society, and one which cannot be easily delegated to other engineering disciplines, civil engineers are obligated to reform their practice and education. Great divides and disconnects that currently exist between design, construction, operation, maintenance and management, ownership and stewardship of constructed systems, as they serve within critical infrastructures and their intersections, have to be identified and bridged. The current process-based design and construction practice should be transformed to a performance-based one where successful lifecycle operation, feasible preservation and protection of an entire infrastructure system, with clearly defined, objective and measurable criteria, should be the warranted outcome. This necessitates field research on constructed systems for understanding: (a) how they are actually constructed as opposed to how they are designed, (b) how they are actually loaded by their construction, operation and the environment, (c) how they actually interact with and effect the human and environmental systems during every one of their critical operational and structural limit-states, and, (d) the associated blind-spots in their feasibility analyses, financing, design, construction, maintenance and operation through their lifecycles.

Such knowledge is essential in order to bound the uncertainty and establishing the risks that are faced by the society associated with a lack of desirable infrastructure performance. Without such research and the corresponding changes in education that can only be led and coordinated by renaissance civil engineers, we cannot identify and bridge the disconnections along the lifecycles of constructed systems, and therefore, we cannot improve the performance and fragility of the broader infrastructure systems that depend on constructed systems. This is why the writer's are motivated to frame the problem of civil engineering education from the context of the reality of infrastructures – and their impacts on society.

It is important to note that the writers cannot claim they are close to having clear answers to how civil engineering education should be reformed. However, they are fully convinced that the state of

civil engineering education is indeed in need of revolutionary and not just evolutionary reform, and that this requires an international and systemic effort, to be grounded in the reality of operating infrastructures and constructed systems. While undeniable and considerable progress has been made in rethinking engineering and civil engineering education by NAE and NSF, as well as professional organizations such as ASCE, ASEE and ABET, we question whether these are sufficient to lead to an optimum product (civil engineers) who can properly respond to the challenges and societal expectations formulated in the Engineer 2020 and as articulated by many visionaries.

OBJECTIVES AND SCOPE

The objectives of this paper follow from the writer's motivations presented above: (a) to provide an overview of the ***system of systems issues that impact the broader engineering education today.*** The paper will discuss the most critical global drivers for change, with the corresponding and/or related recommendations made by the leaders of engineering education as well as the recent recommendations by professional organizations such as ASCE and ABET; (b) to review and ***frame the challenge of reforming the civil engineering education*** both in the context of the broader engineering education as well as by recognizing the distinctions between civil engineering and other engineering disciplines; (c) to offer their views and recommendations ***for additional efforts related to civil engineering education, so that we may better address the societal concerns discussed in (a).*** The author's are highly motivated to strive for a meaningful process for reform that will indeed lead to a renaissance in civil engineering education and practice.

A brief history of civil engineering education, with the major changes that occurred since the 1950's, will be presented. How the innovations in the broader engineering education, such as the tDEC initiative that was pioneered by Drexel's College of Engineering in the 1980's and similar efforts by several education coalitions may have impacted the civil engineering education, will be discussed. The special concerns with the status of civil engineering graduates relative to the others, as articulated by Sack et al (2000) are related to a widening gulf between engineering disciplines that cater to industry and to research agencies supporting research on defense, medicine and health, and those agencies supporting research on public infrastructure systems and whose budgets have been shrinking especially in the last five years. There are additional issues relating to a balance between an apprentice-ship based as opposed to a science-and-systems based approach to engineering education. Whether most civil engineering programs can afford to become entirely science oriented, and whether a science-based education based on the current systems engineering methods and tools can effectively address the engineering and management of human, natural and engineered systems that make up our infrastructures are valid questions that deserve discussion.

This paper is therefore intended to serve as a draft position paper for posing a number of questions and issues that should justify future international workshops and summits. These events should bring together all of the critical stakeholders of civil engineering education and practice to seek the resolution of the critical issues. The writer's expect to continue their efforts for formulating effective multi-disciplinary research and field-centered implementations for reforming civil engineering education following ISHMII's 2005 workshop.

EVOLUTION OF CIVIL ENGINEERING EDUCATION

According to Grayson (1993), by the mid-1600s artillery and fortifications had grown so complex that armies began training officers in math and mechanics. What started as military engineering gradually turned into civil engineering. In 1775, King Louis XV of France authorized Jean Perronet to set up a School of Bridges and Highways with a three-year program. After the French Revolution, in 1794 Napoleon replaced Perronet's school with the Ecole Polytechnique. Ecole Polytechnique is considered as the first university program offering the civil engineering education and degree. Originally under the direction of the Ministry of the Interior, Ecole Polytechnique was later transformed into a military school by Napoleon in 1804.

In 1819 West Point began modeling itself on the Ecole Polytechnique. Rensselaer Polytechnic Institute first offered a civil engineering education in 1828 followed by the University of Virginia in 1833. Rensselaer issued the first civil engineering degree in the US in 1835. In England, the founders of University College London appointed a professor of engineering, John Millington, to teach civil engineering in 1827, the first such appointment in

England. The engineering disciplines soon became more distinct, and the first professor of civil engineering was appointed at University College, London, in England in 1841.

In 1850 the US census included engineer as a profession for the first time, 2000 engineers were recorded as civil engineers. Until the late 1800s, engineering training emphasized craft skills more than scientific background. In 1862 the Morrill Act established land-grant institutions to teach agriculture & mechanics to the children of "farmers & mechanics." In 1870 just 5% of US engineers had a college degree since the vast majority of civil engineers still trained through practice as an apprentice. The conflict between "shop culture" and the new "school culture" continued until early 1900's. Following the establishment of American Society of Civil Engineers in 1852, the concept of learning engineering at school as opposed to just by apprenticeship at a shop prevailed, and eventually a formal college degree became the norm for practicing as a professional engineer.

