Global Engineering Education for a Small Planet

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Abstract—The engineering profession must embrace a new mission statement—to contribute to the building of a more sustainable, stable, and equitable world. *Global engineers* are needed to address a multitude of global complex challenges faced by humanity today. The world calls for it, the engineering profession calls for it, and students desire a more meaningful education. There is indeed a need to question the orthodoxy of traditional engineering education in general as it is out of context with the challenges society is facing today and out of touch with what its customers (students and professionals) are demanding. Global engineers need to have the tools and skills necessary to operate in a complex world.

Keywords— Global engineering; education; wicked problems; body-of-knowledge

I. Introduction

Let's cut to the chase and start with a simple question: Do today's engineering graduates and engineers have the skills and tools to address the global problems that our planet and humans are facing today, or will be facing within the next 20 years? The list of global problems is long and include: conflict and human rights violations; terrorism; human migration and refugee crisis; climate change; poverty; insecurity in water, energy, and food resources; land tenure issues; inadequate shelter and uncontrolled urbanization; pollution and environmental degradation; lack of communication and transportation; and transboundary issues, to name a few. All these problems share many characteristics. First, they are all complex, ill-defined, messy, and sometimes referred to as wicked [1]. As a result, they are open-ended, do not have clear and unique solutions, and cannot be completely addressed using the deterministic tools used in science and engineering over the last century. They require instead using tools derived from system and complexity sciences. Second, all the problems mentioned above stand at the crossroads between science, technology, and engineering on the one hand and societal/environmental/economic issues on the other. Finally, the problems are not usually addressed in traditional compartmentalized undergraduate engineering curricula due to their multidisciplinary nature. As a result, the majority of engineering students graduating today are ill-prepared to deal with global problems once they enter practice.

Since the answer to the question mentioned above is negative, and we cannot solve tomorrow's problems with just yesterday's tools and skills, a new epistemology of engineering education is urgently needed; one that is based on the idea of awareness, systems thinking, engagement, leadership, teamwork, reflective and adaptive practice, and field exposure to global problems during the students' formative years. This new form of engineering education must be designed with the overarching goal of creating *global engineers* capable of operating in a multi-cultural and increasingly challenging world during their lifetime.

Quoting Albert Einstein, "the significant problems we face today cannot be solved at the same level of thinking we were at when we created them," developing a new engineering education mindset does not come without its own share of challenges. It represents a quantum leap very similar to previous ones that have shaped the engineering profession and its relation to society over the past 200 years. As an example, for the first part of the 19th century, the dominant view was that engineering should develop apart from society and that technology was nothing more than applied science and economics [2]; an approach that was called "internalist" or "determinist" by history of science experts [3]. The second half of the 19th century and the first half of the 20th century witnessed a change in the dynamic between technology and society. The 1850-1950 period is often regarded as the first Golden Age of engineering where the importance of engineers and their contribution to society was unquestionable [4].

Another controversial change and a quantum leap in the relationship between engineering/technology and society took place in the 1960s and 1970s in association with the environmental and sustainability movement. One must wait until the mid-1990s to early 2000s for the industry to partially endorse the value proposition of sustainable development. The 1992 United Nations Conference on Environment and Development also known as the Rio Summit helped pave the way for many issues that are still of concern today in the areas of economic development, climate change, and poverty reduction. The meeting exemplified the critical role played by science and technology in shaping up future societies and the health of the planet in general. It also emphasized the critical role of society in shaping up technology and economics decisions.

The Rio Summit and subsequent initiatives such as the Millennium Development Goals (MDGs), the more recent Sustainable Development Goals (SDGs), and the National Academy of Engineering (NAE) Grand Challenges have created a platform for a renewed sense of purpose for the engineering profession. All these initiatives have the potential to elevate the image of the engineer among the younger generation. They also help reassert the fact that "our economic and social health depends directly on the health of the engineering endeavor, and the health of engineering depends, in turn, on the support of society." [5].

