A systems model for global engineering education: The 15 Grand Challenges

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Abstract
This is a position paper on connecting engineering education to the prevailing needs of society. Engineering is the foundation for national development and engineers work at the intersection of science, technology, and societal needs. Throughout history, engineering has played a crucial role in the advancement of commerce, development of society, and the pursuit of human welfare. The application of engineering to the problems of society is predicated on structured education programs. This paper addresses how engineering education is progressively important to society and what must be done to continually advance the quality and effectiveness of engineering education. The paper proposes 15 grand challenges for global engineering education, based on the premise of the 14 grand challenges for engineering published in 2008 by the US National Academy of Engineering and highlights the role of diverse disciplinary viewpoints needed to ensure that engineering education addresses economic, cultural, and social factors that impinge upon engineering solutions to societal problems. The premise of the paper is to spark more interest in research into models, techniques, and tools essential for making engineering education more robust in solving global society problems.

Introduction
The fourteen grand challenges of engineering, compiled by the US National Academy of Engineering (NAE, 2008), have implications for the future of engineering education and...
practice. Engineers of the future will need diverse skills to tackle the multitude of issues and factors involved in adequately and successfully addressing the challenges. An extract from the NAE document on the 14 grand challenges reads as follows:

“In sum, governmental and institutional, political and economic, and personal and social barriers will repeatedly arise to impede the pursuit of solutions to problems. As they have throughout history, engineers will have to integrate their methods and solutions with the goals and desires of all society’s members”.

This statement emphasizes the relevance of a holistic systems thinking approach in solving the multi-faceted global problems that we face now and will face in the future. Global situational awareness (Badiru, 2009) is essential for solving the world’s most pressing problems. Robust engineering education programs around the world will be the cornerstone for integrating the multiple skills across geographical boundaries as well as across cultural divides. This paper suggests how the versatility of engineering can be brought to bear on solving societal challenges. With the approach of this paper, positive outcomes of multinational engineering education coalition can be achieved so that we can improve the global quality of life. Engineering educators must come together to develop robust curricula to adequately prepare students for the challenges that lie ahead.

The 14 Grand Challenges for Engineering

It is a systems world. Whatever affects one subsystem of the global infrastructure, will eventually percolate through the whole system. Engineering, by virtue of its versatility and systems viewpoint, can be the anchor for solving the challenges. The 14 NAE Grand Challenges for Engineering can help educators to target research and education directions to collectively solve those problems that affect the global society. The challenges highlight the relevance of a holistic systems thinking approach in solving the multi-faceted global problems that we face now and will face in the future. This is in perfect alignment with the premise of the 15 grand challenges for engineering education proposed in this paper. The 14 grand challenges are summarized below.

1. **Make solar energy economical**: Solar energy provides less than one percent of the world’s total energy, but it has the potential to provide much, much more.
2. **Provide energy from fusion**: Human-engineered fusion has been demonstrated on a small scale. The challenge is to scale up the process to commercial proportions, in an efficient, economical, and environmentally benign way.
3. **Develop carbon sequestration methods**: Engineers are working on ways to capture and store excess carbon dioxide to prevent global warming.
4. **Manage the nitrogen cycle**: Engineers can help restore balance to the nitrogen cycle with better fertilization technologies and by capturing and recycling waste.
5. **Provide access to clean water**: The world’s water supplies are facing new threats; affordable, advanced technologies could make a difference for millions of people around the world.
6. **Restore and improve urban infrastructure**: Good design and advanced materials can improve transportation, energy, water, and waste systems, and also create more sustainable urban environments.
7. **Advance health informatics**: Stronger health information systems not only improve everyday medical visits, but they are essential to counter pandemics and biological or chemical attacks.

8. **Engineer better medicines**: Engineers are developing new systems to use genetic information, sense small changes in the body, assess new drugs, and deliver vaccines.

9. **Reverse-engineer the brain**: The intersection of engineering and neuroscience promises great advances in health care, manufacturing, and communication.

10. **Prevent nuclear terror**: The need for technologies to prevent and respond to a nuclear attack is growing.