World War II changed the perception of engineering since it was widely recognized as a technological battle that was won by engineers and scientists working on mega-projects such as radar and the atomic bomb. In 1950, the National Science Foundation was created, and together with other Federal agencies, provided a continuing stream of funds for advancing technology. Around 1950, Karl Compton became the president of the Massachusetts Institute of Technology (MIT). He observed that technology had begun to advance too fast to pass down from generation to generation by a process that still had a substantial element of apprenticeship (Hazelrigg, 1996). MIT started to offer a science-based civil engineering education with a systems-orientation and various other institutions (CALTECH, COLUMBIA, several campuses of the University of California system, Carnegie Mellon University, University of Pennsylvania and others) followed suit, becoming schools of "Applied Science," some even dropping "Engineering" from the name of their programs. These universities teach "applied science" as their engineering curriculum, hence the term "science-based engineering education." The understanding implicit in such an education is that upon graduation, an engineer must obtain experience (that is, become an apprentice) to round out ones' education.

Civil engineering programs currently accredited by Abet (2004) are expected to adopt curricula offering (We note the existence of many excellent programs that choose not to be accredited):

a) "one year of a combination of college level mathematics and basic sciences (some with experimental experience) appropriate to the discipline,
b) one and one-half years of engineering topics, consisting of engineering sciences and engineering design appropriate to the student's field of study. The engineering sciences have their roots in mathematics and basic sciences but carry knowledge further toward creative application. These studies provide a bridge between mathematics and basic sciences on the one hand and engineering practice on the other. Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.
c) a general education component that complements the technical content of the curriculum and is consistent with the program and institution objectives."

Given that proficiency in at least four major sub-disciplines of civil engineering (e.g. architectural engineering; coastal, ports, rivers and waterways engineering; geotechnical and geo-environmental engineering; construction engineering; environmental engineering; structural engineering; systems, informatics and logistics engineering; transportation engineering; water resources engineering; etc) is required for Abet accreditation, the one and one-half years of engineering science and design topics offer both the greatest challenges and the opportunities to any program. These courses are expected to "*provide a bridge between mathematics and basic sciences on the one hand and engineering practice on the other. Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs."*

Some of the important issues in the implementation of Abet criteria are ensuring that the engineering science and design courses can take full advantage of the basic science courses as a foundation, and, how the design courses can fully

capitalize on the applied science content. For example, design course syllabi and delivery may take advantage of laboratory experiments and field observations to deliver a conceptual understanding of materials, components, sub-systems and system of systems behaviors, and recommend best practices in design, construction, operation and management. At the other end of the spectrum we see a delivery of code specifications and/or how to use computer programs (often in the context of an advanced calculator) to facilitate design computations.

Another issue relates to category ©, i.e. the general education component of Abet requirements. This category is expected to help deliver many of the 11 Abet and 15 ASCE BOK Criteria. For example, many engineering schools offer voluntary co-operative education programs and a few have mandatory co-op programs (e.g. University of Cincinnati, Drexel University, Northeastern University, etc). In schools without co-op, students seek summer or term break employment with engineering firms. Para-professional engineering employment for undergraduates may greatly contribute to their education and professional development, and serve to ensure many of the Abet and ASCE outcomes that are mainly related to category ©. However, how to structure and design the details of para-professional engineering employment such that its outcomes may be tested and taken advantage as a component of Abet's general education requirement needs to be resolved.

While many institutions and programs may consider Abet accreditation a most important test of the adequacy of the education they are providing, we note the distinction between ASTM specifications for testing concrete cylinders, or the ACI Code for design of reinforced concrete buildings as opposed to actually creating a landmark building. Abet accreditation may correspond to ASTM specifications for concrete testing, the curriculum designed by a program may correspond to the ACI code, but the quality and success of the graduating students will depend on how the test specifications and code requirements are really implemented in conjunction with a grand vision of the institution, the experience, skills, dedication and competence of the program faculty, in conjunction with many additional parameters as discussed by the Boyer Commission. To identify, structure and discuss the critical and unresolved issues that should govern education reform, first an overview of the critical issues in the broader engineering education, followed by additional critical issues specific to civil engineering education are presented in the following.

OVERVIEW OF CRITICAL ISSUES IN ENGINEERING EDUCATION

The critical drivers changing the world and therefore compelling education reform have been articulated by some of the leading engineering educators (NAE 2004, Akay, 2003, Splitt (2003), Clough (2000), Wulf (2000), Sack et al (2000) and are summarized in the following, the inserts in italics are adopted from a review of the Engineer of 2020 Report at a Workshop at Berkeley (http://best.me.berkeley.edu/~aagogino/papers/NAE_Engineer2020.ppt):

Technology: The growing complexity, scale, uncertainty, and interdisciplinary characteristics of engineered systems, and the accelerating pace of technological advances are major drivers for reforming engineering education. The leaps in bioengineering, biotechnology and biomedical technology, information and communication technology, miniaturization (MEMS, nanotechnology, advanced materials), and, smart materials and structures are additional opportunities and challenges that impact education.

Societal Needs: Technology challenges for engineers should address the concerns related to physical infrastructures in urban settings, including information and communications Infrastructures. Societal expectations that are shaped by the rapid improvements in information and communication technology and manufacturing are becoming impossible to satisfy with the current level of performance of many critical infrastructures such as transportation, water, fuel, etc. Societies will need to leverage technology for addressing the needs associated with dramatically changing demographics, especially related to the health care needs of an aging population.