As we approach the end of the second decade of the 21st century, the engineering profession is being challenged again in addressing more complex issues related to rapid population growth, urbanization, and climate change. In the next two decades, an additional 1.5 billion people are expected to populate the Earth, 97% of them in developing regions or currently-labeled least developed countries [6]. Population growth combined with a worldwide increase in food and energy prices has forced the international community to consider more closely the links between water, energy, and food resources [7]. By 2050, global food demand is expected to grow by 60 percent, energy demand by 80 percent, and water demand by 55 percent [8]. This growth will occur in an existing context of uneven resource scarcity and in which the consumptions of water, energy, and food resources are already interconnected. In addition to meeting the demands associated with population growth and providing the necessary infrastructure, other issues affecting human development are climate change mitigation and adaptation; increasingly competitive demands for water, energy, and food resources within and across various sectors (domestic, industrial, agricultural); and demands from groups of consumers who may or may not be on different sides of a geopolitical border. If resource allocations are not properly addressed, trade-offs in natural resource development, management, and allocation across groups and sectors have the potential to create unintended negative consequences, risks, and uncertainties that could negatively affect large populations, especially those living in poor and marginalized communities.

In general, the role of engineers is critical in fulfilling the demands mentioned above at various scales, ranging from small remote communities to large urban areas such as megacities. A question now arises about what needs to be done, now and in the immediate future, for *all* humans to enjoy a quality of life where basic needs of water, sanitation, nutrition, health, safety, and meaningful work are fulfilled. Another way of phrasing that question is how "to feed more people with lesser water, in a context of climate change and growing energy demand, while maintaining healthy ecosystems" [9].

Considering the problems facing the planet today and those expected to arise in the next 40 to 50 years, the engineering profession must revisit its mindset and adopt a new mission statement—*to contribute to the building of a more sustainable, stable, and equitable world*, not only in the developed countries but also in the countries with are still in various stages of development. It is noteworthy that despite 20+ years of discussion among academics about engineering education, multiple initiatives and recommendations to develop a modern engineering body of knowledge [10-12], and the recent introduction of the NAE Grand Challenges for Engineering [13], there is still a large disconnect between the limited skills and tools acquired by students in engineering programs in U.S. universities and the day-to-day complex problems faced by humanity. Whether colleges and universities are doing proactively enough to teach students what they need to know to operate in a global environment is an open question that is worth exploring further [14].

II. GLOBAL ENGINEERING

A. Guiding Principles

There is no doubt that engineering has been an integral part of the development of human society and has driven the advance of civilization. A list of the greatest engineering achievements of the 20th century can be found at a National Academy of Engineering (NAE) website [15]. Better living conditions and greater life expectancy that people experience in western countries today are the results of major achievements in medicine and engineering practice during the past 200 years. Today, our quality of life is built upon a complex and highly productive set of technological, industrial, and municipal systems and structures.

It should be noted, however, that these technical successes have benefitted only a small fraction of humanity and have had a limited impact in improving the livelihood of the most destitute people on our planet. For instance, life expectancy in many developing countries is still low and very similar to what it was in the U.S. 100 years ago. The engineering profession still has an important role to play in providing support systems to those living in unhealthy, degrading, inequitable, and unsustainable conditions. As remarked by the National Academy of Engineering [13], "A world divided by wealth and poverty, health and sickness, food and hunger, cannot long remain a stable place for civilization to thrive."

The technical successes in the developed world have also contributed to unplanned or undesirable effects of technology on natural and human systems. As mentioned by Berry [16], over the past 100 years we have witnessed in the developed world the creation of a technical wonderland side by side with a technical wasteland. Such undesirable effects have been objects of criticism by society. As noted by Hollomon [17], Bugliarello [18] and others, these effects have forced the engineering profession to acknowledge its limitations, revisit its assumptions, and propose guiding principles, some of which are presented below:

- Many engineering decisions cannot be made independently of the surrounding natural and human-made systems because modern engineering systems have the power to significantly affect social, economic, and environmental systems far into the future.
- Our ability to cause planetary change through technology is growing faster than our ability to understand and manage the non-technical consequences of such change.
- The traditional approach that engineering is only a process to devise and implement a chosen solution amid several purely technical options must be challenged.
- A more holistic approach to engineering requires an understanding of interactions between engineered and non-engineered systems, inclusion of non-technical issues, and a system approach to comprehend such

interactions. A challenge is to reconcile the linear models of engineering with the complex, non-linear, and adaptive nature of natural and human systems.

- 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.
- The compartmentalized 19^{th} century model of engineering education no longer fits the needs of society.
- Engineers must become more engaged in major societal leadership positions.