11. **Secure cyberspace**: It's more than preventing identity theft. Critical systems in banking, national security, and physical infrastructure may be at risk.

12. **Enhance virtual reality**: True virtual reality creates the illusion of actually being in a difference space. It can be used for training, treatment, and communication.

13. **Advance personalized learning**: Instruction can be individualized based on learning styles, speeds, and interests to make learning more reliable.

14. **Engineer the tools of scientific discovery**: In the century ahead, engineers will continue to be partners with scientists in the great quest for understanding many unanswered questions of nature.

Our global society will be tackling these grand challenges for the foreseeable decades and systems-based engineering education is one avenue through which we can ensure that the desired products, services, and results can be achieved. Figure 1 illustrates the central role of global engineering education in addressing NAE's 14 grand challenges.

With the positive outcomes of these projects achieved, we can improve the quality of life for everyone and our entire world can benefit positively. Most of the grand challenges focus on
high-tech developmental issues. Yet, the problems of the world are best solved through integrated approaches focusing on social, cultural, political, and high-tech issues. For example, low-cost and culturally-sensitive adaptation of existing technologies may easily solve some nagging problems in the more depressed parts of the world. Provision of clean water is one such possibility. In the case of energy, advanced countries have well-developed techniques for harnessing energy from waste, but in many developing countries, handling and dealing with waste is culturally seen as taboo. Technologies that are too high-tech (e.g., nano-filtration for water) may be acceptable in a developed country, where clean drinking water already exists (albeit in short supply), but it may not be practical in some developing countries. The 14 grand challenges involve design, installation, improvement, systems integration, people, materials, information, energy, prediction, evaluation, and implementation. Thus, they must be addressed from an expanded global viewpoint.

Semantic network interfaces
A semantic network is a good way to represent the systems interrelationships of NAE’s 14 grand challenges. Figure 2 is an illustrative example of how every element of the challenges is linked to at least two other elements with the diverse practice of industrial engineering. The overall problem sphere is composed of a system of systems (SoS) structure, the interconnectivity of which is embodied in the quote that follows.

![Figure 2: Semantic Network Representation of NAE's Grand Challenges](image-url)
“Clearly, it is now possible for more people than ever to collaborate and compete in real-time, with more people, on more kinds of work, from more corners of the planet, and on a more equal footing, than at any previous tie in the history of the world.”

Thomas L. Friedman – The World is Flat, 2005

Using the tools of engineering requirements analysis, engineering practitioners must appreciate the underlying relationships among the elements of a problem, thereby ensuring that all factors are considered in a global holistic solution.

**Systems interface structure**

The V-model of systems engineering is used by industrial engineers to link and solve complex problems. It is a graphical representation of a system's lifecycle. The model, which relates solution techniques to problem scenarios, is directly applicable to semantic network of the grand challenges. Figure 3 presents a V-model in the context of solving the grand challenges. As indicated in the figure, problem assessment, problem decomposition, lifecycle requirements, solution integration, and global implementation are key elements of solving the 14 grand challenges.

**The implications for engineering education**

Education is the avenue through which the goals and objectives of the 14 grand challenges can be realized. It could be education in terms of preparing the future engineers or education in the form of raising the awareness of members of the society. Table 1 presents a taxonomy of education implications of the 14 grand challenges.

![Figure 3: Systems Engineering V-Model Applied to NAE’s 14 Grand Challenges](image)
Energy, in its various forms, appears to be a common theme. In addition to teaching the technical and analytical topics related to energy, energy-requirement analysis must consider the social and cultural aspects involving the three primary focus areas listed below.