For example, in contrast to the aging of the US, Europe and Japan, the most politically unstable parts of the world will experience a "youth bulge". A mix of 100 people in 2020 would look like the following:

- *56 would be from Asia, including 19 Chinese and 17 Indians*
- *13 would be from the western hemisphere, including 4 from the United States*
- *16 would be from Africa, including 13 from Sub-Saharan Africa*

- *3 would be from the Middle East*
- *7 would be from Eastern Europe and the former Soviet Union*
- *5 would be from Western Europe*

Concerns related to the environment and the drive for sustainability will require:

- *Engineering processes and products in a holistic manner, using systems analysis, and integrating environmental impact assessment tools.*
- *Conserving and improving natural ecosystems while protecting human health and well-being.*
- *Adopting life cycle thinking in all engineering activities.*
- *Ensuring that all material and energy inputs and outputs are as inherently safe and benign as possible.*
- *Minimizing the depletion of natural resources; striving to prevent waste.*
- *Developing and applying engineering solutions, while being cognizant of local geography, aspirations and cultures.*
- *Creating engineering solutions beyond current or dominant technologies; improving, innovating and inventing technologies to achieve sustainability.*

The "sustainability" imperative in the face of global population growth, industrialization, urbanization, and environment degradation will shape the aspiration and attributes of future engineers:

- *Rising concerns regarding the social implications of rapid technological advance.*
- *Socio-political tensions around the world, especially concerns related to homeland security.*
- *Increased focus on managed risk and assessment with a view to public security, privacy, and safety.*
- *Growing diversity of the workforce.*
- *Globalization of industry and engineering practice.*
- *The shift of engineering employment from large companies to small and medium-sized companies, and the growing emphasis on entrepreneurialism.*
- *The growing share of engineering employment in non-traditional, less-technical engineering work (e.g., management, finance, marketing, policy).*
- *The shift to a knowledge-based "services" economy.*
- *Increasing opportunity for using technology in the education and work of the engineer.*

Aspirations of Engineers for 2020 are summarized in the following list. An education founded on these aspirations will lead to engineers' commanding respect of their profession in their service to the society in a fast changing world:

- *Public will understand and appreciate the profound impact of the engineering profession on social-cultural systems, the full spectrum of career opportunities accessible through an engineering education, and the value of an engineering education to engineers working successfully in non-engineering jobs."*
- *Public will recognize the union of professionalism, technical knowledge, social and historical awareness, and traditions that serve to make engineers competent to address the world's complex and changing challenges."*
- *Engineers will remain well grounded in the basics of math and science, and in the humanities, social sciences, and economics.*
- *The engineering profession will rapidly embrace cross-disciplinary fertilization to create and accommodate new fields of endeavor, including those that require openness to interdisciplinary efforts with non-engineering disciplines such as science, social science and business.*
- *Engineers will assume leadership positions from which they can serve as positive influences in making of public policy and in the administration of government and industry.*
- *Engineering profession will effectively recruit, nurture and welcome underrepresented groups to its ranks.*
- *Engineering educators and practicing engineers will together undertake a proactive effort to prepare engineering education to address the technology and societal challenges and opportunities of the future. We will reconstitute engineering curricula and related educational programs to prepare today's engineers for the careers of the future, with due recognition of the rapid pace of change in the world, and its intrinsic lack of predictability.*
- *The engineering curriculum for 2020 will be responsive to the disparate leaning styles of different student populations and attractive for all of those seeking a full and well-rounded education that prepares for a creative and productive life and positions of leadership.*

Finally, the successful attributes for the Engineer of 2020 are identified as:

- *Possessing strong analytical skills.*
- *Exhibiting practical ingenuity; possessing creativity.*

- *Good communication skills with multiple stakeholders.*
- *Business and management skills; Leadership abilities.*
- *High ethical standards and a strong sense of professionalism.*
- *Dynamic/agile/resilient/flexible.*
- *Lifelong learners.*
- *Ability to frame problems, putting them in a socio-technical and operational context.* ***An ability to plan, create and analyze scenarios.***

Given the above view of the technology, society and the expected aspirations of engineers in 2020, some specific elements of engineering education reform are:

Limits to Formal Education for a Professional Degree and the Importance of Learning to Learn: From "Educating the Engineer of 2020: Adapting Engineering Education to the New Century (2005) http://www.nap.edu/books/0309096499/html/4.html *"Scientific and engineering knowledge doubles every 10 years (Wright, 1999). This geometric growth rate has been reflected in an accelerating rate of technology introduction and adoption. Product cycles continue to decrease, and each cycle delivers more functional and often less expensive versions of existing products, occasionally introduces entirely new "disruptive" technologies, and makes older technologies obsolete at an increasing rate. The comfortable notion that a person learns all that he or she needs to know in a four-year engineering program just is not true and never was. Not even the "fundamentals" are fixed, as new technologies enter the engineer's toolkit. Engineers are going to have to accept responsibility for their own continual re- education, and engineering schools are going to have to prepare engineers to do so by teaching them how to learn. Engineering schools should also consider organizational structures that will allow continuous programmatic adaptation to satisfy the professional needs of the engineering workforce that are changing at an increasing rate. Meeting the demands of the rapidly changing workforce calls for reconsideration of standards for faculty qualifications, appointments, and expectations."* Many other leaders of education reform have presented this view. The half-life of technology skills that are acquired by currently graduating engineers in emerging areas may be around 5 years.

Practice-What-You-Teach: Wulf (2001) articulated the need for engineering faculty to practice what they teach: **"***But in engineering education I think we have an additional problem, and it's one I want to emphasize. Recall that my definition of engineering is design under constraint. I believe the process of design is a synthetic, highly creative activity. Can you think of any other creative field on campus where the faculty are not expected to practice or perform? Art, music, drama? Even if you don't buy that engineering is creative in the same way as art or music, performance-oriented professions such as medicine and law expect their faculty to practice that profession. Can you imagine a medical school where the faculty was prohibited from practicing medicine? Yet, this is just the situation we have in engineering."*

It is not possible to disagree with the above viewpoint, indicated by Wulf and many others. There has been an emphasis by Abet on professional registration of faculty. Registration, however, does not assure faculty engagement in creatively performing what they teach. Consulting for the industry, provided that an academic does not compete for jobs with practicing and consulting engineers, may be a better outlet for faculty to remain engaged in the practice of their art. It is important, however, for faculty to select the consulting engagements that indeed offer challenge and an opportunity for enriching their courses.