These guiding principles must be considered by engineers who are addressing the wide spectrum of global development challenges faced by humanity today. On one end of the spectrum, the challenge of the *developed world* is to consume less and more intelligently while being respectful of human and natural systems. In that context, engineers are called to develop innovative and more efficient ways of providing services and reconsider the take-make-waste process in the production, distribution, and consumption of goods and services. On the other end of the spectrum of development, the challenge of people in the *developing world* is to have access to the resources and skills necessary to meet their daily challenges; for some, it is as basic as staying alive by the end of the day. Engineers need to develop solutions that are available, accessible, and affordable to many people with limited resources. In between these two extremes are burgeoning *emerging markets* which are experiencing rapid economic growth. In that context, engineers need to be innovative in developing leapfrogging solutions that do not duplicate the mistakes made by the developed world over the past 100 years and prevent the new economies from falling back to where they were before.

B. *Educating Global Engineers*

Having defined the global context in which engineers need to operate and the vision of having engineers contribute to the building of a more sustainable, stable, and equitable world, two questions arise as to what constitutes global engineering education and what should be the body of knowledge (BOK) in the education of global engineers.

The concept of educating global engineers is not new and has been discussed quite extensively in the engineering education literature around the world. Global engineering is mostly an umbrella term to emphasize a need to educate more competent engineers [19, 20]. For instance, Bourn and Neal [21] explore the value proposition and the challenges of integrating a global dimension within the higher education of U.K. engineers.

What is global engineering? Although no complete definition has ever been proposed, a possible one is to use a definition proposed by Bugliarello [22] for what he called *Engineering for Development*. According to this author, it: "…responds to the global need for engineers who understand the problems of development and sustainability, can bring to bear on them their engineering knowledge, are motivated by a sense of the future, and are able to interact with other disciplines, with communities and with political leaders to design and implement solutions."

A few remarks need to be made before going into the details of what represents an appropriate BOK in the education of global engineers. First, it is important to realize first that the wide range of global development challenges mentioned above cannot be solely addressed by technology. Global engineering is more than developing technical solutions to solve humanity's problems. Global engineers must be able to take under consideration non-technical socioeconomic, cultural, and political issues that play as much of a role as technical issues in explaining problems faced by humanity today. In short, global engineers need to be versed at dealing with both technical and non-technical tools in their decision-making process.

The second remark about global engineering is that it does not necessarily fit into any specific branch of engineering. Simply put, no single engineering discipline could address in full the global development challenges mentioned above. In addition, there are no grand solutions to wicked problems; only step-by-step ones that require cross-disciplinary tools [23]. Global engineering should be seen instead as an engineering program or field, rather than a discipline, that cuts across different engineering silos and uses tools from different technical and non-technical disciplines. This concept is obviously disruptive to the *orthodoxy* of traditional engineering education which is accustomed to well-defined disciplines and a hierarchical structure [20, 21].

The third remark about global engineering is that it can mean different things to different people. It is possible to envision, for instance, different types of global engineering education programs based on the context (cultural, political, environmental, etc.) being addressed and the scale (physical and temporal) at which problems are being considered. For instance, a global engineering education program interested in the dynamics at play in an urban environment will have a BOK quite different from that of a program interested in rural planning or in the management of slum areas or refugee camps. The same could be said about the BOK of engineering programs addressing issues faced by communities located in different climatic and geographic regions.

All three aforementioned remarks give the impression that it is hard to define a common BOK for the education of global engineers and identify what global engineers should master, their competence, and what they should be exposed to. To a certain extent, this is true since a common BOK would have to be designed to address a wide range of issues as mentioned above. At the same time, defining the BOK is not a random process if one were to see the education of global engineers as a *T-type* of education with both depth and breadth rather than a traditional specialized *I-type* of education [24]. The depth part of the T-type education deals with the technical tools that are commonly expected of engineers in practice. On the other hand, the breath part deals with the various non-technical (e.g., socio-economic, cultural) tools that engineers must be aware of in order to address the global problems mentioned above. These tools are mostly taught in non-engineering colleges.

It is clear that engineers need to have skills other than technical ones to address global development issues. Over the past 15 years, multiple skills have been suggested by accreditation organizations such as ABET, professional organizations such as ASCE, ASME and IEEE, and the National Academy of Engineering (NAE). Examples include an ability to communicate effectively across cultures; an understanding of professional and ethical responsibility; an ability to understand the impact of engineering solutions in different contexts; being able to work in multi-cultural and multi-disciplinary teams; an ability to manage and lead projects; and showing practical ingenuity, to name a few. These skills represent the cement that binds the engineering curriculum together, and if acquired, help differentiate a graduating engineer with no awareness of global issues from one that has the confidence to approach the world and its global issues in an integrated manner and is willing to learn in that process.