- **Energy Distribution**: Transmission Technology, Hydrogen, Distributed Energy Sources, Market
- **Energy Consumption**: Transportation, Storage, Product Requirements, Conservation, Recovery, Recycling

Table 1: Taxonomical Analysis of Engineering Education Alignment with NAE’s Grand Challenges (Adapted from Badiru, 2013)

<table>
<thead>
<tr>
<th>NAE’s 14 Grand Challenges</th>
<th>Research Topics</th>
<th>Education Topics</th>
<th>Practice Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Make solar energy economical</td>
<td>Strategic Investments</td>
<td>Engineering Economics</td>
</tr>
<tr>
<td>2</td>
<td>Provide energy from fusion</td>
<td>Design Safety</td>
<td>Energy Management</td>
</tr>
<tr>
<td>3</td>
<td>Develop carbon sequestration methods</td>
<td>Natural Science Analytics</td>
<td>Storage Systems Design</td>
</tr>
<tr>
<td>4</td>
<td>Manage the nitrogen cycle</td>
<td>System Planning</td>
<td>Systems Optimization</td>
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<tr>
<td>5</td>
<td>Provide access to clean water</td>
<td>Environmental Science</td>
<td>Water Resource Engineering</td>
</tr>
<tr>
<td>6</td>
<td>Restore and improve urban infrastructure</td>
<td>Resilience Engineering</td>
<td>Construction Management</td>
</tr>
<tr>
<td>7</td>
<td>Advance health informatics</td>
<td>Health Systems Engineering</td>
<td>Computer Science &amp; Bio Informatics</td>
</tr>
<tr>
<td>8</td>
<td>Engineer better medicines</td>
<td>Personalized Pharmaceuticals</td>
<td>Biomedical Engineering</td>
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<tr>
<td>9</td>
<td>Reverse-engineer the brain</td>
<td>Human Factors</td>
<td>Cognitive Psychology</td>
</tr>
<tr>
<td>10</td>
<td>Prevent nuclear terror</td>
<td>Deterrent Strategies</td>
<td>Emergency Response</td>
</tr>
<tr>
<td>11</td>
<td>Secure cyberspace</td>
<td>Information Resources Research</td>
<td>Enterprise Design and Management</td>
</tr>
<tr>
<td>12</td>
<td>Enhance virtual reality</td>
<td>Software Engineering</td>
<td>Software Design and Programming</td>
</tr>
<tr>
<td>13</td>
<td>Advance personalized learning</td>
<td>Active Learner Systems</td>
<td>Blended Hybrid Learning</td>
</tr>
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<td>14</td>
<td>Engineer the tools of scientific discovery</td>
<td>Product Design</td>
<td>Scientific Inquiry</td>
</tr>
</tbody>
</table>
The 15 Grand Challenges
Related to the foregoing discussions, this section presents what the author sees as the fifteen pressing and grand challenges for global engineering education. These are referred to as “Badiru’s 15 Grand Challenges for Global Engineering Education.”

1. Systems view of the world in educational delivery modes and methods in order to leverage unique learning opportunities around the world
2. Pursuit of integration and symbiosis of global academic programs
   - Through global educational system integration, we can move toward a mutual-assured advancement of engineering education.
   - Think global, but educate locally to fit domestic needs.
   - Language diversity, for example, can expand thought and understanding to facilitate global communication, cooperation, and coordination.
3. Linking engineering education to the present and future needs of society rather than just a means to better employment
4. Commitment to embrace all engineering disciplines in a collaborative one-focus alliance toward addressing societal challenges
5. Engagement of non-engineering disciplines, such as management and the humanities, in addressing high-value societal problems collectively.
   - There are now medical humanities programs. Consider engineering humanities programs to put a human face to engineering solutions.
6. Adoption and adaptation of e-education to facilitate blended learning modes, flexibility of learning, and diversity of thought in a fast-paced society
   - Of interest in this regard is the evolution of measurement scales for pedagogy and andragogy.
7. Leveraging of social media tools and techniques to facilitate serious and rigorous transmission of knowledge
8. Extension of formal engineering education to encompass continuing engineering education and sustainability of learning
9. Creation of hybrid method of teaching what is researched and researching what is taught
10. Inculcation of global sensitivity into engineering education programs
11. Inclusion of social responsibility in engineering education, research, and practice
12. Making engineering solutions more human-centric solutions
   - Use engineering to solve real human problems. Keep engineering education relevant to the needs of society.
13. Teaching of representational modeling in engineering education
   - Modeling can provide historical connectivity to recognize the present as an output of the past and a pathway for the future.
14. Teaching of “Of-the-Moment Creativity” to spur innovation for the current, prevailing, and attendant problem
15. Introduction of engineering solution “ilities” covering Feasibility, Sustainability, Viability, Desirability of engineering solution approaches
Figure 4 illustrates the linking of Badiru’s 15 challenges for global engineering education from a world systems perspective.