Pedagogy: There has been considerable attention to pedagogy in relation to engineering education. The seminal work on "experiential learning" by Kolb (1984) is especially relevant to the learning of complex concepts that require a creative integration of theory, experiment and field applications. Given the opportunities of integrating and leveraging IT with pedagogy, and the fact that most of the students entering college were born and raised with access to a PC and the Internet, and many come with an intuitive ability to interface with complex software, we cannot justify not to completely question what we have considered as the fundamentals and how we teach these fundamentals. The advances in IT also advanced and in fact compounded our capabilities to demonstrate and experience complex phenomena in the physical laboratory and in the field. The fact remains that the educators have to become more creative and open-minded than ever to fully leverage these opportunities than just focusing on Abet criteria.

In describing an initiative entitled "Department-Level Reform of Undergraduate Engineering Education' (NSF 05-531) *"encouraged proposals that build on the pioneering efforts of the NSF Engineering Education Coalitions, supports the goals of the Accreditation Board for Engineering and Technology (ABET) Criteria for Accrediting Engineering Programs, (http://www.abet.org) and reflects advances in the science of learning. Departments or multiple departments may update and reconstitute elements of the curricula in existing engineering disciplines or invent elements of completely new curricula for emerging engineering disciplines or cross-disciplines. The proposed efforts should define the interfaces between the new elements and existing programs, and streamline and update course offerings to make the curriculum both more attractive and effective by: Introducing emerging knowledge related to information technology, bioengineering, microelectronics, micro-electro-mechanical systems (MEMS), nanotechnology, product design and realization, advanced materials, manufacturing, etc; Using cognitive theory and latest pedagogical concepts to improve learning outcomes; Replacing legacy materials with improved content emphasizing the fundamental, underlying behavior of physical and biological systems and the social systems in which they are employed; Exposing students to the computational methods and design practices employed by practicing engineers to solve engineering problems, preferably in collaboration with industry leaders in developing tools implementing such methods; Emphasizing critical thinking skills as well as communication and interpersonal skills; Ensuring that the course content as well as pedagogy are sensitive to the needs of a diverse student body; Making full use of modern teaching methods, including mentoring, team-based and experience-based learning, computer simulation, and distance learning; Incorporating service learning as a means to broaden students' professional skills and enhance their learning outcomes and academic performance, while providing sustained support for community service organizations."*

Another NSF initiative PD 05-1340 (NSF, 2005) articulates: *"The quality of our engineering education is a national resource that drives economic growth, improvements in health and safety, and provides for our security. The quality of engineering education has a direct impact on our ability as a nation to compete in the increasingly global competitive environment of the 21st Century. However, it is clear increasing globalization of the engineering workforce is placing new pressures on engineering education in this country. With the emergence of engineering talent in developing countries, we must be able to provide an engineer that justifies wage differentials that can be as high as three-fold. In addition, the engineer of the future must be able to deal with a rapid pace of technological change, a highly interconnected world, and complex problems that require multidisciplinary solutions."*

The broader picture related to the environment of education: The Boyer Commission on Educating Undergraduates in the Research University was created in 1995 under the auspices of the Carnegie Foundation for the Advancement of Teaching. The principal concern of the Commission was "Educating Undergraduates in the Research University" indicating that *"research universities share a special set of characteristics and experience a range of common challenges in relation to their undergraduate students. If those challenges are not met, undergraduates can be denied the kind of education they have a right to expect at a research university, an education that, while providing the essential features of general education, also introduces them to inquiry-based learning."* Since many universities that are not included in the 1994 list of Research Universities by the Carnegie Foundation for the Advancement of Teaching, aspire to be a research university, the Boyer Commission Report should be applicable to any PhD offering program. The Boyer Commission articulated two principal tenets of a research university:

The University as Ecosystem: *The interaction of many kinds of stimuli creates at a university a special kind of intellectual environment, with the health of the whole a manifestation of the health of each part. That environment should become an intellectual ecosystem. Universities are communities of learners, whether those learners are astrophysicists examining matter in the far reaches of space or freshmen new to an expanded universe of learning. The shared goals of investigation and discovery should bind together the disparate elements to create a sense of wholeness.*

An Academic Bill of Rights: *By admitting a student, any college or university commits itself to provide maximal opportunities for intellectual and creative development. These should include:*
1. Opportunities to learn through inquiry rather than simple transmission of knowledge.

2. Training in the skills necessary for oral and written communication at a level that will serve the student both within the university and in postgraduate professional and personal life.
3. Appreciation of arts, humanities, sciences, and social sciences, and the opportunity to experience them at any intensity and depth the student can accommodate.
4. Careful and comprehensive preparation for whatever may lie beyond graduation, whether it be graduate school, professional school, or first professional position.

The student in a research university, however, has these additional rights:
1. Expectation of and opportunity for work with talented senior researchers to help and guide the student's efforts.
2. Access to first-class facilities in which to pursue research—laboratories, libraries, studios, computer systems, and concert halls.
3. Many options among fields of study and directions to move within those fields, including areas and choices not found in other kinds of institutions.
4. Opportunities to interact with people of backgrounds, cultures, and experiences different from the student's own and with pursuers of knowledge at every level of accomplishment, from freshmen students to senior research faculty.