It should be noted that the balance between the T-type and I-type of education continues to be a topic of major discussion in the engineering profession today. In that discussion, the concern is not about whether a T-type of education is better suited than an I-type education to address today's global world's issues; this is usually accepted by academia. The concern is rather about the perceived difficulty in integrating all non-technical components of a T-type of education, such as the skills mentioned above, into a four-year (BS) or five-year (BS/MS) curriculum that is already at capacity.

Among the "why," "what," "how," and "who," of a T-type of engineering education, the first two are generally better defined. Regardless of the global engineering emphasis, global engineers must have, at least, acquired the following core competencies:

- Personal awareness and understanding of what it means to be a global citizen;
- Awareness of the social and environmental components of engineering decision making;
- Skills (hard and soft) and tools appropriate to approach ill-defined world issues;
- Being able to think across disciplines and handle technical and non-technical issues;
- Project management skills for a wide range of contexts and at different scales;
- Flexibility and resourcefulness to deal with unfamiliar equipment and approaches;
- Systems thinking skills by acquiring the habits outlined in Table 1;
- Familiarization with decision-making methods ranging between objective and subjective ones;
- Hands-on engineering and service learning experience in their formative years; and
- Awareness that in addition to being providers of technical solutions, they are also called to be change-makers, peacemakers, and facilitators of sustainable development.

The "how" and "who" of a T-type of engineering education is more difficult to address. Questions remain, for instance, as to how to: (i) expose engineering students to real-world problems through internships, co-op programs, and/or outreach/service learning activities? (ii) promote leadership and integrate social responsibility and ethics across the entire curriculum? (iii) encourage students to explore a minor around at least one global issue (e.g., human development, sustainability, peace and conflict studies, etc.)? (iv) encourage traditional research-oriented and teaching-oriented faculty members to include new concepts on world issues in their work? (v) engage stakeholders from non-academic sectors in curriculum development? and (vi) define success?

TABLE 1.
Fourteen habits of a system thinker according to the Waters Foundation. Source: <http://watersfoundation.org/> (March 13, 2015).

• Seek to understand the big picture
• Observe how elements within systems change over time, generating patterns and trends
• Recognize that a system's structure generates its behavior
• Identify the circular nature of complex cause and effect relationships
• Make meaningful connections within and between systems
• Change perspectives to increase understanding
• Surface and test assumptions
• Consider an issue fully and resist the urge to come to a quick conclusion
• Consider how mental models affect current reality and the future
• Use an understanding of system structure to identify possible leverage actions
• Consider short-term, long-term and unintended consequences of actions
• Pay attention to accumulations and their rates of change
• Check results and change actions if needed: "successive approximation"
• Recognize the impact of time delays when exploring cause and effect relationships

Despite the resistance of some engineering educators to change and address the questions mentioned above, it should be noted that several independent initiatives are underway at some U.S. universities toward changing the traditional engineering education mindset. They include specialized certificates, minors, and programs (e.g., humanitarian engineering, engineering for developing communities, peace engineering, sustainability, etc.) and outreach and service learning initiatives (e.g., the Talloires network, Engineers without Borders, Engineering Projects in Community Service, Engineering World Health, etc.). All these initiatives are already changing the landscape of engineering education and practice. They were developed by innovative faculty interested in creating change in otherwise stale engineering programs. They have also attracted many students and have received the support of industry interested in hiring new cohorts of young leaders.

III. CONCLUSIONS

Creating a sustainable world that provides a safe, secure, healthy, productive, and sustainable life for all peoples should be a priority for the engineering profession. Engineers have an ethical obligation to meet the basic needs of all humans for security, water, sanitation, food, health, energy, transportation, communication, as well as to protect cultural and natural diversity.

Global engineering education is about creating a new generation of engineers who can address the global challenges faced by humanity today or will be facing in the foreseeable future. These challenges cannot be addressed using only the tools that have led to the grand engineering achievements of the 20th century. A new mindset is needed to train engineers who have the technical know-how but also a breath of tools and skills that are needed to address the challenges. Of course, this type of education can be threatening to a classical establishment afraid of change. At the same time, archaic engineering education programs are out of touch with the reality of the world. They may survive for some time but will fail to attract students and young faculty members interested in meaningful education and innovation. In short, the age of archaic engineering program will not end by running out of such programs with narrow-minded administrators and educators. It will end because more interesting alternatives to engineering education will be offered to young people who want to make the world a better place and are not afraid of doing something to meet that goal. Global engineering provides a unique opportunity for renewing the leadership of the U.S. engineering profession in the 21st century.

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