**Literature relevance of the 15 Challenges**

Throughout history, engineering has answered the call of the society to address specific challenges (Grayson, 1993; Kirby et al., 1990). With such answers comes a greater expectation of professional accountability. Consider the level of social responsibility that existed during the time of the Code of Hammurabi (Bryant, 2005), two laws of which are echoed below:

Hammurabi’s Law 229: “If a builder build a house for someone, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.”

Hammurabi’s Law 230: “If it kills the son of the owner the son of that builder shall be put to death.”

These are drastic measures design to curb professional dereliction of duty and enforce social responsibility. Duckworth and Moore (2010) present modern aspects of social responsibility in the context of day-to-day personal and professional activities. The global responsibility of the greater society is presented by Bhargava (2006) with respect to world development challenges covering the global economy, human development, global governance, and social relationships. Engineering solutions require creative problem solving (Fogler and LeBlanc, 1994) and sensitivity to subtle issues around the problem scenario.
Lanzerotti et al (2014) present a practical example of transforming undergraduate education through hands-on summer internships that engage students in real-life engineering problem-solving settings with a focus on career-broadening opportunities. Carberry and McKenna (2014) illustrate the use of modeling in engineering design. They contend that, in spite of modeling being so pervasive in the practice of engineering, it is rarely taught explicitly as a subject. This agrees with the premise of this paper that modeling is one challenge area for engineering education. A similar exposition of the efficacy of modeling is presented by Doerr et al (2014).

Broadening of participation, from a team perspective, is addressed by Klotz (2014), using the topic of sustainability as a rallying point. As addressed in Challenge number 3 for linking engineering education to the present and future needs of society, Johri and Olds (2014) present reflections on the future of the engineering education research. In a similar vein, Daly et al (2014) call for an explicit teaching of creativity in engineering courses. Focusing on the emerging field of Big Data, Xian and Madhavan (2014) advocates engineering education collaboration, which aligns well with Challenge number 4.

The role of social capital and gender diversity is addressed by Martin et al (2013). This fits the theme of social responsibility addressed in Challenge number 11. Borrego et al (2013) suggest team theory as a vehicle for enhancing engineering education research. This fits the notion of using teaching to enhance research and vice versa as opined in Challenge number 9.

Engineering is the anchor of the much-touted STEM (Science, Technology, Engineering, and Mathematics) career fields. As such, advancements in engineering education positively affect the other STEM areas as purported by Landivar (2013). Of relevance to Challenge number 6, Conner (2004) summarizes the five principles of andragogy:

1. Letting learners know why something is important to learn
2. Showing learners how to direct themselves through information
3. Relating the topic to the learners’ experiences
4. Realizing that people will not learn until they are ready and motivated to learn
5. Helping learners overcome inhibitions, behaviors, and beliefs about learning

With the above principles as possible tenets for continuing engineering education, the challenges presented in this paper can be better addressed in the pursuit of more robust engineering education.

### DEJI model for education integration

Education misapplied is education missed. A systems model that can help ensure effective design, evaluation, justification, and integration is the DEJI model (Badiru, 2014). The model has been applied to product quality management as well as aerospace product development (Badiru, 2012) to affect the cycle of design-evaluation-justification-integration in the operating environment. Education is the ultimate operating environment where several subsystems must interact to bring about a successful end product. Some unique education environments require specialized views and practices. For example, in military education systems, a hybrid credit assessment process leverages military service for advancing STEM career development (Seaver, 2015). In general, every aspect of engineering education, from curriculum development to
educational outcome assessment can benefit from a structured application of a systems model. Using curriculum development as an illustrative example, consider the following stages:

**Design of Curriculum**: An educational curriculum must be designed to fit the current technological tools and the prevailing needs in the job market.