The Boyer Commission report identified the following issues summarized in ***"Ten Ways to Change Undergraduate Education:***
(1) Make Research-Based Learning the Standard: "*learning is based on discovery guided by mentoring rather than on the transmission of information. Inherent in inquiry-based learning is an element of reciprocity: faculty can learn from students as students are learning from faculty".*
(2) Construct an Inquiry-based Freshman Year
(3) Build on the Freshman Foundation
(4) Remove Barriers to Interdisciplinary Education
(5) Link Communication Skills and Course Work
(6) Use Information Technology Creatively
(7) Culminate with a Capstone Experience
(8) Educate Graduate Students as Apprentice Teachers
(9) Change Faculty Reward Systems
(10) Cultivate a Sense of Community

It is important to recognize that the recommendations by the Boyer commission are based on the understanding that undergraduate education should be approached as a "system-of-systems". All of the recommendations should be applied holistically, with an institution-wide dedication starting from the President all the way to the students. Some institutions, colleges and programs find it convenient to pick some of the criteria and not the others. For example, if an institution is not taking special measures to promote, encourage and reward multi-disciplinary interactions and cultivate a sense of community between faculty, groups, programs and colleges, it is unlikely that the adoption of the remaining recommendations may have as important an impact. For example, the Drexel tDEC curriculum, when launched, greatly innovated the first two years of the engineering curriculum by adopting the recommendations (2), (5), (6) and (7). However, due to a lack of adopting the entirety of the Boyer Commission recommendations holistically throughout the university, many of the opportunities intrinsic in tDEC are not being leveraged. tDEC has become a virtually separate program with its own administration, completely isolated from the engineering science and design curriculum offered by the traditional engineering programs.

Recommendations of the NAE Report: Educating the Engineer of 2020: Adapting Engineering Education to the New Century (http://books.nap.edu/catalog/11338.html):

We conclude this section by listing the final recommendations of the Phase II of the NAE Engineer of 2020 program (2005):

- *The BS degree should be considered as a pre-engineering or "engineer-in-training" degree.*
- *Engineering programs should be accredited at both the BS and MS levels, so the MS degree can be recognized as the engineering "professional" degree.*
- *Institutions should take advantage of the flexibility inherent in the ABET EC2000 accreditation criteria in developing curricula, and students should be introduced to the "essence" of engineering early in their undergraduate careers.*
- *Colleges and universities should endorse research in engineering education as a valued and rewarded activity for engineering faculty and should develop new standards for faculty qualifications.*
- *That, in addition to producing engineers who have been taught the advances in core knowledge and are capable of defining and*

solving problems in the short term, institutions must teach students how to be lifelong learners.

- *Engineering education should introduce interdisciplinary learning in the undergraduate curriculum and explore the use of case studies of engineering failures successes and failures as a learning tool.*
- *Four year schools should accept the responsibility of working with local community colleges to achieve workable articulation with their 2-year engineering programs.*
- *Institutions should encourage domestic students to obtain the MS and/or PhD degrees.*
- *The engineering education establishment should participate in efforts to improve public understanding of engineering and the technology literacy of the public and efforts to improve math, science and engineering education at the K-12 level.*
- *NSF should collect and assist collection of data on program approach and student outcomes for engineering departments/schools so prospective freshmen can better understand the "marketplace" of available engineering baccalaureate programs.*

ADDITIONAL CHALLENGES AND OPPORTUNITIES FOR CIVIL ENGINEERING EDUCATION

G. Wayne Clough, President of Georgia Institute of Technology indicated (2000): *"Today, most of the buzz is about biotechnology and information technology, but the future of our society also rests on technologies that are more basic to its functioning. The combination of a growing world population with the human tendency to delay dealing with infrastructure and environmental needs until they have reached crisis proportions, means that our profession will become more essential than ever before."*
"…there are some matters related to the future to which we can speak with clarity. First, the basic challenges to our society that require civil engineering talent are increasing in number and importance. They include housing an expanding population, addressing decaying urban infrastructure, maintaining our environment, dealing with the effects of natural disasters and climate change, and transporting ever more people and goods in a safe and efficient manner. ***Addressing these challenges successfully will take a new kind of technology and a new kind of civil engineer."***
"…the emerging hot fields of biotechnology, materials and nanotechnology, electronic commerce, advanced communications and information technology will have a major impact on civil engineering. …The driving forces behind developments like these come from outside civil engineering. ***We need to actively seek to understand and use technology developments from other fields to our advantage, and that will call for a new curriculum for our students and a more entrepreneurial mindset for our engineers and businesses.***
*"…****for civil engineering to be a vital profession in the next century, it must attract its share of the best and the brightest.*** *All else falls below this in priority, since talent and the ideas it generates are the taproot of innovation and success."*

The concerns about the status of civil engineering amongst other engineering programs were well articulated by Sack et al (2000) "*the new civil engineering graduate is typically no longer offered a long-term position in the firm, but more frequently is hired for a specific design project, and the appointment may end when the project is completed. With the availability of civil engineering technology graduates from both two- and four-year programs, there is a temptation on the part of employers to hire technology graduates in preference to graduate civil engineers to minimize personnel costs. Today's entry-level positions in civil engineering are among the lowest paid in the engineering profession."*

It is clear that civil engineering faces daunting challenges as a profession losing stature and failing to deliver the expectations of the society, especially in view of the increasing societal impacts of technologies developed by other engineering and science disciplines. A fundamental concern is the lack of desirable performance delivered by the infrastructure systems constructed by civil engineers. US infrastructure systems are in serious decline. The aging water treatment, waste disposal, transportation, and energy facilities are among the top concerns for public officials and citizens alike. The American Society of Civil Engineers (ASCE) issued an update to its 2003 report card on Americas' aging infrastructure systems (http://www.asce.org/reportcard/2005/index.cfm). Each category in the ASCE reports was evaluated on the basis of condition and performance, capacity versus need, and funding versus need. The 2005 report gives America an overall grade of D on its

physical infrastructure and estimates that $1.6 trillion would be needed to restore it over a five-year period.

It is quite clear that we cannot afford to continue to engineer and manage our infrastructures as we have done in the past, ***even if it was possible to finance infrastructure renewal at the amounts estimated in the ASCE report.*** To take a closer look at infrastructure concerns, we note a paper issued by the Transportation Research Board (TRB) of the National Academies. In this position paper entitled "Critical Issues in Transportation 2002, *TR News* 217, November–December 2001", the scale and the importance of the US transportation system for the National economy and well-being are described. The critical issues that are identified are:

- *The transportation system is vulnerable to attacks by terrorists and saboteurs.*
- *Fatalities and injuries from transportation crashes are a major public health problem.*
- *The demand for passenger travel and freight movement is straining the capacity of the U.S. transportation system.*
- *Current institutional arrangements constrain the orderly development, operation, and coordination of the U.S. transportation system, including facilities, modes, and services.*
- *Worthy environmental goals and values pose serious challenges to the operation and expansion of transportation facilities to meet growing demand.*
- *The U.S. transportation system, which depends on fossil fuels, faces an uncertain future with respect to the availability and cost of energy.*
- *The aging transportation infrastructure must be rebuilt, but the costs involved exceed revenues.*
- *The financing of publicly provided transportation infrastructure is not adequately matched to use or need.*
- *Transportation organizations are having difficulty attracting and retaining the technically diverse personnel needed in the 21st century.*
- *Consumer benefits from deregulation are threatened by industry consolidation.*
- *An aging population poses special safety and mobility challenges.*
- *The burden of owning and operating vehicles is increasing for the lowest-income families.*
- *Telecommunications and information technologies are likely to have significant but uncertain consequences.*
- *Transportation faces formidable barriers to innovation, which are compounded by growing constraints on research investments.*

The TRB further identified the following opportunities for transportation research:

• New intelligent technologies in all modes can improve safety and service quality as transportation, information, and telecommunications infrastructures merge. New traffic operations centers could help operate traffic more efficiently and also provide a more focused response during emergencies.
• Improved materials can extend the service life of assets and can lower maintenance costs.
• New construction techniques can permit replacement and upgrading of congested facilities with less disruption and delay.
• Innovative approaches to purchasing services from the private sector promise a better return for the public sector in terms of quality and life cycle cost.
• Enhanced understanding of public preferences and behavior with regard to safety and trip making can guide better investment decisions.
• Better tools for predicting, managing, and avoiding environmental impacts can improve environmental stewardship.
• Better understanding of complex and long-term side effects—such as sprawl—can improve decisions about development.
• Deeper understanding of the causes of crashes can lead to more cost-effective countermeasures.
• More efficient, less-polluting vehicles and fuels that are less environmentally disruptive are within reach in terms of availability and cost.
• Analysis of newly emerging institutional experiments within states and regions can indicate new and better ways to make decisions and to manage and operate facilities.

Finally, the TRB asserts that "But despite this promise, transportation R&D is out of balance with national needs and with the sector's importance. Although transportation's share of the GDP is nearly equal to that of health care, the federal R&D investment in health care is 10 times that in transportation. Moreover, the national investment in science, engineering, and health has increased sharply in recent years, but the investment in transportation has remained low and unchanged. This under-investment makes it difficult to attract the best minds to work on solving transportation problems and leads to insufficient development of intellectual capital in agencies and universities. Federal investment in highway research as a share of expenditures, for example, is a mere 0.5 percent—a share substantially lower than that for low-tech industries.

HOW MUCH AND HOW TO CHANGE CIVIL ENGINEERING EDUCATION

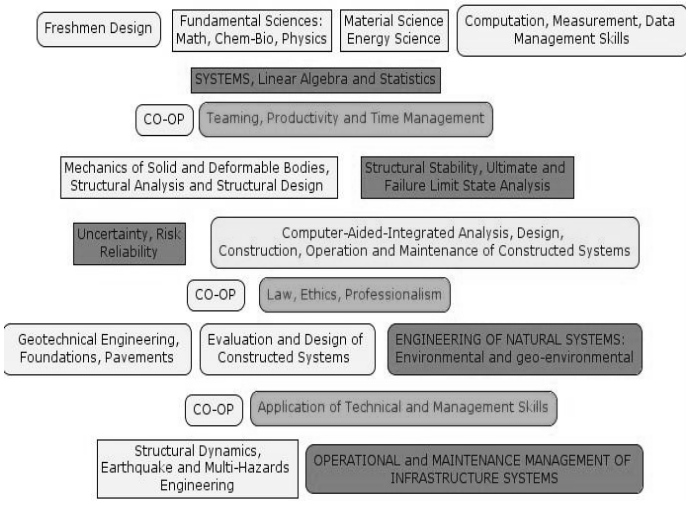
Based on the discussions presented above, Civil engineers face great challenges as well as opportunities. There are pressing societal problems that cannot be effectively addressed unless civil engineers are educated and trained to address these. First, civil engineers need to be able to effectively address system-of-systems problems such as critical infrastructures. Civil engineers are the only engineers qualified to effectively address the engineered systems within system-of-systems that are "constructed." Distinctions in their uniqueness, financing, stewardship, lifecycle cost, size, lifecycle, social and environmental impacts and the mechanisms of uncertainty and risks affecting their performance separate constructed systems from other engineered systems. Successful engineering and management of such systems, especially when their performance is governed by their constructed elements, require a holistic systems approach in conjunction with new knowledge and tools.

The critical societal problems that civil engineers have to start immediately addressing, that we may lump under "engineering and management of infrastructures" are:

1) Effective, safe and sustainable planning, feasibility analysis and financing of infrastructures.
2) Effective, safe and sustainable design, construction and operations of infrastructures.
3) Maintaining the serviceability and durability of constructed infrastructures and their effective and optimum lifecycle preservation.
4) Performance of constructed infrastructures under occasional as well as rare but credible hazards with respect to standards that meet societal expectations.
5) Effective virtual and physical protection measures and threat mitigation systems for infrastructures.
6) Emergency response planning and emergency response management.
7) Recovery planning and management following an event.
8) Effective preservation of historic monuments and treasures.
9) Transforming, adapting and demonstrating implementation of paradigms such as systems engineering and science, performance-based engineering, health monitoring, intelligent systems, asset management and others to infrastructure systems.
10) Technology transferring, customizing and integrating for the innovation of any aspect of infrastructure engineering and management.