**Evaluation of Curriculum**: The curriculum must be evaluated periodically to ensure that it continues to meet the identified needs of the education process.

**Justification of Curriculum**: There should not be a de facto curriculum. Every curriculum should be evaluated and justified to ensure a continuity alignment with educational objectives.

**Integration of Curriculum**: Each educational outcome must be integrated to the prevailing needs of the society. What is desirable and practical in one system may be unrealistic in other systems. To minimize disconnect, the local environment of education must be considered when designing, evaluating, and justifying new or existing curricula. For example, the social environment, economic scenario, cultural needs, and political requirements are all essential within the systems view of global engineering education.

Figure 5 summarizes the potential application of the DEJI model to global engineering education curriculum. Some of the critical issues to be brought to the forefront as a result of applying a structural model to engineering education include the following:

- Focus on learner-centered curriculum design
- Pursuit of transformational engineering education that is aligned with the prevailing times
- Recognition of active and passive learning modes
- Perspective of a holistic view of engineering education input and output processes
- Essentials of teaching with the latest technology
- Appreciation of the cultural, social, political, and economic limitations affecting engineering education in some nations

**Figure 5**: Application of the DEJI Model to Global Engineering Education Curriculum Design
- Governmental competence in initiating and/or supporting engineering education programs
- Appreciation of hybrid education resources, including distance learning and online resources
- Emergence of new engineering education standards as a result of structural design, evaluation, justification, and integration of engineering education processes
- Encouragement of engineering education outcomes through diversity of backgrounds and views
- Facilitation of self-motivational and self-regulated student learning

A case example

The DEJI model was successfully applied to a program realignment and consolidation (PRAC) challenge in the Department of Systems Engineering and Management at the Air Force Institute of Technology (AFIT) in 2012. A haphazard evolution of academic programs and tracks over the years had led to a proliferation of several disjoint offerings in the department.

Through an application of the structural application of the DEJI model, a series of faculty meetings, debates, and deliberations took place at the design stage of the model. This was followed by an evaluation of how and where some academic offerings have some common basis and suitable for consolidation. Justification exercises were then organized to ensure that any consolidated offering was still needed to meet what the Air Force needs with respect to academic specialty codes (ASC) to meet Air Force needs. The integration stage of the model focused on ensuring that streamlined and consolidated academic programs were still aligned with the key priorities of the Air Force as well as the Department of Defense.

**Figure 6:** Application of DEJI Model to PRAC Exercise at AFIT
Significant efficiency, effectiveness, and operational cost savings were achieved as a result of the PRAC process. More importantly, the process facilitated full buy-in and support of all faculty members. The DEJI process allayed the fears and concerns that some academic areas might be relegated to the background. The key was that all the nuances of all the programs were considered and integrated value propositions were developed collectively by the faculty team.

The DEJI model mitigated the trepidation of disenfranchisement in the program consolidation process. With this approach, a previously humongous slate of nine programs in the department was streamlined to a track-based slate of three focus areas without compromising the overall academic offerings in the department. Figure 6 illustrates the PRAC layout used through the program consolidation exercise. Figure 7 was developed to ensure and articulate how the PRAC process still aligned with Defense priorities areas.

**Conclusion**

Engineering education is the foundation for solving complex problems now and in the future. In order to educate and inspire the present and future generations of engineering students to tackle the pressing challenges of the world, a global systems perspective must be pursued. The 14 grand challenges for engineering released by the National Academy of Engineering in 2008 highlight the pressing needs. But until we can come up with practical and viable models and templates, the challenges will remain only in terms of ideals rather than implementation ideas. In this paper, we present Badiru’s 15 grand challenges for global engineering education as one practical pathway for addressing NAE’s 14 challenges for engineering. The paper also introduces the DEJI model for a structural approach to engineering curriculum design, evaluation, justification, and integration.

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