Authors are convinced that it is necessary for civil engineers and all other stakeholders to come together for an integrated education and research agenda that is grounded in the reality of the actual operating infrastructure systems. The authors with many of their colleagues have formed an international, multi-disciplinary academe, government and industry partnership, including infrastructure owners, to develop an innovative infrastructure research, education and training agenda. The international societies of: (a) International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII, http://www.ishmii.org/), and, (b) the International Association for Bridge Management and Safety (IABMAS, http://ceae.colorado.edu/IABMAS/) have shared in their motivation to serve as an umbrella for renaissance civil engineers with an interest to contribute to innovating the engineering and management of infrastructures through scientific field research, demonstrations and implementations on actual infrastructures.

Returning focus to undergraduate education, the following concept diagram may serve as an example of a starting point for building a new curriculum. This tentative civil engineering curriculum concept diagram has been constructed by taking the program at Drexel as a model. The concepts paired with CO-OP are envisioned to be best delivered through a combination of structured instruction and professional experience. The remaining concepts



would be delivered by structured instruction, however, essentially integrated with a combination of virtual (IT-based), physical and field laboratory

experience. Some of the concepts require teams of academic and practicing engineers taking advantage of selected case studies of actual infrastructures at various stages of their life cycles. Finally, the concepts highlighted in red (dark background) are those that are typically missing from most curricula, and need to be sufficiently ***developed and integrated.*** These concepts as well as their teaching require further research and development due to knowledge gaps that exist in their conceptual understanding and integration, or due to resource needs for their effective instruction within an infrastructure system of systems focus.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, the writers took advantage of seminal papers and presentations by leaders of engineering education in order to review and evaluate the issues impacting engineering education. They also evaluated some additional issues that have been traditionally entrusted to civil and environmental engineers for their resolution, but that have become crises since civil engineers have not been able to properly address these. Professional organizations such as the ASCE and the TRB have recognized such challenges faced by the profession, and they are advocating change. However, whether the state-of-the-practice is sufficiently qualified to address the mounting infrastructure problems with the current approaches to feasibility analysis, financing, design, construction, operation, inspection, maintenance and renewal is questioned. Unless we have the courage to systemically reform civil engineering education by transforming it into a field-centered one grounded in the current reality of infrastructure engineering and management, it will be very difficult if at all possible to advance the manner we engineer and manage infrastructures.

It is also important to note that the impetus to reform the broader undergraduate education, followed by the impetus to reform engineering education have so far came with little or no participation from civil engineers (Clough, 1997). While the health care, defense, manufacturing and other industries employing electrical, mechanical, materials and chemical engineers have been active in the innovation of their practice, and exerted a pull for education reform in their respective programs, we do not see a similar effective pull from the civil engineering profession. Civil engineering professionals have to start more effectively criticizing their state-of-practice, and, seek new paradigms that will transform their practice. Improving the performance of a product necessitates a product-and-performance-based as opposed to a process-based approach to design, construction and operation. Various committees and segments of ASCE have been cognizant of this and they are seeking ways for transitioning to a performance-based practice. However, the broader civil engineering community should recognize the following critical issues and the education and research needed for their resolution.

1) Critical infrastructure systems are made of interacting engineered, human and natural sub-systems and elements. In addition, many infrastructure systems are inter-twined into “system of systems”. Engineered systems or elements within system-of-systems need to be further classified into “constructed” and “manufactured” due to distinctions in their uniqueness, financing, stewardship, lifecycle cost, size, lifecycle, social and environmental impacts and the mechanisms of uncertainty and risks affecting their performance. Successful engineering and management of such systems, especially when their performance is governed by their constructed elements, require a holistic systems approach in conjunction with new knowledge and tools.

Highway transportation offers an excellent example of a critical infrastructure system. A large variety of both constructed and manufactured engineered elements, a very wide spectrum of embedded human, organizational and social systems, and natural elements such as soil and water as well broad impacts of nature on the system all interact within the system-of-systems. Defining the performance of highway transportation requires an integration of many complex limit-states, controlled by dynamic phenomena such as traffic, accidents and earthquakes as well as extremely slow events such as material aging and deterioration that take place over many decades. The return periods of events that control the performance limit-states vary between 0 and 2500 years. The contiguous elements of the highway transportation system represent one of the largest geographic scales of any engineered system. The highway transportation system connects, both physically and through its users, to all other transportation systems and other critical infrastructures. A coordinated research and demonstration program that would focus on the highway transportation system offers both system-specific returns as well as great generic payoff in knowledge and insight for advancing the engineering and management of all infrastructures.

2) Various civil engineering programs and researchers have been transforming and integrating systems engineering principles and tools, developed by electrical, industrial, materials and other engineering disciplines, for applications to infrastructure components. However, real-life applications demonstrating how an integrated systems approach would improve the performance of highway transportation are not yet accomplished. Research, education and practice should emphasize the adoption of systems engineering and operations research tools and their meaningful implementations for solving real infrastructures concerns. The size, complexity, cost, heterogeneity, incremental constructions over Decades to Centuries, and long life-cycles of infrastructures makes it very difficult to observe, measure, model and simulate, analyze, synthesize and control them by using generic systems engineering tools. Correspondingly, advances in the current practice of engineering and management of infrastructures are necessary for improving how we plan, finance, construct, manufacture, operate, preserve and protect infrastructures as systems. ***Currently, the operational efficiency and safety of most infrastructures are not satisfactory, public funds available for this purpose are clearly insufficient, and the natural resources are not sustainable if we maintain status-quo. The risks in not making major improvements in the operational safety and efficiency, preservation and protection are simply too great for every stakeholder.***

Current education, research and practice regarding any aspect of infrastructure operation, preservation or protection are greatly fragmented. Integrative, multi-disciplinary education, research and practice is essential, however, we have not yet fully discovered the keys to integration (NAE (2005) http://www.nap.edu/books/0309094356/html/). Although we see many examples of inter-disciplinary collaboration, these are often ad-hoc, depending on serendipity. Policy and strategy changes are essential at university and government for ***designed*** integrative approaches. In fact, many academic leaders have been rightfully questioning the validity of continuing with a discipline-based education. It follows that we need to do multi-disciplinary research for learning and teaching how we can treat infrastructures as interconnected and integrated systems, by taking full advantage of systems engineering and the related sciences, and by further improving these to become effective and suitable for large-scale complex system-of-systems;

3) There is great promise in adopting powerful concepts and paradigms that we are not currently fully taking advantage of for improving infrastructure efficiency, protection and preservation. Integrated asset management, risk-and-performance-based engineering, health monitoring and proactive health management, systems engineering tools such as modeling, identification, control, optimization, decision theory and ***intelligent systems*** paradigms offer great promise if we could effectively capitalize on them. The issue is in being able to transform, integrate and adopt these paradigms to infrastructures. This cannot happen by hypothesis, or just by computer simulations. ***Research and demonstrations on actual operating infrastructure systems are necessary since we cannot yet properly simulate infrastructure systems analytically or physically.***

4) The US National Science Foundation (NSF), Federal Highway Administration (FHWA) and many other federal agencies such as the Environmental Protection Agency, National Institute for Standards and Technology, etc. offer exceptionally complementary resources that, if integrated, would very much enhance our capabilities for scientific and engineering research and demonstrations to advance the engineering and management of infrastructures. For example, a joint NSF-FHWA Engineering Research Consortium may serve as a vehicle for taking advantage of the significant synergy that exists between FHWA and the NSF's research and technology demonstration programs.

The single most important attribute of such inter-agency partnerships would be developing and connecting various operating and decommissioned components of infrastructures such as the highway transportation system, water distribution systems, etc. as ***field test-sites*** for serving problem-focused, multi-disciplinary systems research in conjunction with technology development and demonstrations at field laboratories. There is consensus amongst stakeholders that research and demonstrations on actual infrastructure test-sites is essential for advancing the states-of-the-art and practice in engineering and management of the highway transportation and other critical infrastructures.

5) There have been very few examples of research and technology demonstrations at infrastructure field test-sites. The Far East offers a larger number of examples. Extracting generic knowledge from test-sites requires considerable ingenuity and creativity

in their selection, their development into field laboratories, and, exacting scientific standards for research. Civil engineers have yet to discuss and establish all of the critical issues and their possible resolutions for successfully designing and implementing scientific research and technology demonstrations on field test-sites. Issues related to ***observability, measurability and systemic nature*** in conjunction with the applications of systems-identification, integration and control concepts to large and complex systems. Standards for reliability and completeness in measuring, documenting and interpreting phenomena affected by many less known and unknown mechanisms of uncertainty pose additional challenges.

Additional critical barriers to successful research at field test-sites include: difficulties for accessing a site and various critical locations within large structures, a lack of experience in coordinated integrative research involving large real-life field test-sites, and, a lack of adequate research support (both funding and in-kind support). The latter is necessary for maintaining a safe conduct of research with high standards. Partnerships between infrastructure owner-operators, academe and industry are essential vehicles for access and for in-kind support necessary to conduct scientific research and technology demonstrations on actual operating infrastructure test-sites.

6) The opportunity of fostering coordinated, integrative multi-disciplinary research, similar in context and importance to the well-known space, arctic and deep ocean explorations supported by the federal government, anchored by constructed systems such as highway bridges, may appear as difficult to accept. However, in spite of constructing bridges for more than millennia, there are many loading mechanisms and behaviors that we are only now beginning to understand and only by taking advantage of the recent advances in digital imaging, sensing, nondestructive probing, data acquisition and networking hardware, software and associated information technology. It is now possible to develop integrated wide-area imaging and sensing networks that may employ many hundreds of cameras and sensors, processing, archiving and providing real-time displays of data anywhere through the Internet. The remaining critical issue is the integration of data, information and heuristics, interpretation and decision-making. In other words, we have developed and are developing excellent health monitoring tools but still lack the most basic knowledge about our patient.

7) The creation of an integrated community of stakeholders, a connected multi-disciplinary International Nexus, dedicated to advancing infrastructures operation, preservation and protection in a problem-focused manner is critical. Only by integrating researchers who have gained experience in developing and conducting research at field test-sites, we will be able to answer fundamental questions such as the definition of objective and conceptual measurement indices defining the health and performance of an infrastructure system and its components. The issue of defining "similitude" when we are observing and experimenting with a prototype system-of-systems have to be resolved if we wish to derive generic knowledge from measurements at field test-sites. We need to learn how to integrate modeling and simulation, experiments on distorted phenomenological models, on physical models designed for similitude of critical behaviors, and, the observations and measurements on actual infrastructures. Finally, we need to understand at which levels of resolution we would need to study various aspects of infrastructure hyper-system behavior.

Just as we have learned how to expand, reduce or condense structural analysis models for simulating phenomena at different resolutions, we would need to learn analytical modeling of infrastructures based on different tools, formats and resolutions for reliably simulating individual element, sub-system and entire infrastructure system behaviors. Behavior simulation can only be useful if in conjunction with various realistic scenarios such as day-to-day operation along lifecycle, or hazards. Scientific research at properly designed and developed field test-sites is essential before we may understand and establish all of the behavior scenarios that need modeling, and how to construct meaningful models for reliably simulating important phenomena.

8) The formation and coordination of research teams for integrative research on field laboratories is an issue that warrants consideration. Engineers and scientists from all disciplines as well as all other infrastructure stakeholders certainly have much to contribute to infrastructure research. However, renaissance civil engineers are perhaps the best equipped to frame the problems of large, heterogeneous infrastructure system-of-systems, and help develop a new terminology, data, information and knowledge so that we may adopt and develop new systems engineering tools for a holistic, integrative approach to infrastructures.

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